No. A-______

In the Supreme Court of the United States

Capella Photonics, Inc.,

Applicant,

v.

Cisco Systems, Inc., *et al.*,

Respondents.

On Application for Extension of Time to File a Petition for Writ of Certiorari to the United States Court of Appeals for the Federal Circuit

APPENDIX TO APPLICATION TO THE HONORABLE CHIEF JUSTICE JOHN G. ROBERTS, JR. AS CIRCUIT JUSTICE TO EXTEND TIME TO FILE A PETITION FOR A WRIT OF CERTIORARI

ROBERT GREENE STERNE
Counsel of Record
JASON D. EISENBERG
WILLIAM H. MILLIKEN
Sterne, Kessler, Goldstein & Fox, PLLC
1100 New York Avenue, N.W.
Washington, D.C. 20005
(202) 772-8555
rsterne@sternekessler.com

Counsel for Applicant

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NOTE: This order is nonprecedential.

United States Court of Appeals for the Federal Circuit

CAPELLA PHOTONICS, INC.,
Appellant

v.

CISCO SYSTEMS, INC., CIENA CORPORATION, CORIANT OPERATIONS, INC., CORIANT (USA) INC., FUJITSU NETWORK COMMUNICATIONS, INC., LUMENTUM HOLDINGS, INC., LUMENTUM INC., LUMENTUM OPERATIONS, LLC,
Appellees

2016-2394, 2016-2395, 2017-1105, 2017-1106, 2017-1107, 2017-1108

Appeals from the United States Patent and Trademark Office, Patent Trial and Appeal Board in Nos. IPR2014-01166, IPR2014-01276, IPR2015-00726, IPR2015-00727, IPR2015-00731, IPR2015-00739, IPR2015-00816, IPR2015-00894, IPR2015-01958, IPR2015-01961, IPR2015-01969, IPR2015-01971.

ON PETITION FOR PANEL REHEARING

Before DYK, O'MALLEY, and HUGHES, *Circuit Judges.*

PER CURIAM.

ORDER

Appellant Capella Photonics, Inc. filed a petition for panel rehearing.

Upon consideration thereof,

IT IS ORDERED THAT:

The petition for panel rehearing is denied.

The mandate of the court will issue on April 16, 2018.

FOR THE COURT

April 9, 2018
Date

/s/ Peter R. Marksteiner
Peter R. Marksteiner
Clerk of Court

NOTE: This disposition is nonprecedential.

United States Court of Appeals for the Federal Circuit

CAPELLA PHOTONICS, INC.,
Appellant

v.

CISCO SYSTEMS, INC., CIENA CORPORATION, CORIANT OPERATIONS, INC., CORIANT (USA) INC., FUJITSU NETWORK COMMUNICATIONS, INC., LUMENTUM HOLDINGS, INC., LUMENTUM INC., LUMENTUM OPERATIONS, LLC,
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JUDGMENT

ROBERT GREENE STERNE, Sterne Kessler Goldstein & Fox, PLLC, Washington, DC, argued for appellant. Also represented by TYLER DUTTON, JASON DANIEL EISENBERG, DEIRDRE M. WELLS.

SARAH J. GUSKE, Baker Botts LLP, San Francisco, CA, argued for appellee Cisco Systems, Inc. Also represented by WAYNE O. STACY, Dallas, TX.

NATHANIEL T. BROWAND, Milbank, Tweed, Hadley & McCloy, LLP, New York, NY, argued for appellee Fujitsu Network Communications, Inc. Also represented by CHRISTOPHER JAMES GASPAR; MARK C. SCARSI, Los Angeles, CA.

JOEL SAYRES, Faegre Baker Daniels LLP, Denver, CO, argued for appellees Lumentum Holdings, Inc., Lumentum Inc., Lumentum Operations, LLC. Also represented by KENNETH LIEBMAN, Minneapolis, MN.

MATTHEW J. MOORE, Latham & Watkins LLP, Washington, DC, for appellee Ciena Corporation. Also represented by CHI CHEUNG, CLEMENT J. NAPLES, New York, NY; ROBERT STEINBERG, Los Angeles, CA.

JONATHAN PIETER VAN ES, Banner & Witcoff, Ltd., Chicago, IL, for appellees Coriant Operations, Inc., Coriant (USA) Inc. Also represented by THOMAS KENT PRATT; MICHAEL STEVEN CUVIELLO, Washington, DC.

THIS CAUSE having been heard and considered, it is

ORDERED and ADJUDGED:

PER CURIAM (DYK, O'MALLEY, and HUGHES, *Circuit Judges*).

AFFIRMED. *See* Fed. Cir. R. 36.

ENTERED BY ORDER OF THE COURT

February 12, 2018
Date

/s/ Peter R. Marksteiner
Peter R. Marksteiner
Clerk of Court

Trials@uspto.gov
571-272-7822

Paper 44
Entered: January 28, 2016

UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

CISCO SYSTEMS, INC., CIENA CORPORATION,
CORIANT OPERATIONS, INC., CORIANT (USA) INC., and
FUJITSU NETWORK COMMUNICATIONS, INC.,
Petitioner,

v.

CAPELLA PHOTONICS, INC.,
Patent Owner.

Case IPR2014-01166[1]
Patent RE42,368

Before JOSIAH C. COCKS, KALYAN K. DESHPANDE, and
JAMES A. TARTAL, *Administrative Patent Judges*.

TARTAL, *Administrative Patent Judge*.

FINAL WRITTEN DECISION
35 U.S.C. § 318(a) and *37 C.F.R. § 42.73*

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[1] IPR2015-00816 was joined with IPR2014-01166 on September 4, 2015, by Order in IPR2015-00816, Paper 12 (IPR2014-01166, Paper 26).

I. INTRODUCTION

Petitioner, Cisco Systems, Inc., Ciena Corporation, Coriant Operations, Inc., Coriant (USA) Inc., and Fujitsu Network Communications, Inc., filed petitions requesting an *inter partes* review of claims 1–6, 9–13, and 15–22 of U.S. Patent No. RE42,368 ("the '368 patent"). Paper 2 ("Petition" or "Pet."); *see also* IPR2015-00816, Paper 1. Based on the information provided in the Petition, and in consideration of the Preliminary Response (Paper 7; *see also* IPR2015-00816, Paper 10) of Patent Owner, Capella Photonics, Inc., we instituted a trial pursuant to 35 U.S.C. § 314(a) of: (1) claims 1–6, 9–11, 13, and 15–22 as obvious over Bouevitch,[2] Smith[3], and Lin[4] under 35 U.S.C. § 103(a); and, (2) claim 12 as obvious over Bouevitch, Smith, Lin, and Dueck[5] under 35 U.S.C. § 103(a). Paper 8 ("Institution Decision"); *see also* IPR2015-00816, Paper 11.

After institution of trial, Patent Owner filed a Response (Paper 19, "Response" or "PO Resp.") and Petitioner filed a Reply (Paper 25, "Pet. Reply"). The Petition is supported by the Declaration of Dr. Dan Marom (Ex. 1028). The Response is supported by the Declaration of Dr. Alexander V. Sergienko (Ex. 2004).

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[2] U.S. Patent No. 6,498,872 B2, issued December 24, 2002 (Ex. 1003, "Bouevitch")
[3] U.S. Patent No. 6,798,941 B2, issued September 28, 2004 (Ex. 1004, "Smith").
[4] U.S. Patent No. 5,661,591, issued August 26, 1997 (Ex. 1010, "Lin")
[5] U.S. Patent No. 6,011,884, issued January 4, 2000 (Ex. 1021, "Dueck")

A transcript of the Oral Hearing conducted on November 5, 2015, is entered as Paper 43 ("Tr.").[6]

We issue this Final Written Decision pursuant to 35 U.S.C. § 318(a) and 37 C.F.R. § 42.73. For the reasons that follow, Petitioner has shown by a preponderance of the evidence that claims 1–6, 9–13, and 15–22 of the '368 patent are unpatentable.

II. BACKGROUND

A. The '368 patent (Ex. 1001)

The '368 patent, titled "Reconfigurable Optical Add-Drop Multiplexers with Servo Control and Dynamic Spectral Power Management Capabilities," reissued May 17, 2011, from U.S. Patent No. 6,879,750 ("the '750 patent"). Ex. 1001. The '750 patent issued April 12, 2005, from application number 10/745,364, filed December 22, 2003.

According to the '368 patent, "fiber-optic communications networks commonly employ wavelength division multiplexing (WDM), for it allows multiple information (or data) channels to be simultaneously transmitted on a single optical fiber by using different wavelengths and thereby significantly enhances the information bandwidth of the fiber." *Id.* at 1:37–42. An optical add-drop multiplexer (OADM) is used both to remove wavelengths selectively from a multiplicity of wavelengths on an optical fiber (taking away one or more data channels from the traffic stream on the

[6] Patent Owner's objections to Petitioner's demonstrative slides for the oral hearing are denied because we are not persuaded that Petitioner's demonstratives add new argument. *See* Paper 41. Moreover, demonstrative slides are not evidence and have not been relied upon for this final decision.

fiber), and to add wavelengths back onto the fiber (inserting new data channels in the same stream of traffic). *Id.* at 1:45–51.

The '368 patent describes a "wavelength-separating-routing (WSR) apparatus that uses a diffraction grating to separate a multi-wavelength optical signal by wavelength into multiple spectral channels, which are then focused onto an array of corresponding channel micromirrors." *Id.* at Abstract. "The channel micromirrors are individually controllable and continuously pivotable to reflect the spectral channels into selected output ports." *Id.* According to Petitioner, the small, tilting mirrors are sometimes called Micro ElectroMechanical Systems or "MEMS." Pet. 7.

The WSR described in the '368 patent may be used to construct dynamically reconfigurable OADMs for WDM optical networking applications. *Id.* Figure 1A of the '368 patent is reproduced below.

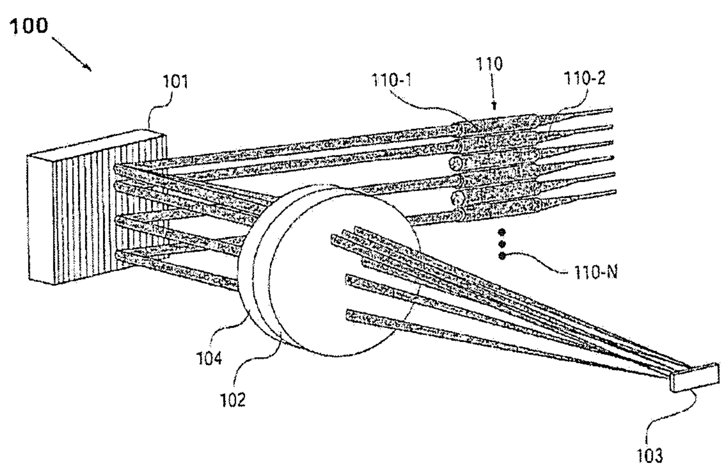

Fig. 1A

Figure 1A depicts wavelength-separating-routing (WSR) apparatus 100, in accordance with the '368 patent. WSR apparatus 100 is comprised of an array of fiber collimators 110 (multiple input/output ports, including input port 110-1 and output ports 110-2 through 110-N), diffraction grating 101 (a wavelength separator), quarter wave plate 104, focusing lens 102 (a beam-focuser), and array of channel micromirrors 103. Ex. 1001, 6:57–63, 7:55–56.

A multi-wavelength optical signal emerges from input port 110-1 and is separated into multiple spectral channels by diffraction grating 101, which are then focused by focusing lens 102 into a spatial array of distinct spectral spots (not shown). *Id.* at 6:64–7:2. Channel micromirrors 103 are positioned such that each channel micromirror receives one of the spectral channels.

Figure 1B of the '368 patent is reproduced below.

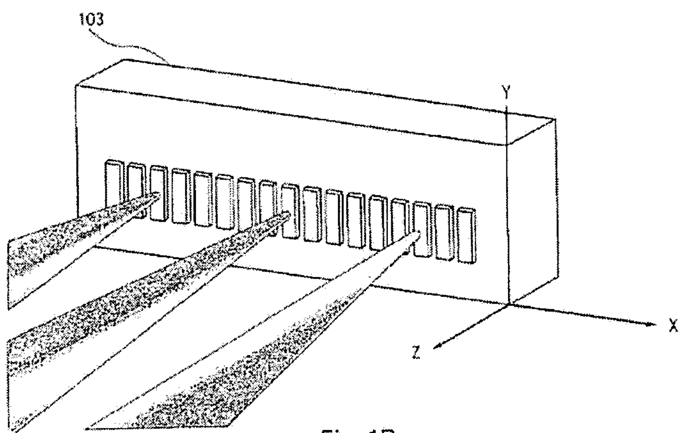

Fig. 1B

Figure 1B depicts a close-up view of the array of channel micromirrors 103 shown above in Figure 1A. *Id.* at 8:6–7. The channel micromirrors "are individually controllable and movable, e.g. pivotable (or rotatable) under analog (or continuous) control, such that, upon reflection, the spectral channels are directed" into selected output ports by way of focusing lens 102 and diffraction grating 101. *Id.* at 7:6–11.

According to the '368 patent:

> each micromirror may be pivoted about one or two axes. What is important is that the pivoting (or rotational) motion of each channel micromirror be individually controllable in an analog manner, whereby the pivoting angle can be continuously adjusted so as to enable the channel micromirror to scan a spectral channel across all possible output ports.

Id. at 9:8–14.

Figure 3 of the '368 patent is reproduced below.

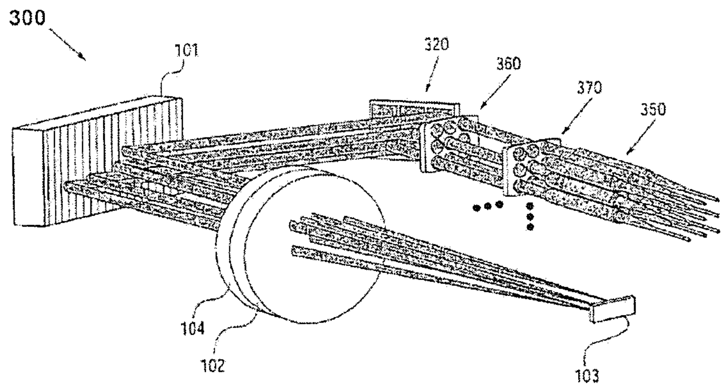

Fig. 3

Similar to Figure 1A, above, Figure 3 also shows a WSR apparatus as described by the '368 patent. Ex. 1001, 10:25–26. In this embodiment, two-dimensional array of fiber collimators 350 provides an input port and plurality of output ports. *Id.* at 10:31–32. First and second two-dimensional arrays of imaging lenses 360, 370 are placed in a telecentric arrangement between two-dimensional collimator-alignment mirror array 320 and two-dimensional fiber collimator array 350. *Id.* at 10:37–43. "The channel micromirrors 103 must be pivotable biaxially in this case (in order to direct its corresponding spectral channel to anyone of the output ports)." *Id.* at 10:43–46.

The WSR also may incorporate a servo-control assembly (together termed a "WSR-S apparatus"). *Id.* at 4:65–67. According to the '368 patent:

> The servo-control assembly serves to monitor the power levels of the spectral channels coupled into the output ports and further provide control of the channel micromirrors on an individual basis, so as to maintain a predetermined coupling efficiency of each spectral channel in one of the output ports. As such, the servo-control assembly provides dynamic control of the coupling of the spectral channels into the respective output ports and actively manages the power levels of the spectral channels coupled into the output ports.

Id. at 4:47–56.

Figure 5 of the '368 patent is reproduced below.

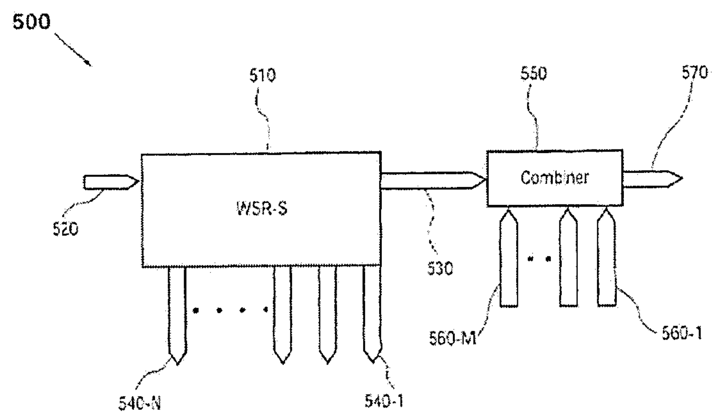

Fig. 5

Figure 5 depicts OADM 500 in accordance with the '368 patent composed of WSR-S (or WSR) apparatus 510 and optical combiner 550. *Id.* at 12:40–44. Input port 520 transmits a multi-wavelength optical signal, which is separated and routed into a plurality of output ports, including pass-through port 530 and one or more drop ports 540-1 through 540-N. *Id.* at 12:44–48. Pass-through port 530 is optically coupled to optical combiner 550, which combines the pass-through spectral channels with one or more add spectral channels provided by one or more add ports 560-1 through 560-M. *Id.* at 12:52–56. The combined optical signal is then routed into an existing port 570, providing an output multi-wavelength optical signal. *Id.* at 12:56–58.

B. Illustrative Claims

Challenged claims 1, 15, 16, and 17 of the '368 patent are independent. Claims 2–6 and 9–13 ultimately depend from claim 1 and claims 18–22 ultimately depend from claim 17. Claims 1 and 17 of the '368 patent are illustrative of the claims at issue:

> 1. An optical add-drop apparatus comprising
> an input port for an input multi-wavelength optical signal having first spectral channels;
> one or more other ports for second spectral channels; an output port for an output multi-wavelength optical signal;
> a wavelength-selective device for spatially separating said spectral channels; [and]
> a spatial array of beam-deflecting elements positioned such that each element receives a corresponding one of said spectral channels, each of said elements being individually and continuously controllable *in two dimensions* to reflect its corresponding spectral channel to a selected one of said ports *and to control the power of the spectral channel reflected to said selected port.*

Ex. 1001, 14:6–20.

> 17. A method of performing dynamic add and drop in a WDM optical network, comprising
> separating an input multi-wavelength optical signal into spectral channels;
> imaging each of said spectral channels onto a corresponding beam-deflecting element; and
> controlling dynamically and continuously said beam-deflecting elements *in two dimensions* so as to combine selected ones of said spectral channels into an output

> multi-wavelength optical signal *and to control the power of the spectral channels combined into said output multi-wavelength optical signal.*

Ex. 1001, 16:3–14.

III. ANALYSIS

A. Real Party-In-Interest

Patent Owner contends that trial should be terminated because Petitioner did not identify "Cisco's indemnified for the accused products" as a real party-in-interest "pursuant to California Commercial Code § 2312(3)." PO Resp. 59. Patent Owner provides virtually no explanation of its contention, fails to analyze any facts relative to its contention, and directs us to no legal authority in support of its contention. Accordingly, we are not persuaded that trial should be terminated under the circumstances presented.

B. Claim Construction

Only terms which are in controversy need to be construed, and then only to the extent necessary to resolve the controversy. *Vivid Techs., Inc. v. Am. Sci. & Eng'g, Inc.*, 200 F.3d 795, 803 (Fed. Cir. 1999).

1. *"to reflect"* and *"to control"*

Independent claims 1, 15, and 16 each recite outside of the preamble:

> a spatial array of beam-deflecting elements positioned such that each element receives a corresponding one of said spectral channels, each of said elements being individually and continuously controllable in two dimensions <u>to reflect its corresponding spectral channel</u> to a selected one of said ports and <u>to control the power of the spectral channel reflected</u> to said selected port.

Ex. 1001, 14:14– 20, 15:14–20, 15:31–37 (emphases added). Independent claim 17 contains a similar limitation.[7] Petitioner contends that the "to reflect" and "to control" clauses are non-functional clauses that say nothing about the claimed structure, and, therefore, are non-limiting. Pet. 10–11. We disagree. Although "apparatus claims cover what a device is, not what a device does," the language at issue here describes the function that the apparatus must be capable of performing. *Hewlett-Packard Co. v. Bausch & Lomb, Inc.*, 909 F.2d 1464, 1468 (Fed.Cir.1990); *see also K-2 Corp. v. Salomon S.A.*, 191 F.3d 1356, 1363 (Fed. Cir. 1999) (explaining that functional language is an additional limitation in the claim). In that regard, the pertinent clauses are, thus, functional rather than non-functional. Accordingly, the claimed "spatial array of beam-deflecting elements" is further limited to a spatial array that satisfies the "to reflect" and "to control" functional limitations.

2. *"continuously controllable"*

Claim 1 requires "a spatial array of beam-deflecting elements . . . each of said elements being individually and continuously controllable." Similarly, claim 17 requires "controlling dynamically and continuously said beam-deflecting elements." Petitioner asserts that "continuously controllable" should be construed to mean "under analog control." Pet. 12.

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[7] Claim 17 recites: "controlling dynamically and continuously said beam-deflecting elements in two dimensions so as to combine selected ones of said spectral channels into an output multi-wavelength optical signal and to control the power of the spectral channels combined into said output multi-wavelength optical signal." Ex. 1001, 16:9–14.

Petitioner identifies the following disclosures of the '368 patent as supporting its proposed construction:

> The patent explains that "[a] distinct feature of the channel micromirrors in the present invention, in contrast to those used in the prior art, is that the motion…of each channel micromirror is under ***analog control*** such that its pivoting angle can be ***continuously adjusted***." ([Ex. 1001], 4:7–11; emphasis added). Another passage in the specification states that "[w]hat is important is that the pivoting (or rotational) motion of each channel micromirror be individually ***controllable in an analog manner***, whereby the pivoting angle can be continuously adjusted so as to enable the channel micromirror to scan a spectral channel across all possible output ports." (*Id.*, 9:9–14; emphasis added). Yet another passage states that "channel micromirrors 103 are individually controllable and movable, e.g., pivotable (or rotatable) under analog (or continuous) control." (*Id.*, 7:6–8).

Pet. 12–13.

Dr. Marom also explains that "MEMS can be operated using analog voltage for continuous control," and states that a person of ordinary skill in the art would understand continuous control "is achieved via analog voltage control." Ex. 1028 ¶¶ 36, 58.

Patent Owner suggests in its Response that analog control does not necessarily provide the claimed "continuously controllable" beam deflecting elements (PO Resp. 42 n.4),but during the oral hearing counsel for Patent Owner indicated that "continuously controllable" was defined as "analog control," and then clarified that Patent Owner "did not offer a specific definition of continuously control." Paper 43, 57:1–58:2. Additionally, according to Dr. Sergienko, "continuous control cannot be shown by the input signal (*i.e.*, analog vs. digital) alone." Ex. 2004 ¶ 181.

Based on all of the evidence presented, we are not persuaded that "continuously controllable" is limited to "analog control," or that "analog control" necessarily corresponds to "continuous" control under all circumstances. Indeed, counsel for Petitioner suggested that although the art at issue disclosed analog control that provided continuous control, counsel further recognized that it may operate differently outside of that art. *See* Paper 43, 30:24–31–6. We determine that "continuously controllable," in light of the specification of the '368 patent, encompasses "under analog control such that it can be continuously adjusted."

3. "port"

Claim 1 requires "an input port . . . one or more other ports. . . [and] an output port." Patent Owner contends that in the '368 patent "the structure or elements making up the ports are collimators." PO Resp. 33. Patent Owner offers no definition of "port," and does not suggest that the '368 patent provides an express definition of the term, but instead argues that a "port," as claimed, is not a "circulator port" because the '368 patent "disavows circulator-based optical systems." *Id.* at 34. We disagree.

There is no dispute that the ordinary and customary meaning of "port" encompasses circulator ports, and, indeed, any "point of entry or exit of light." *See* Dr. Sergienko Deposition Transcript (Ex. 1039), 43:16–23, 45:12–13 ("The circulator ports are ports with constraints."). Nor does the '368 patent equate the term "port" to "collimator," as both "port" and "collimator" appear separately in the claims of the '368 patent. Ex. 1001, 14:7, 14:48–51. We have considered the testimony of Dr. Sergienko as well (Ex. 2004 ¶¶ 146–167), and find that even if certain fiber collimators serve as ports in the '368 patent, that does not redefine the term "port" to mean "collimator." *See id.* at ¶ 154. Thus, the primary issue is whether the '368 patent disavows circulator ports from the scope of the term "port."

Although the broad scope of a claim term may be intentionally disavowed, "this intention must be clear," *see Teleflex, Inc. v. Ficosa N. Am. Corp.*, 299 F.3d 1313, 1325 (Fed. Cir. 2002) ("The patentee may demonstrate an intent to deviate from the ordinary and accustomed meaning of a claim term by including in the specification expressions of manifest exclusion or restriction, representing a clear disavowal of claim scope,"), and cannot draw limitations into the claim from a preferred embodiment." *Conoco, Inc. v. Energy & Envtl. Int'l.*, 460 F.3d 1349, 1357 (Fed. Cir. 2006).

Patent Owner fails to show any "expressions of manifest exclusion or restriction, representing a clear disavowal of claim scope" with respect to the use of "port" in the '368 patent. Patent Owner argues that the '368 patent provides a scalable system without circulator ports, that a provisional application to the '368 patent "describes existing add/drop architectures that had a number of problems" (PO Resp. 36), that Dr. Marom obtained a patent in which collimators serve as the ports, and that "[b]ecause the inventors of the '368 [p]atent consistently emphasized the limitations of circulators and the '368 [p]atent discloses an alternative configuration, a [person of ordinary skill in the art] would have understood that the inventors were disavowing the use of optical circulators." PO Resp. 37; *see also* PO Resp. 33–35 and 38–40 (citing Ex 2004 ¶ 161).

We do not discern any "clear disavowal of claim scope" from the arguments advanced by Patent Owner. Dr. Sergienko merely states that a person of ordinary skill in the art "would read the '368 patent as teaching away from or at the least discouraging the use of circulators." Ex. 2004, ¶ 160. Even if the '368 patent were viewed as Dr. Sergienko suggests, teaching away or discouragement is not disavowal. Moreover, Petitioner further demonstrates that a provisional application to the '368 patent in fact uses circulator ports as "ports." Pet. Reply 12–13 (citing Ex. 1008, 4, Fig. 9). Such usage undermines Patent Owner's disavowal contention. We have considered all of the arguments advanced by Patent Owner in its effort to redefine "port" as excluding "circulator ports" (PO Resp. 33–40), and find insufficient support for Patent Owner's contention that the '368 patent disavows circulator ports from the scope of the term "port." We determine that "port," in light of the specification of the '368 patent, encompasses "circulator port."

4. *"beam focuser"*

Claim 11 requires a "beam-focuser for focusing said separated spectral channels onto said beam deflecting elements." The '368 patent states that "[t]he beam-focuser may be a single lens, an assembly of lenses, or other beam focusing means known in the art." Ex. 1001, 4:20–22.

Petitioner contends that "beam focuser" is "a device that directs a beam of light to a spot." Pet. 15–16. According to Petitioner:

> The Summary of the '368 patent states that the "beam-focuser focuses the spectral channels into corresponding spectral spots." ([Ex. 1001], 3:63-64.) The specification also explains that the beams of light are "focused by the focusing lens 102 into a spatial array of distinct spectral spots (not shown in FIG. lA) in a one-to-one correspondence." (*Id.*, 6:65-7:5.) The MEMS mirrors are in turn "positioned in accordance with the spatial array formed

> by the spectral spots, such that each channel micromirror receives one of the spectral channels." *Id.*)

Id. Patent Owner does not dispute expressly Petitioner's proposed construction, and provides no alternative construction of "beam focuser." Consistent with Petitioner's proposed construction, Dr. Sergienko testified that "focusing means bringing of the energy in the original image limited to the focal spot." Ex. 1039, 245:17–19. We agree that, based on the specification of the '368 patent, "beam focuser" means "a device that directs a beam of light to a spot."

5. *"dynamically"*

Claim 17 recites "[a] method of performing dynamic add and drop in a WDM optical network, comprising: . . . controlling dynamically and continuously said beam-deflecting elements in two dimensions." Ex. 1001, 16:3–10. Petitioner contends that "[t]he plain and ordinary meaning of 'dynamically' in the context of the '368 patent is 'during operation.'" Pet. 55 (citing Ex. 1003, 3:22–23 (contrasting routing that is fixed during operation: "the [prior art] wavelength routing is intrinsically static, rendering it difficult to dynamically reconfigure these OADMs."); Ex. 1028 ¶ 121)). It is unclear how Petitioner equates "dynamically" to "during operation" from the citation provided. Patent Owner does not propose a definition of "dynamically."

The '368 patent uses "dynamic" and "dynamically" throughout the specification, stating, for example, that "[t]he power levels of the spectral channels in the output ports may be dynamically managed according to demand." Ex. 1001, 11:30–32. We determine from the specification that the '368 patent uses "dynamically" in contrast to "static," in accordance with its ordinary and customary meaning.

6. Additional Claim Terms

Petitioner addresses several additional claim terms, including "servo-control assembly," "spectral monitor," and "in two dimensions." Pet. 9–15. For purposes of this decision, no express construction of any additional claim term is necessary.

C. References Asserted as Prior Art

Petitioner relies on Bouevitch, Smith, Lin, and Dueck with respect to its assertion that the challenged claims would have been obvious.

1. Bouevitch

Bouevitch describes an optical device for rerouting and modifying an optical signal, including modifying means such as a MEMS array and a liquid crystal array which function as an attenuator when the device operates as a dynamic gain equalizer (DGE), and as a switching array when the device operates as a configurable optical add/drop multiplexer (COADM). Ex. 1003, Abstract. According to Petitioner, the COADM described in Bouevitch "uses MEMS mirrors with 1 axis of rotation." Pet. 19. Petitioner also contends that the Bouevitch COADM controls the power of its output channels by tilting beam-deflecting mirrors at varying angles. Pet. 18.

2. Smith

Smith describes an optical switch including an array of mirrors tiltable about two axes, permitting a mirror tilt axis to be used for switching and a perpendicular axis to be used for power control. Ex. 1004, Abstract, 16:34–51; *see also* Ex. 1005, 6 (describing the same). Petitioner contends that "to the extent Bouevitch does not disclose 2-axis mirrors and their intended use for power control, both the Smith Patent and the Smith ['683] Provisional each does so." Pet. 19. Petitioner asserts that Smith is § 102(e) prior art as of the September 22, 2000, filing date of the Smith '683 Provisional. Pet. 17–18, 60. Patent Owner argues that Smith is not prior art to the '368 patent because the portions of Smith Petitioner relies upon are not entitled to the filing date of the Smith '683 Provisional. PO Resp. 56–59.

During this proceeding, the Federal Circuit issued a decision in *Dynamic Drinkware, LLC, v. National Graphics, Inc.*, 800 F.3d 1375 (Fed. Cir. 2015), addressing the necessary showing for a patent to claim priority from the filing date of its provisional application. The court found that the petitioner in the underlying *inter partes* review proceeding did not demonstrate that the prior art patent relied upon was entitled to the benefit of the filing date of its provisional application because the petitioner did not show written description support in the prior art provisional application *for the claims of the prior art patent*. *Id.* at 1378. Thus, demonstrating only that the provisional application of the prior art patent provided a written description of the *subject matter* in the prior art patent relied upon to establish the unpatentability of the challenged claims was insufficient to show that the prior art patent was entitled to the benefit of the filing date of its provisional application. *Id.*

In this case, Petitioner recognized that it had not shown in the Petition that the Smith '683 Provisional provided written description support *for the claims of Smith* and requested an opportunity to address the issue in light of *Dynamic Drinkware*. *See* Paper 28 (authorizing additional briefing). With our prior authorization, Petitioner filed a brief addressing the holding in *Dynamic Drinkware* and whether the Smith '683 Provisional provides written description support for the claims of Smith (Paper 34). Patent Owner filed a brief in response (Paper 37).

The parties generally agree that Smith is § 102(e) prior art as of the filing date of the Smith '683 Provisional if the Smith '683 Provisional provides written description support for: (1) the subject matter Petitioner relies upon in Smith to show the unpatentability of the challenged claims of the '368 patent, and (2) the invention of Smith.[8] *See* Paper 34, 2; *see also* Paper 37, 1 ("When relying on a provisional's filing date for a § 103 rejection, a petitioner must show: (1) the subject matter was carried over from the provisional application and (2) the patent's claims have § 112 support in the provisional application.")

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[8] We agree with Petitioner that it need not show that every claim of Smith is supported by the Smith '683 Provisional to demonstrate that subject matter disclosed in both Smith and the Smith '683 Provisional is entitled to the benefit of the filing date of the Smith '683 Provisional. *See* Paper 34, 3. We also need not reach, and take no position on Petitioner's suggestion that *Dynamic Drinkware* is invalid to the extent it conflicts with *In re Klesper*, 397 F.2d 882 (CCPA 1968) (stating "[i]t is also well settled that where a patent purports on its face to be a "continuation-in-part" of a prior application, the continuation-in-part application is entitled to the filing date of the parent application as to all subject matter carried over into it from the parent application, whether for purposes of obtaining a patent or subsequently utilizing the patent disclosure as evidence to defeat another's right to a patent. 35 U.S.C. §§ 102(e), 120; *Goodyear Tire & Rubber Co. v. Ladd*, 121 U.S. App. D.C. 275, 349 F.2d 710, (1965), certiorari denied 382 U.S. 973, 86 S. Ct. 536, 15 L.Ed.2d 465; *Asseff v. Marzall*, 88 U. S. App. D.C. 358, 189 F.2d 660, (1951), certiorari denied 342 U.S. 828, 72 S. Ct. 51, 96 L. Ed. 626; *In re Switzer*, 166 F.2d 827, 35 CCPA 1013.").

First, Petitioner has shown sufficiently that the Smith '683 Provisional provides written description support for at least two claims of Smith. Petitioner provides a claim chart identifying each of the limitations of claim 1 of Smith and the corresponding written description support as disclosed by the Smith '683 Provisional. Paper 34, attached claim chart. Petitioner also identifies written description support in the Smith '683 Provisional for Smith claim 28. *Id.* at 5.

We have considered Patent Owner's argument that the claim chart provided by Petitioner "is mere attorney argument and does not even attempt to demonstrate what a [person of ordinary skill in the art] would understand or whether the disclosure has §112 support in the Provisional," and find it not persuasive. Paper 37, 5. Patent Owner identifies no authority for the proposition that an expert declaration is necessary to show written description support. Patent Owner's further argument that Petitioner "is wrong" in its assertion that the "movable mirror" of Smith is supported by the disclosure of "elements that can be rotated in an analog fashion," is not persuasive because it is conclusory and does not address the full disclosure identified by Petitioner.

Second, Petitioner has shown sufficiently that the Smith '683 Provisional provides written description support for certain subject matter Petitioner relies upon in Smith to show the unpatentability of the challenged claims of the '368 patent (i.e., that "the subject matter was carried over from the provisional application.") According to Petitioner, the Smith '683 Provisional "describes 'a mirror array with elements that can be rotated in an analog fashion about two orthogonal axes,' with one axis for switching, and one axis for power." Pet. 19 (quoting Ex. 1004, 6). In support of Petitioner's contention that Smith is § 102(e) prior art, Dr. Marom testifies that the Smith '683 Provisional discloses all of the features of Smith relied upon to demonstrate unpatentability. Ex. 1028 ¶ 131. In his declaration, Dr. Marom provides a chart identifying the claimed subject matter of the '368 patent and the corresponding disclosures in both Smith and the Smith '683 Provisional. *Id.* ¶ 132. In particular, Dr. Marom identifies the "individually and continuously controllable in two dimensions" limitation of claims 1, 15, 16, and 17 of the '368 patent as being described by the Smith '683 Provisional as a "mirror array with elements that can be rotated in an analog fashion about two orthogonal axes." *Id.* (quoting Ex. 1005, 6) (emphasis omitted).

Patent Owner argues that the Smith '683 Provisional does not provide written description support for Smith's disclosure of the "continuously controllable" limitation of the '368 patent. PO Resp. 57–58. Although Dr. Marom expressed the opinion that the Smith '683 Provisional discloses the "continuously controllable" limitation based on its disclosure of "analog" control, Petitioner does not rely only on Smith as disclosing the "continuously controllable" limitation. *See* Pet. 19. Accordingly, whether the Smith '683 Provisional discloses the "continuously controllable" limitation has no bearing on whether Smith is available as prior art for any other disclosure upon which Petitioner relies. Similarly, to the extent Patent Owner argues that a gimbal structure described in Smith was not disclosed in the Smith '683 Provisional, Patent Owner's argument is beyond the scope of the claims of the '368 patent, which do not require a particular gimbal structure, and is not persuasive as Petitioner does not rely on the disclosure of a gimbal structure to demonstrate the unpatentability of any claim of the '368 patent.

Patent Owner also contends that the Smith '683 Provisional does not disclose certain limitations of claim 17 concerning dynamic control. We will discuss whether the Smith '683 Provisional and Smith disclose these features of claim 17 in our analysis of claim 17 below. *See* PO Resp. 58–59. More broadly, we determine that Smith is available as prior art with an effective date of the filing date of the Smith '683 Provisional for subject matter carried over to Smith from the provisional application, including the disclosure of 2-axis mirrors to control switching and power.

3. Lin

Lin describes a "spatial light modulator… operable in the analog mode for light beam steering or scanning applications." Ex. 1010, Abstract. Lin explains that the angular deflection of a mirror about the torsional axis is a function of the voltage potential applied to an address electrode. *Id.* at 6:29–32. Petitioner contends that Figure 3B of Lin depicts a continuous and linear relationship between the deflection angle of the MEMS mirrors and the applied voltage. Pet. 29.

4. Dueck

Dueck describes a wavelength division multiplexer that integrates an axial gradient refractive index element with a diffraction grating to provide efficient coupling from a plurality of input sources. Ex. 1021, Abstract. Petitioner contends that Dueck describes various diffraction gratings for use in WDM devices. Pet. 18.

D. Asserted Obviousness Over Bouevitch, Smith, and Lin

Petitioner asserts that claims 1–6, 9–11, 13, and 15–22 would have been obvious over Bouevitch, Smith, and Lin.[9] Pet. 23–60.

1. Claim 1

Claim 1, directed to an optical add-drop apparatus, requires "an input port . . . one or more other ports . . . [and] an output port." Petitioner asserts that Bouevitch discloses an optical add-drop apparatus, including an input port (labeled "IN"), one or more other ports (labeled 80b "IN ADD" and "OUT DROP"), and an output port (labeled "OUT EXPRESS"), as recited by claim 1 of the '368 patent. Pet. 24 (citing Ex. 1003, Fig. 11). Petitioner's contentions are supported by Dr. Marom. Ex. 1028 ¶¶ 49–52.

Patent Owner argues that, under its proposed claim construction of "port," Bouevitch discloses at most two ports because the '368 patent equates "port" to "collimator" and disavows circulator ports. PO Resp. 31–41. For the reasons explained above in our claim construction analysis for "port," we reject Patent Owner's claim construction for "port." Accordingly, we do not agree with Patent Owner's contention that the only

[9] Petitioner initially argues that Patent Owner admitted in a Replacement Reissue Application Declaration by Assignee that all elements of claim 1, except for two-axis mirrors, were disclosed by Bouevitch. Pet.7–9 (quoting Ex. 1002, 81–82). Petitioner identifies no persuasive authority for the proposition that such a statement should be treated as an admission in this proceeding. Moreover, rather than admit that all original elements of claim 1 are disclosed by Bouevitch, the statement makes clear that three additional references not relied upon by Petitioner in this proceeding were considered in combination with Bouevitch. As a result, we are not persuaded that Patent Owner has admitted all elements of claim 1, except for two-axis mirrors, were disclosed by Bouevitch.

ports disclosed by Bouevitch are collimator lenses 12a and 12b. Petitioner has shown, as discussed above and as supported by Dr. Marom, that Bouevitch discloses the recited input, output, and one or more other ports, as recited by claim 1.

Claim 1 requires "a wavelength-selective device" for spatially separating spectral channels. Petitioner identifies diffraction grating 20 of Bouevitch as corresponding to the recited "wavelength-selective device." Pet. 26. Claim 1 also requires "a spatial array of beam-deflecting elements." Petitioner identifies MEMS mirror array 50 of Bouevitch as corresponding to the recited "spatial array of beam-deflecting elements positioned such that each element receives a corresponding one of said spectral channels." Pet. 26–27. Patent Owner does not dispute Petitioner's contentions, with which we agree.

For each of the beam-deflecting elements, claim 1 further requires that they be "individually and continuously controllable *in two dimensions* to reflect its corresponding spectral channel to a selected one of said ports *and to control the power of the spectral channel reflected to said selected port*." As explained by Dr. Marom, Bouevitch discloses the use of variable attenuation for power control, and a person of ordinary skill in the art would understand that the necessary level of control required to balance the optical power differentials among the wavelength channels is achieved in Bouevitch with continuous control over the mirror tilt via analog voltage control. *See* Ex. 1028 ¶ 58, *see also* Ex. 1003, 7:35–37 ("The degree of attenuation is based on the degree of deflection provided by the reflector (i.e., the angle of reflection)." Patent Owner does not dispute Petitioner's contention that

Bouevitch discloses continuous control of beam-deflecting elements via analog voltage control with respect to a single axis. Instead, Patent Owner argues that "Petitioner explicitly concedes that Bouevitch does not teach or suggest beam-deflection elements that are continuously controllable *in two dimensions*." PO Resp. 42 (emphasis added).

There is no dispute that Petitioner relies on Smith as disclosing the control of beam-deflection elements in two dimensions. Petitioner explains that Smith describes a "multi-wavelength . . . optical switch including an array of mirrors tiltable about two axes, both to control the switching and to provide variable power transmission." Pet. 31 (quoting Ex. 1004, Abstract). Patent Owner does not dispute that Smith discloses beam-deflecting elements individually controllable in two dimensions, or that such control is used "to reflect" and "to control the power," as recited by claim 1.

The dispute of the parties with regard to Smith more significantly focuses on whether Smith discloses "continuous control." As discussed above, we reject Petitioner's assertion that "continuous control" means "under analog control," and determine instead that the term encompasses "under analog control such that it can be continuously adjusted." According to Petitioner:

> Smith teaches continuous control of its MEMS mirrors in an analog manner, where the force used to tilt the mirrors is "approximately ***linearly*** proportional to the magnitude of the applied voltage." (*Id.*, 15:41–42, 6–35; 17:1–23; Ex. 1028 at ¶ 59.) This linear proportionality is another way of describing a continuous, analog, relationship between the voltage driving the mirrors and the resulting mirror angle. (Ex. 1028 at ¶ 59.)

Pet. 28. The Smith '683 Provisional also states that elements "can be rotated in an analog fashion." Ex. 1005, 7. Stating that the control is "in an analog manner" or reflects an "analog" relationship, however, is not sufficient to persuasively establish that the mirrors of Smith are "under analog control." Nor has Petitioner sufficiently shown that the "analog fashion" referred to in the Smith '683 Provisional necessarily was carried forward to Smith.

Patent Owner further asserts with respect to Smith that a person of ordinary skill in the art "would view tilting according to large and small angles and [pulse width modulation] more akin to step-wise digital control than analog control." PO Resp. 45–46 (further indicating that other patents and patent applications related to Smith use digital control). In response, Petitioner does not dispute that Smith relies on digital control, but instead argues that Dr. Sergienko testified that digital control does not preclude "continuous control." Pet. Reply 22. We agree that "continuous control" is not limited to analog control; however, Petitioner's contention is that Smith discloses "continuous control" because Smith discloses "analog control," not that digital control in Smith is "continuous control." We are not persuaded that Smith discloses "continuous control" on this record because Petitioner has not shown either that the mirrors of Smith are "under analog control" or that Smith's use of digital control constitutes "continuous control."

Petitioner also contends that Lin discloses "continuous control." Pet. 29–30. Lin describes a spatial light modulator (SLM) operable in the analog mode for light beam steering or scanning applications. Ex. 1010, Abstract. Figures 3A and 3B of Lin are reproduced below.

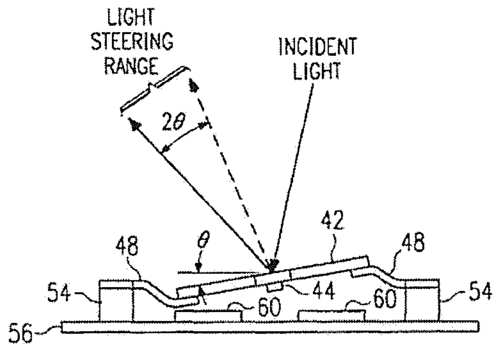

FIG. 3A

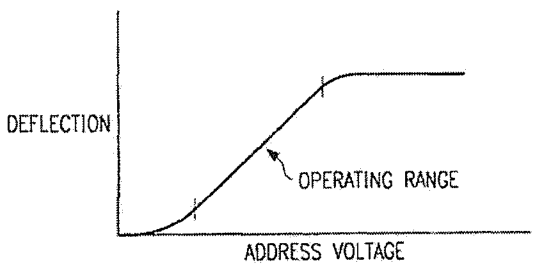

FIG. 3B

Figure 3A is a spatial light modulator, "illustrating the pixel being deflected about the torsion hinge to steer incident light in a selected direction, the deflection of the pixel being a function of the voltage applied to the underlying address electrode." Ex. 1010, 5:20–25. As Petitioner explains, Figure 3B shows a graph disclosing the continuous deflection angle of MEMS mirrors as a function of the voltage applied to affect that deflection. Pet. 29. Dr. Marom testifies that Lin "confirms that continuous and analog control of MEMS mirrors was known prior to the '368 patent's priority date." Ex. 1028 ¶ 61. Lin explains that "the angular deflection of mirror 42 about the torsional axis defined by hinges 44 is seen to be a function of the voltage potential applied to one of the address electrodes 60." Ex. 1010, 6:29–32. Lin further explains that:

> With an address voltage being applied to one address electrode 60 being from 0 to 20 volts, mirror 42 is deflected proportional to the address voltage. When SLM 40 is operated as an optical switch or light steerer, incident light can be precisely steered to a receiver such as an optical sensor or scanner. The mirror tilt angle can be achieved with a excellent accuracy for pixel steering.

Id. at 7:13–19.

Patent Owner argues that Petitioner hasn't shown that Lin discloses continuous control because such control cannot be shown by the input signal alone, and Petitioner did not "look at the structure of the mirror and how the voltage affects movement of the mirror." PO Resp. 49. Patent Owner's conclusory and unsupported argument is not persuasive because it does not address the disclosures of Lin as summarized above, which we find establish "continuous control," as recited in claim 1.

Patent Owner also argues that Lin does not disclose continuous control in two dimensions. *Id.* at 49–50. Petitioner, however, relies on Smith, not Lin, as disclosing 2-axis mirrors, and there is no contention that Lin, alone, discloses continuous control in two dimensions.

In summary, for the reasons discussed above, Petitioner has established that Bouevitch discloses all of the recited limitations of claim 1 for an array of mirrors individually and continuously controllable on a single axis, but not on a two axis (i.e., two dimension) array "to reflect its corresponding spectral channel to a selected one of said ports and to control the power of the spectral channel reflected to said selected port." Patent Owner did not dispute that Bouevitch discloses continuous control of beam-deflecting elements via analog voltage control with respect to a single axis, and Petitioner has demonstrated that Lin also discloses such "continuous control." Finally, Petitioner has established that Smith discloses an array of mirrors controllable in two dimensions "to reflect" and "to control," as recited by claim 1. Thus, the remaining issue is whether Petitioner has provided "some articulated reasoning with some rational underpinning to support the legal conclusion of obviousness." *KSR Int'l Co. v. Teleflex Inc.*, 550 U.S. 398 (2007).[10]

With respect to a rationale for combining Bouevitch and Smith, Petitioner contends the use of the two-axis mirror of Smith in Bouevitch: (1) is a simple substitution of one known element for another yielding predictable results, (2) is the use of a known technique to improve similar devices, (3) would be obvious to try as there are only two options for tilting MEMS mirrors: one-axis and two-axis mirrors, and (4) would be motivated to reduce crosstalk in attenuation and to increase port density. Pet. 20–21.[11]

Petitioner also contends that several reasons support the addition of Lin's continuous, analog control to the asserted combination, including

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[10] The question of obviousness is resolved on the basis of underlying factual determinations including (1) the scope and content of the prior art, (2) any differences between the claimed subject matter and the prior art, and (3) the level of skill in the art; and (4) secondary considerations, i.e. objective evidence of unobviousness. *See Graham v. John Deere Co.*, 383 U.S. 1, 17–18 (1966). We have considered each of the Graham factors and incorporate our discussion of those considerations, to the extent there is a dispute, in our evaluation of the reasoning that supports the asserted combination. We further observe that, in this proceeding, evidence of secondary considerations has not been offered for evaluation.

[11] Petitioner also argues, without citing authority, that Patent Owner admitted the "combinability" of references during prosecution, and that such admission applies to the references identified by Petitioner in "the identical technology area." Pet. 22–23. We find no such admission.

interchangeability with discrete-step mirrors and more precision in matching the optimal coupling value. Pet. 30.

Patent Owner disputes the sufficiency of the rationale provided in the Petition. PO Resp. 17–31. First, Patent Owner argues that Petitioner "conflates disparate embodiments of Bouevitch," "one functioning in a DGE to control power [shown in Bouevitch Figure 5] and one functioning in COADM to control switching [shown in Bouevitch Figure 11]." *Id.* at 17–18. Petitioner, however, persuasively explains that it does not rely on an embodiment of Bouevitch functioning to control power to show that the features of claim 1 were disclosed in the asserted art. Pet. Reply 2–3 ("[Bouevitch] Fig. 5 is not relevant to Petitioner's positions or the institution. . . . Figure 11 includes the relevant disclosure."). Instead, Petitioner relies on Smith as disclosing power control, stating in the Petition that "Smith describes a 'multi-wavelength . . . optical switch including an array of mirrors tiltable about two axes, both to control the switching and to provide variable power transmission.'" Pet. 31 (quoting Ex. 1004, Abstract).

Although Petitioner includes a discussion of Bouevitch's disclosure of power control in the Petition, it is clear that the asserted combination does not stand or fall on that disclosure. The Petition states that a person of ordinary skill in the art "would be motivated to use the 2-axis system of Smith within the system of Bouevitch for power control." Pet. 34. Petitioner's discussion of the power control embodiment of Bouevitch in support of the rationale for the asserted combination with Smith (i.e., both Smith and Bouevitch address power control) does not impose an obligation on Petitioner to articulate a rationale for including the power control embodiment of Bouevitch in the asserted combination.

Patent Owner also argues that Petitioner implicitly relies on the power control embodiment of Bouevitch to show that Bouevitch discloses beam deflecting mirrors that are continuously controllable. PO Resp. 21. We are persuaded that, to the extent Petitioner relies on Bouevitch as disclosing reflectors that are continuously controllable based on the power control embodiment of Bouevitch (*see* Pet. 28 (quoting Ex. 1001 discussing the embodiment shown in Figure 5 of Bouevitch)), Petitioner was obligated to, and did not, provide a rationale for combining an embodiment of Bouevitch directed to power control with an embodiment relied on by Petitioner to show switching control.[12] Petitioner, however, further relies on Lin as disclosing continuous control. Accordingly, Petitioner may show unpatentability based on the combination of Bouevitch, Smith, and Lin without relying on the power control embodiment of Bouevitch, and without providing a rationale for incorporating the power control embodiment of Bouevitch in the asserted combination.

Patent Owner also argues that a person of ordinary skill in the art would not have combined Bouevitch and Smith for various reasons. PO

[12] Petitioner argues in its Reply that Bouevitch teaches a MEMS structure for switching in Figure 11 that also performs power control; however, Petitioner has not shown sufficiently that it presented this contention in the Petition, or that its arguments were not intertwined with its assertions related to Bouevitch Figure 5. Similarly, Petitioner did not contend in the Petition, as it does in its Reply, that Bouevitch inherently discloses angular misalignment for power control. *See* Pet. Reply 5–6. Arguments made for the first time in a reply generally are not given consideration.

Resp. 22–31. Patent Owner argues that Petitioner has not reconciled "the technical differences between the references," or explained whether the components "would continue to operate as desired." *Id.* at 23. Patent Owner lists many considerations an optical system architect would have to take into account purportedly not addressed in the Petition. *Id.* at 23–24. Patent Owner further asserts that Dr. Marom has designed a two-axis mirror to replace a two-axis mirror, and that "[r]e-designing micromirrors is not a simple substitution because the redesign is complex." *Id.* at 24–25. In this proceeding, however, Dr. Sergienko was asked whether such technical considerations presented problems that could not be overcome by one of skill in the art, and indicated "no." Ex. 1039, 266:16–267:25. Moreover, "[t]he test for obviousness is not whether the features of a secondary reference may be bodily incorporated into the structure of the primary reference. . . . Rather, the test is what the combined teachings of those references would have suggested to those of ordinary skill in the art." *In re Keller*, 642 F.2d 413, 425 (CCPA 1981). Here, the test for obviousness reflects what the combined teachings of Bouevitch, Lin, and Smith would have suggested to one of ordinary skill in the art, and does not require that any one particular component of a reference must be bodily incorporated, or physically inserted, into another reference.

Patent Owner argues more particularly that a person of ordinary skill in the art "would not have been motivated to use Smith's mirrors in the Figure 5 embodiment in Bouevitch." PO Resp. 25. Patent Owner's argument is not persuasive because, as discussed above, Petitioner does not rely on the Figure 5 embodiment in Bouevitch.

Next, Patent Owner argues that a person of ordinary skill in the art would not have been motivated to combine Smith's tiltable mirrors with Bouevitch because it would disrupt Bouevitch's explicit teaching of parallel alignment," and "Bouevitch discourages, if not teaches away from, misalignment to control power." PO Resp. 26–30. "The prior art's mere disclosure of more than one alternative does not constitute a teaching away from any of these alternatives because such disclosure does not criticize, discredit, or otherwise discourage the solution claimed in the … application." *In re Fulton*, 391 F.3d 1195, 1201 (Fed. Cir. 2004). While Bouevitch discusses how angular displacement is disadvantageous in certain respects (*see* Ex. 1028, 2:1–7), we are not persuaded such discussion is sufficient to constitute a teaching away. To the contrary, Petitioner has shown persuasively that Bouevitch uses angular misalignment to control power in at least some embodiments of Bouevitch. Pet. Reply 3–5; *see also* Ex. 1028 ¶ 71.

Patent Owner also argues that absent hindsight, a person of ordinary skill would not have incorporated the two-axis mirror of Smith into Bouevitch, which uses a one-axis mirror, because a two-axis mirror is "a more complex structure." PO Resp. 30–31. We find Patent Owner's argument conclusory and not persuasive because it fails to address the benefits of a two-axis mirror disclosed by Smith which would be apparent to one of skill in the art without hindsight. *See* Ex. 1004, 7:1–52. We also find persuasive Petitioner's contention that it would have been obvious to try, because, as Dr. Marom testified, (1) there were only two solutions to the known need to deflect light beams with MEMS: 1-axis or 2-axis, (2) a person of ordinary skill would have had a high expectation of success to try two-axis mirror control in Bouevitch, and (3) the result of the combination would be predictable. *See* Pet. 21–22; Reply 8–9; Ex. 1045 ¶ 45.

With respect to Lin, Patent Owner argues that Petitioner fails to explain either how the multiple axes of Smith could be combined with Lin's analog control or how to modify Lin's structural elements to incorporate a two-dimensional rotation, and further asserts that, because it would require an engineering feat, it is not a simple substitution. PO Resp. 50–51. As explained above, however, the test for obviousness is not whether the features of one reference may be bodily incorporated into the structure of another reference. Moreover, the references of record reflect that there are routinely complex design considerations in the fiber optic communications field. Patent Owner does not explain persuasively why combining the teachings of Smith and Lin would be beyond the skill of a skilled artisan, even if feats of engineering are contemplated.

Petitioner has articulated sufficiently reasoning with some rational underpinning to support the legal conclusion of obviousness based on the asserted combination of Bouevitch, Smith, and Lin. With regard to incorporating the teaching of a two-axis mirror in Smith with Bouevitch, we are persuaded that it is a simple substitution, notwithstanding the fact that it may require substantial engineering as a practical matter. Single-axis and two-axis mirrors were known to be interchangeable. Smith not only expressly acknowledges this interchangeability, but also identifies benefits to the use of a two-axis mirror: "in comparison to the two-axis embodiment, single axis systems may be realized using simpler, single axis MEMS arrays but suffer from increased potential for crosstalk between channels." Ex. 1004, 18:17–18; Ex. 1005, 12; *see also* Ex. 1004, 16:55–58, Ex. 1005, 11 ("both single and dual axis mirror arrays may be used in a variety of switching configurations, although the two-axis components are preferred.") The asserted combination of Smith and Bouevitch and Lin yields a predictable result. *See KSR*, 550 U.S. at 416 ("The combination of familiar elements according to known methods is likely to be obvious when it does no more than yield predictable results.").

We are further persuaded that Petitioner has identified additional "rational underpinning" in supported of the asserted combination. Dr. Marom testified that applying the two-axis mirror of Smith to Bouevitch would have been beneficial "because choosing only a single axis for both port selection and attenuation may result in dynamic fluctuations of power crosstalk between ports as attenuation level is varied," would reduce "the risk of the signal bleeding into a port that is adjacent to the output port along the switching axis, and would provide finer control over attenuation by allowing the use of the full dynamic range of the mirror tilt in the first axis for attenuation. *See* Ex. 1028 ¶¶ 73–75; *see also* Pet. 22. For similar reasons Petitioner has also shown that the application of Smith to Bouevitch constitutes the use of known techniques to improve similar devices. *See* Pet. 20–21.

We also find persuasive Petitioner's contention that a person of ordinary skill in the art would have combined the teachings of Lin with Bouevitch and Smith because:

> (1) continuously controlled mirrors were known to be interchangeable with discrete-step mirrors; (2) continuously

> controlled mirrors allow arbitrary positioning of mirrors and can more precisely match the optimal coupling value; and (3) Lin specifically teaches that its analog, continuous MEMS mirrors would be useful in optical switching applications like Bouevitch's and Smith's ROADM devices.

Pet. 30 (citing Ex. 1010 at 2:6–9; Ex. 1028 ¶ 62). Petitioner also has shown that the use of analog continuous control was the known alternative to discrete (or step-wise) control, and would have been obvious to try and expected to work when applied to Bouevitch. Pet. 30–31 (citing Ex. 1028 ¶¶ 61–65).

For the foregoing reasons, Petitioner has established by a preponderance of the evidence that claim 1 would have been obvious over Bouevitch, Smith, and Lin.[13]

2. Claims 2, 5, 6, 9, 10, 13, 15, and 16

Claims 2, 5, 6, 9, 10, 13, 15, and 16 ultimately depend from claim 1. In addition to addressing the elements of claim 1, we agree with Petitioner's identification of how claims 2, 5, 6, 9, 10, 13, 15, and 16 would have been obvious over Bouevitch, Smith, and Lin, as supported by the declaration of Dr. Marom. Pet. 35–37, 42–46, 49–53. For example, claim 2 requires "a control unit for controlling each of said beam-deflecting elements," and Petitioner has shown that it would have been obvious to apply the control unit disclosed by Smith to Bouevitch as it is the addition of a known element which yields the predictable result of electronic control. *See* Pet. 35–37. As another example, claim 13 requires that "beam-deflecting elements comprise micromachined mirrors." Petitioner has shown that mirrors disclosed in

[13] Patent Owner provides no persuasive evidence of secondary considerations to support the patentability of claims of the '368 patent.

Bouevitch and Smith are "micromachined mirrors." Pet. 49. Patent Owner has not raised additional arguments with respect to claims 2, 5, 6, 9, 10, 13, 15, and 16 beyond those asserted with respect to claim 1, addressed above. We have assessed the information provided and determine that Petitioner has established by a preponderance of the evidence that claims 2, 5, 6, 9, 10, 13, 15, and 16 would have been obvious over Bouevitch, Smith, and Lin.

3. Claims 3 and 4

Claim 3, which depends from claim 1, further requires that the control unit "comprises a servo-control assembly, including a spectral monitor for monitoring power levels of selected ones of said spectral channels, and a processing unit responsive to said power levels for controlling said beam deflecting elements." Claim 4, which depends from claim 3, further requires that the "servo-control assembly maintains said power levels at predetermined values." The '368 patent states that:

> The electronic circuitry and the associated signal processing algorithm/software for such processing unit in a servo-control system are known in the art. A skilled artisan will know how to implement a suitable spectral monitor along with an appropriate processing unit to provide a servo-control assembly in a WSP-S apparatus according to the present invention, for a given application.

Ex. 1001, 12:9–15. Accordingly, the '368 patent expressly recognizes that the additional features of claims 3 and 4 were "known in the art" to a skilled artisan and would have been obvious to implement.

We agree with Petitioner's contention that Smith's disclosure of a controller that receives feedback from an optical power monitor corresponds to the claimed servo-control assembly and spectral monitor, and serves the same purpose. Pet. 38–41 (citing, *inter alia*, Ex. 1004, Fig. 8, 18:42–53, 13:20–24). With regard to claim 4, Petitioner directs us to Smith, which teaches that the controller "adjust[s] the mirror positions to adjust the transmitted power to conform to one or more ***predetermined criteria***." Pet. 41–42 (quoting Ex. 1004, 11:48–51).

Petitioner also provides sufficient articulated reasoning with some rational underpinning to support the combination of the Smith controller and optical power monitor with Bouevitch, including "as an alternative to the 'external feedback' for power control that Bouevitch explains should be eliminated," and that a person of ordinary skill "would appreciate that the feedback-driven control of Smith would improve the precision of the mirror-based switching system of Bouevitch." Pet. 39–41. Petitioner also reasons that it would have been obvious to try the predetermined power settings of Smith within Bouevitch, because "Smith teaches that predetermined power values could make up for inherent problems in optical switching, such as power variations from optical amplifiers and manufacturing and environmental variations, and because 'WDM systems must maintain a significant degree of uniformity of power levels across the WDM spectrum.'" *Id.* at 42 (quoting Ex. 1004, 6:24–50; citing Ex. 1028 ¶ 92).

Patent Owner argues, with virtually no explanation, that "Smith does not teach the service control and spectral monitory elements, as claimed." PO Resp. 55. Patent Owner also asserts that Petitioner fails to explain how or why a person of ordinary skill would have been able to add Smith's control features to Bouevitch without disrupting Bouevitch's operation because they are disparate technologies. *Id.* Patent Owner does not address the disclosure of the '368 patent, which states that a "skilled artisan will know how to implement a suitable spectral monitor," or the reasoning provided by Petitioner. We have considered Patent Owner's arguments and find them to be insufficiently supported and conclusory. On the other hand, we conclude that Petitioner's reasoning is sound and supported adequately by the record. Petitioner has established by a preponderance of the evidence that claims 3 and 4 would have been obvious over Bouevitch, Smith, and Lin.

4. Claim 11

Claim 11 depends from claim 1 and further requires "a beam-focuser for focusing said separated spectral channels onto said beam deflecting elements." Petitioner contends, and we agree, that Bouevitch discloses a "beam-focuser element at reflector 10 in Figure 11." Pet. 46; *see also* Ex. 1028 ¶ 101. Petitioner further explains that in Bouevitch "reflector 10 directs the separated beams of light λ_1 and λ_2 from the points on the reflector annotated as R onto the corresponding beam deflecting mirrors 51 and 52 in MEMS array 50." Pet. 46.

Patent Owner argues that Petitioner ignores the distinction between imaging/directing, as recited in claims 1 and 17, and "focusing" as recited in claim 11. PO Resp. 55–56. Patent Owner identifies no persuasive evidence in support of its argument, and does not explain what the distinction is that has been ignored. Claim 21 of the '368 patent recites "imaging comprises focusing," and Dr. Sergienko testified that "focusing" is a type of "imaging" in the '368 patent. *See* Ex. 1039, 245:13–19.

Petitioner has established by a preponderance of the evidence that Bouevitch discloses a "beam focuser," as recited in claim 11, and that claim 11 would have been obvious over Bouevitch, Smith, and Lin.

5. Claims 17–22

Claim 17 is directed to "a method of performing dynamic add and drop in a WDM optical network" which includes elements substantially similar to features of apparatus claim 1. Petitioner contends, and we agree, that Bouevitch discloses the first step of "separating an input multi-wavelength optical signal into spectral channels" at Figure 11, where diffraction grating 20 spatially separates combined channels $\lambda_1\lambda_2$ into spatially-separated channels. Pet. 54 (citing Ex. 1003, 14:48–53, 8:10–22; Ex. 1028 ¶ 117). Petitioner also contends that Bouevitch discloses imaging spectral channels onto a corresponding beam-deflecting element by using reflector 10 to image each channel onto a corresponding MEMS mirror element. Pet. 54. Petitioner asserts that other than for "dynamically," the method step for "controlling dynamically and continuously said beam-deflecting elements *in two dimensions* so as to combine selected ones of said spectral channels into an output multi-wavelength optical signal *and to control the power of the spectral channels combined into said output multi-wavelength optical signal*" would have been obvious for the same reasons articulated with regard to claim 1. Pet. 55. Petitioner also contends that:

> Both Bouevitch and Smith teach dynamic control during the operation of their add/drop devices. (Ex. 1028 at ¶ 122.) Bouevitch's device can be used as a "dynamic gain equalizer and/or configurable add/drop multiplexer," which plainly includes dynamic control of the mirrors that perform those actions. (*Id.*, 2:24-25.) Smith notes that it "is well known" that

> power control "should be dynamic and under feedback control since the various wavelength components ***vary in intensity with time***." (*Id.*, 6:37-50; emphasis added, 2:23-31, 7:24-31). The Smith Provisional also supports dynamic control, as is apparent from the fact that the Smith OADM accepts control signals/commands as it operates. (*See* Smith Provisional, Fig. 11 (noting "continuous" calibration and control by "network commands"), 7 (add/drop under control of an external (and thus changeable) signal); Ex. 1028 at ¶ 122.

Id. at 56. We find Petitioner's contentions persuasive.

In addition to relying on its arguments asserted with respect to claim 1, which we address above, Patent Owner further argues that Petitioner mistakenly asserts that Bouevitch teaches "imaging" because it teaches "focusing," and does not describe with any particularity how Bouevitch teaches "imaging." PO Resp. 51–52. As discussed above with regard to claim 11, we find Patent Owner's argument unpersuasive because Patent Owner offers no explanation for how it contends imaging should be distinguished from focusing, and identifies no evidence in support of its argument. Dr. Marom testified that "Claim 21 confirms that one type of such 'imaging' is focusing, by reciting 'the method of claim 17, wherein said ***imaging comprises focusing*** said spectral channels onto said beam–deflecting elements.'" Ex. 1028 ¶ 118. Dr. Sergienko testified that "focusing" is a type of "imaging" in the '368 patent. *See* Ex. 1039, 245:13–19.

Patent Owner also argues that Petitioner has shown no disclosure corresponding to controlling beam-deflecting elements so as to combine spectral channels into an output signal. PO Resp. 52. To the contrary, we agree with Petitioner that Bouevitch discloses a configurable optical add/drop multiplexer (COADM) which combines spectral channels into an output signal. Pet. 55–56. Contrary to Patent Owner's argument, Petitioner also notes that Dr. Sergienko agreed that one point of a COADM is to combine one of the selected signals into the multi-wavelength output of the device. Ex. 1039, 96:14–22.

Claims 18–22 ultimately depend from claim 17. In addition to addressing the elements of claim 17, we agree with Petitioner's identification of how claims 18–22 would have been obvious over Bouevitch, Smith, and Lin, as supported by the declaration of Dr. Marom. Pet. 56–60. We understand Patent Owner to assert the same argument with respect to claim 21, which recites "imaging comprises focusing said spectral channels onto said beam –deflecting element," as Patent Owner asserts in regard to the focusing limitation of claim 11, and we find it not persuasive for the same reasons discussed above.[14] We have assessed the information provided and determine that Petitioner has established by a preponderance of the evidence that claims 17–22 would have been obvious over Bouevitch, Smith, and Lin.

E. Asserted Obviousness Over Bouevitch, Smith, Lin, and Dueck

Petitioner contends claim 12 would have been obvious over Bouevitch, Smith, Lin, and Dueck. Pet. 47–49. Claim 12 recites the device of claim 1, wherein the wavelength-selective device comprises a device selected from the group consisting of ruled diffraction gratings, holographic

[14] The Patent Owner Response refers to claim 22 in regard to Patent Owner's contention that Bouevitch fails to teach "focusing;" however, claim 22 does not recite "focusing," whereas claim 21 does. *See* PO Resp. 55–56.

diffraction gratings, echelle gratings, curved diffraction gratings, and dispersing prisms. Ex. 1001, 14:63–67.

Petitioner contends that any of the types of wavelength-selective devices recited in claim 12 would have been obvious because "[e]ach type was known in the prior art, each was interchangeable as a wavelength selective device, and each was one of a small set of possible choices." Pet. 48 (citing Ex. 1028 ¶¶ 103–104).[15] Petitioner also contends that Dueck discloses ruled diffraction gratings, as claimed. Pet. 48. Petitioner further asserts that it would have been obvious to try Dueck's ruled diffraction gratings in the devices of Bouevitch and Smith because it represents the "best mode" of separating wavelengths in WDM devices. *Id.* at 48–49.

Patent Owner argues that a person of ordinary skill would not have been motivated to use Dueck's diffraction grating. PO Resp. 52–54. According to Patent Owner, Dueck discloses a diffraction grating that reflects an input light beam to an output port at very nearly the same angle as the incident angle. *Id.* Patent Owner reasons that because no configuration shown in Bouevitch is designed to reflect a light beam at the same angle as Dueck, there is no motivation to use Dueck's diffraction grating in Bouevitch. *Id.* In reply, Petitioner asserts that Dueck was relied on only to show "prior art knowledge of diffraction gratings in general." Pet. Reply 23. As noted above, the obviousness test has no bodily incorporation requirement, and is instead focused on "what the combined teachings of

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[15] Patent Owner suggests that because trial was instituted on a ground that included Dueck, we are precluded from considering Petitioner's arguments that claim 12 would have been obvious without Dueck. Our Institution Decision in this case contained no such limitation.

those references would have suggested to those of ordinary skill in the art." *In re Keller*, 642 F.2d at 425. While the particular configuration of the ruled diffraction grating in Dueck may not be readily incorporated into Bouevitch, Dueck nonetheless discloses the broader concept of a ruled diffraction grating. Indeed, Dr. Sergienko testified that a ruled diffraction grating could have been used in Bouevitch, as well as holographic diffraction grating, or an echelle grating, as they are all reasonable substitutes for one another and would be expected to work. *See* Ex. 1039, 256:13–259:7.

We have assessed the information provided and determine that Petitioner has established by a preponderance of the evidence that claim 12 would have been obvious over Bouevitch, Smith, Lin, and Dueck.

F. Conclusion

Petitioner has shown by a preponderance of the evidence that claims 1–6, 9–11, 13, and 15–22 would have been obvious over Bouevitch, Smith, and Lin, and that claim 12 would have been obvious over Bouevitch, Smith, Lin, and Dueck.

IV. ORDER

In consideration of the foregoing, it is hereby:

ORDERED that, based on a preponderance of the evidence, claims 1–6, 9–13, and 15–22 of U.S. Patent No. RE42,368 are unpatentable; and,

FURTHER ORDERED that, because this is a Final Written Decision, the parties to the proceeding seeking judicial review of the decision must comply with the notice and service requirements of 37 C.F.R. § 90.2.

For PETITIONER:

Wayne O. Stacy
Sarah Guske
COOLEY LLP
wstacy@cooley.com
CapellaCisco@cooley.com

For PATENT OWNER:

Robert Greene Sterne
Jon E. Wright
Jason D. Eisenberg
Jonathan Tuminaro
STERNE, KESSLER, GOLDSTEIN & FOX P.L.L.C.
rsterne-PTAB@skgf.com
jwright-PTAB@skgf.com
jasone-PTAB@skgf.com
jtuminar-PTAB@skgf.com

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(19) **United States**
(12) **Reissued Patent**
Chen et al.

(10) **Patent Number: US RE42,368 E**
(45) **Date of Reissued Patent: May 17, 2011**

(54) **RECONFIGURABLE OPTICAL ADD-DROP MULTIPLEXERS WITH SERVO CONTROL AND DYNAMIC SPECTRAL POWER MANAGEMENT CAPABILITIES**

(75) Inventors: **Tai Chen**, San Jose, CA (US); **Jeffrey P. Wilde**, Morgan Hill, CA (US); **Joseph E. Davis**, Morgan Hill, CA (US)

(73) Assignee: **Capella Photonics, Inc.**, San Jose, CA (US)

(21) Appl. No.: **12/816,084**

(22) Filed: **Jun. 15, 2010**

Related U.S. Patent Documents

Reissue of:
(64) Patent No.: **6,879,750**
Issued: **Apr. 12, 2005**
Appl. No.: **10/745,364**
Filed: **Dec. 22, 2003**

U.S. Applications:
(63) Continuation of application No. 10/005,714, filed on Nov. 7, 2001, now Pat. No. 6,687,431, which is a continuation of application No. 09/938,426, filed on Aug. 23, 2001, now Pat. No. 6,625,346.

(60) Provisional application No. 60/277,217, filed on Mar. 19, 2001.

(51) **Int. Cl.**
G02B 6/28 (2006.01)
H04J 14/02 (2006.01)

(52) **U.S. Cl.** **385/24**; 385/10; 385/33; 385/37; 398/83

(58) **Field of Classification Search** 385/24, 385/11, 10, 37, 34, 33; 398/79, 82, 83, 84, 398/88, 87
See application file for complete search history.

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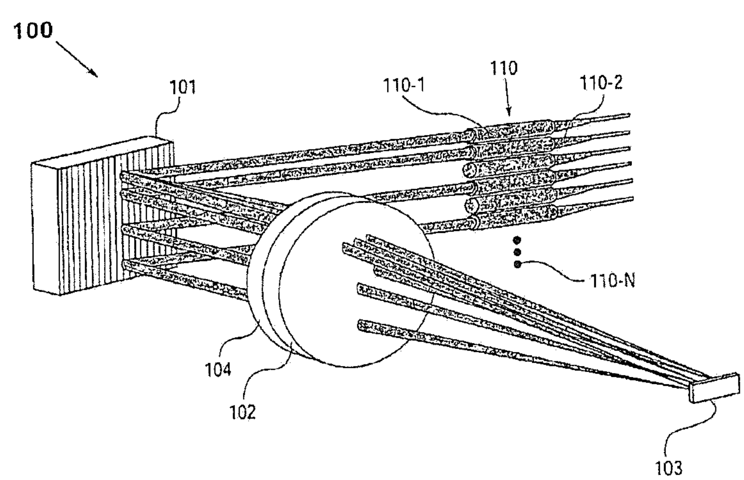
(Continued)

Primary Examiner — Brian M Healy
(74) *Attorney, Agent, or Firm* — Barry N. Young

(57) **ABSTRACT**

This invention provides a novel wavelength-separating-routing (WSR) apparatus that uses a diffraction grating to separate a multi-wavelength optical signal by wavelength into multiple spectral channels, which are then focused onto an array of corresponding channel micromirrors. The channel micromirrors are individually controllable and continuously pivotable to reflect the spectral channels into selected output ports. As such, the inventive WSR apparatus is capable of routing the spectral channels on a channel-by-channel basis and coupling any spectral channel into any one of the output ports. The WSR apparatus of the present invention may be further equipped with servo-control and spectral power-management capabilities, thereby maintaining the coupling efficiencies of the spectral channels into the output ports at desired values. The WSR apparatus of the present invention can be used to construct a novel class of dynamically reconfigurable optical add-drop multiplexers (OADMs) for WDM optical networking applications.

22 Claims, 12 Drawing Sheets



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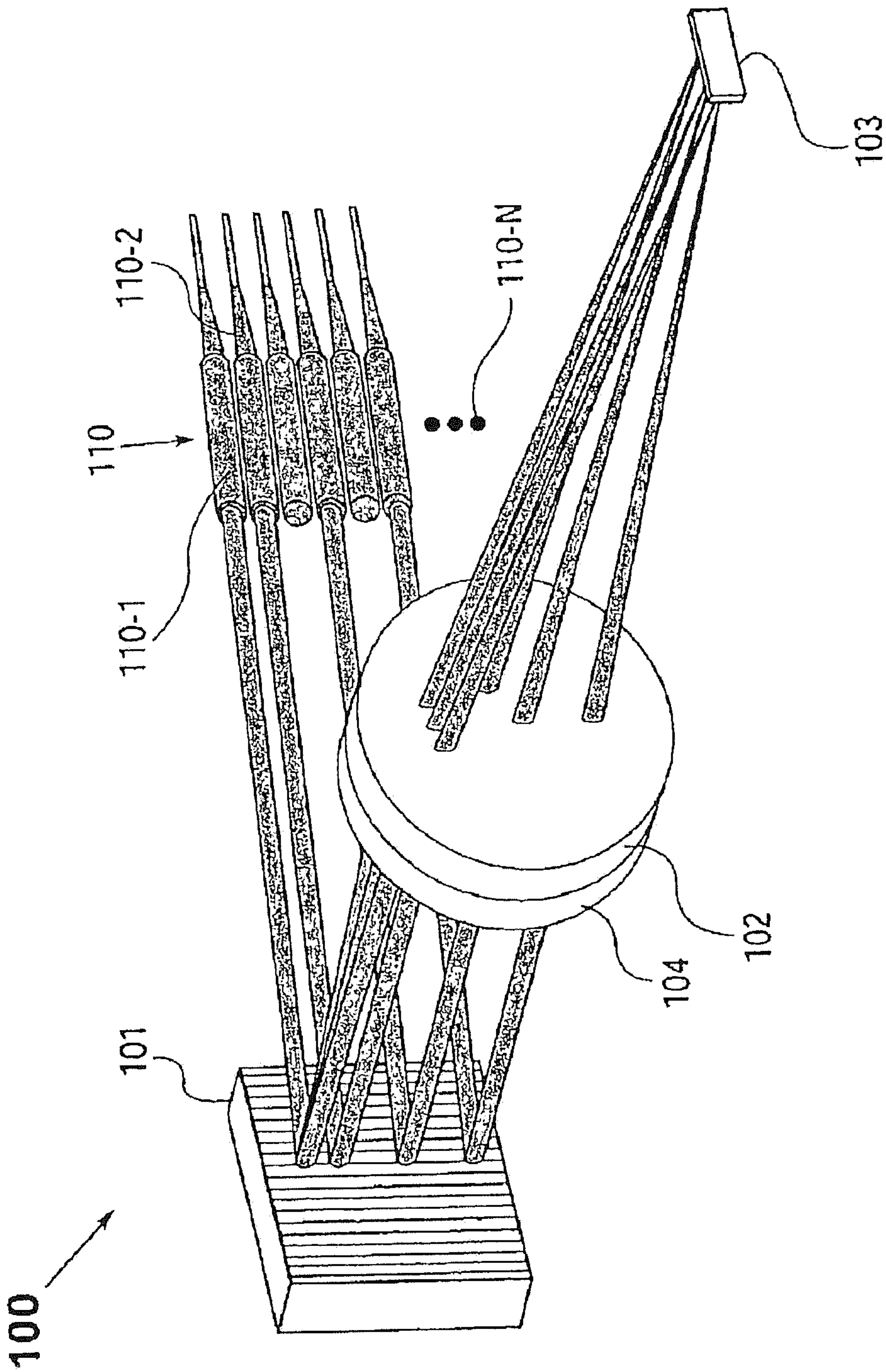


Fig. 1A

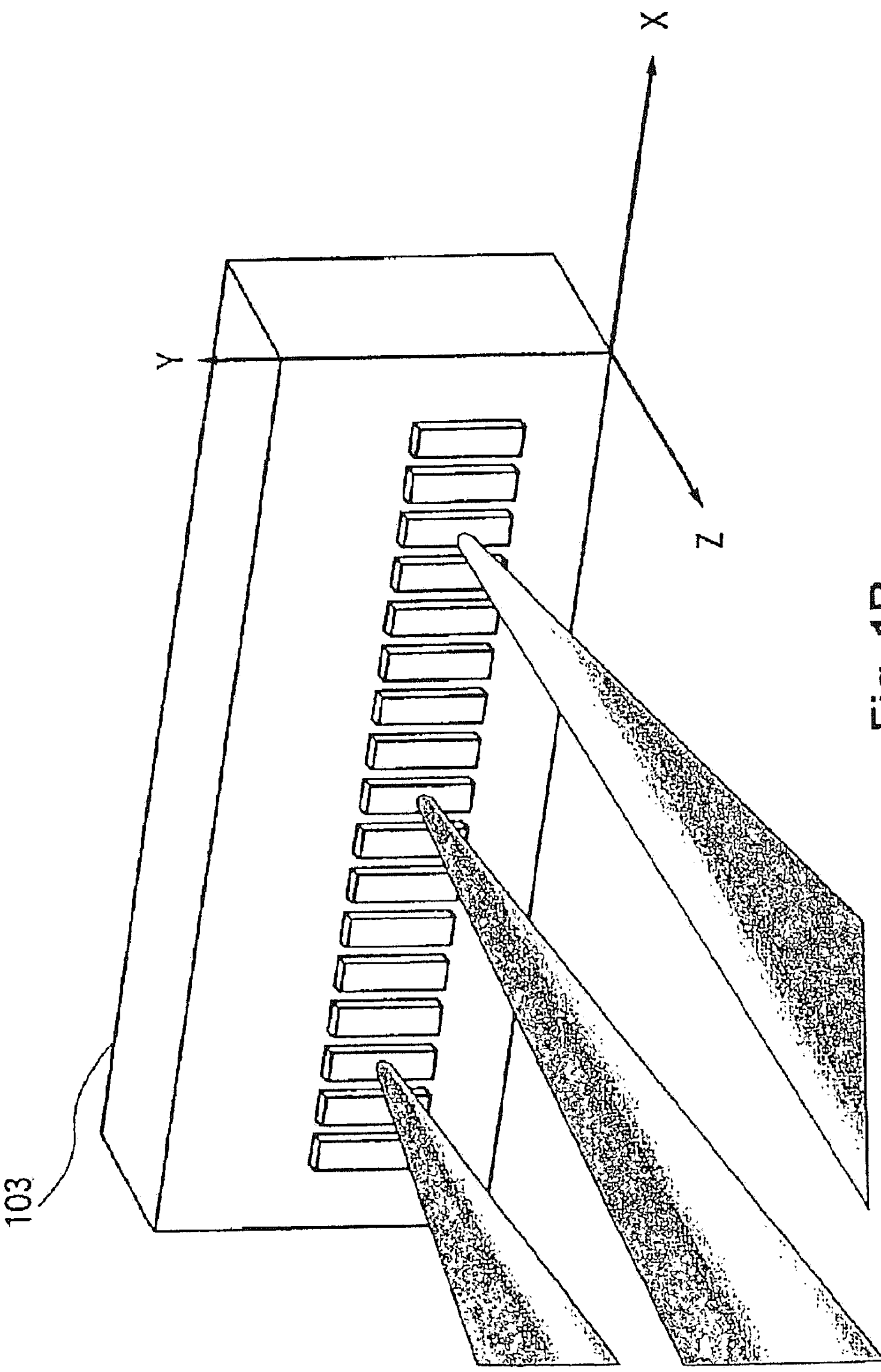
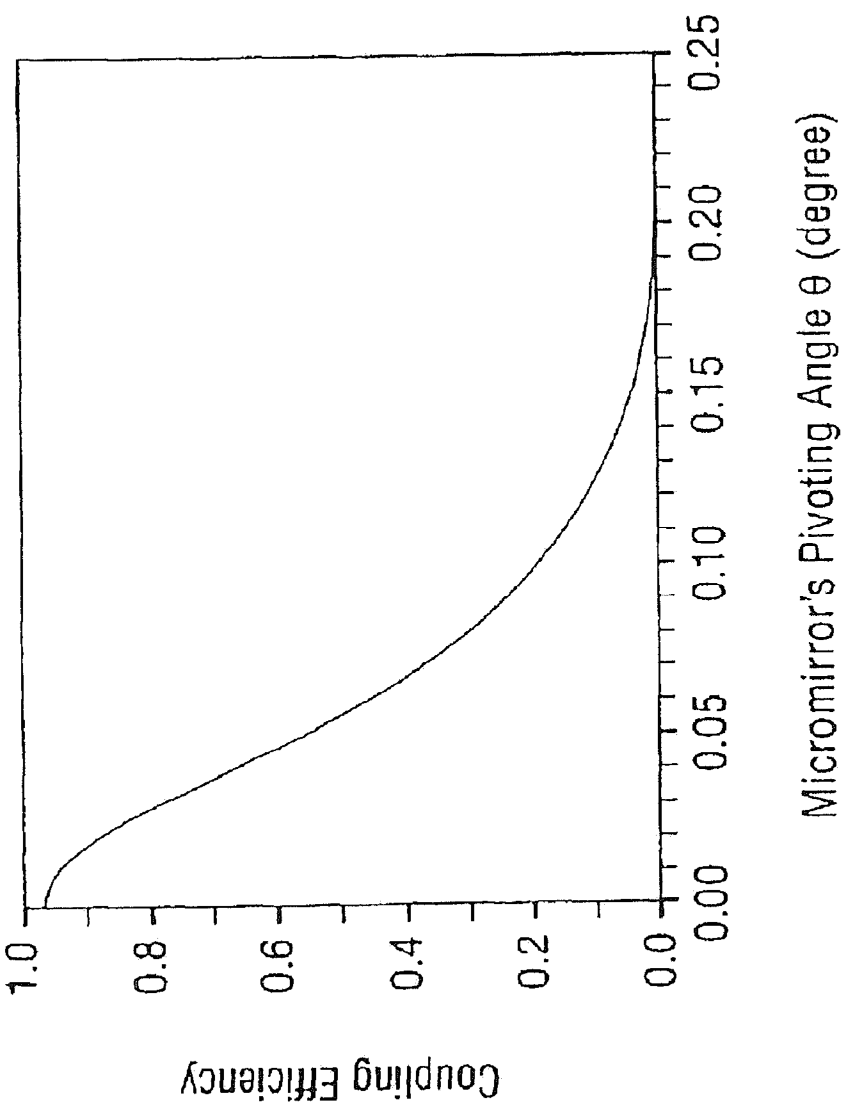


Fig. 1B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0.8
0.6
0.4
0.2
0.0
0.00
0.05
0.10
0.15
0.20
0.25
Micromirror's Pivoting Angle θ (degree)

Fig. 1C

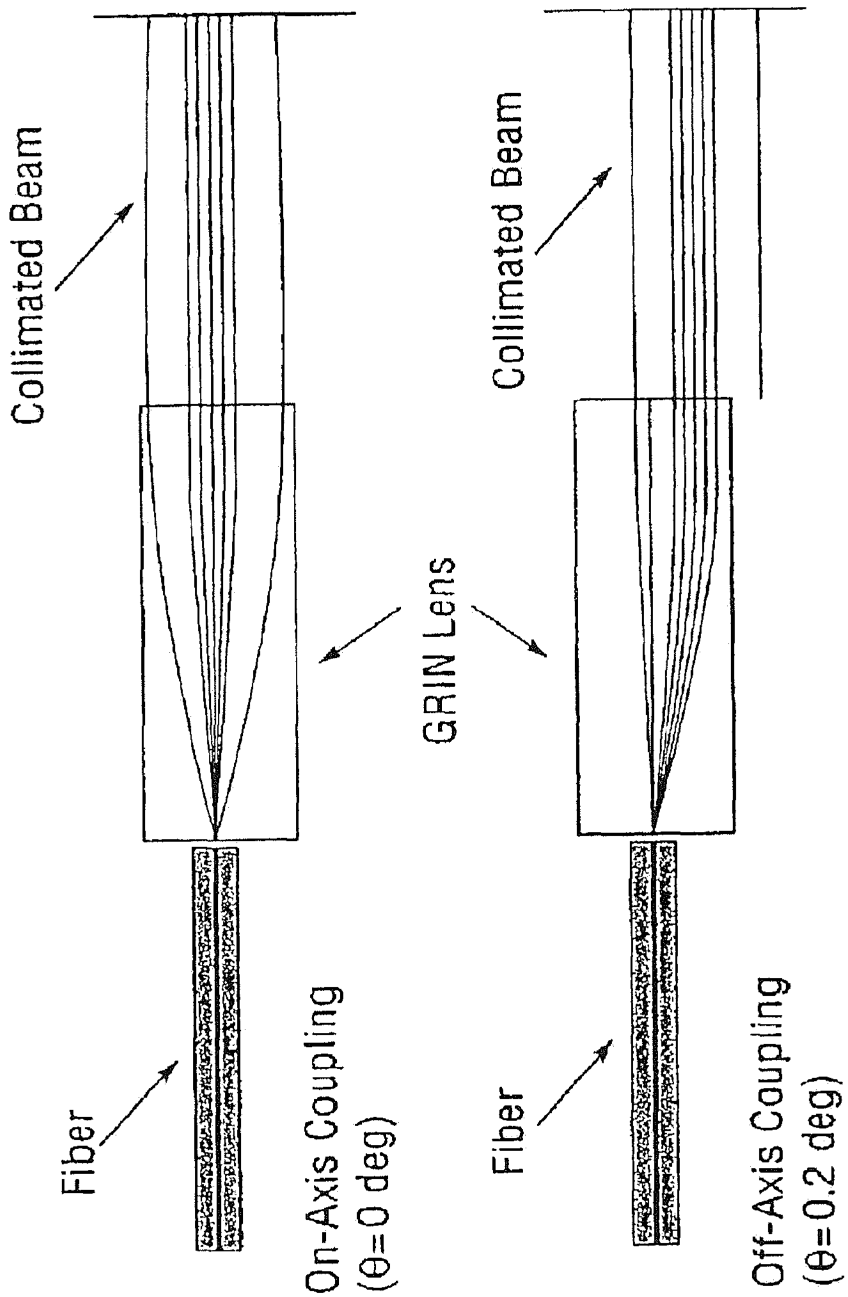

Collimated Beam
Collimated Beam
GRIN Lens
Fiber
Fiber
On-Axis Coupling
(θ=0 deg)
Off-Axis Coupling
(θ=0.2 deg)

Fig. 1D

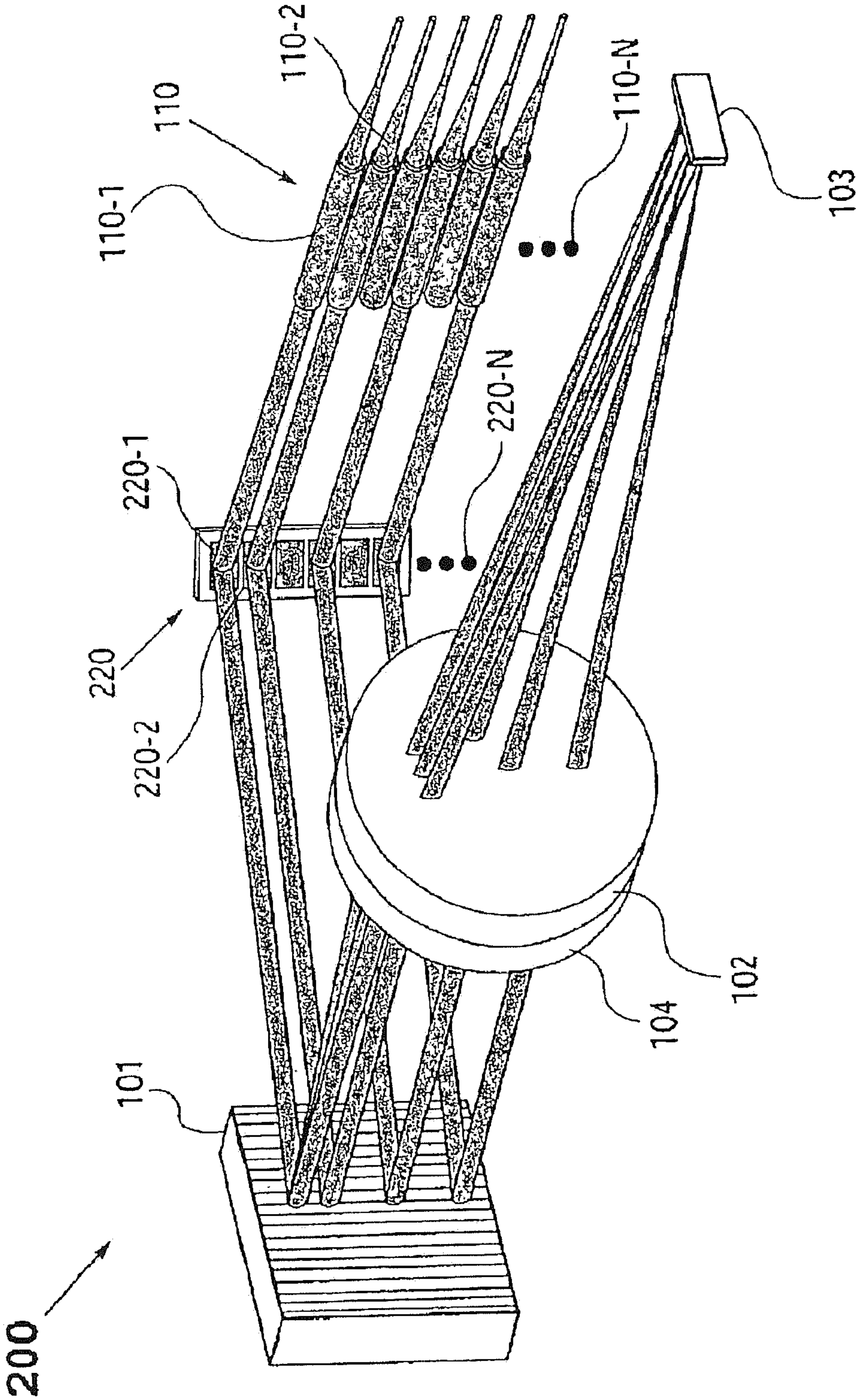


Fig. 2A

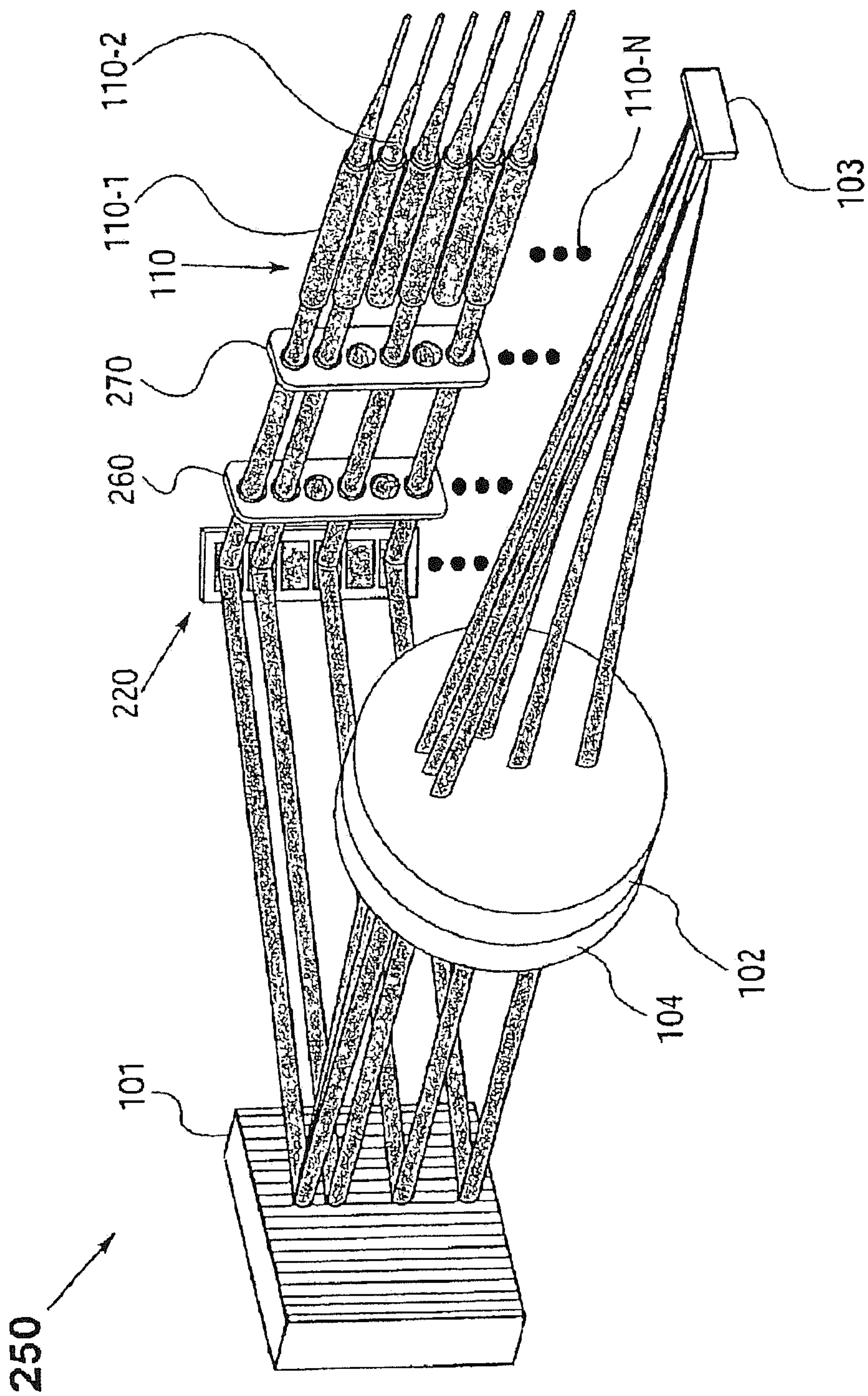


Fig. 2B

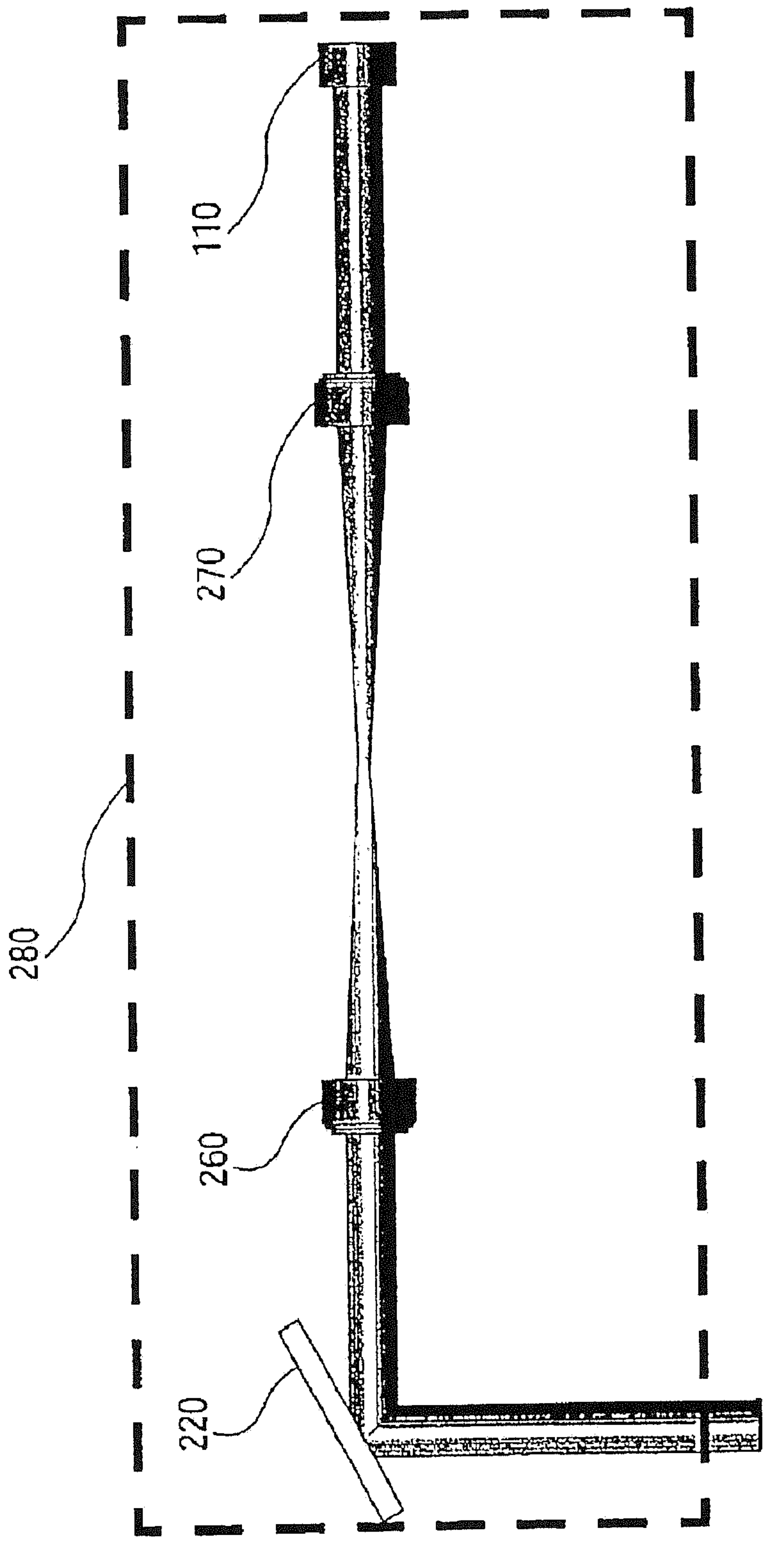


Fig. 2C

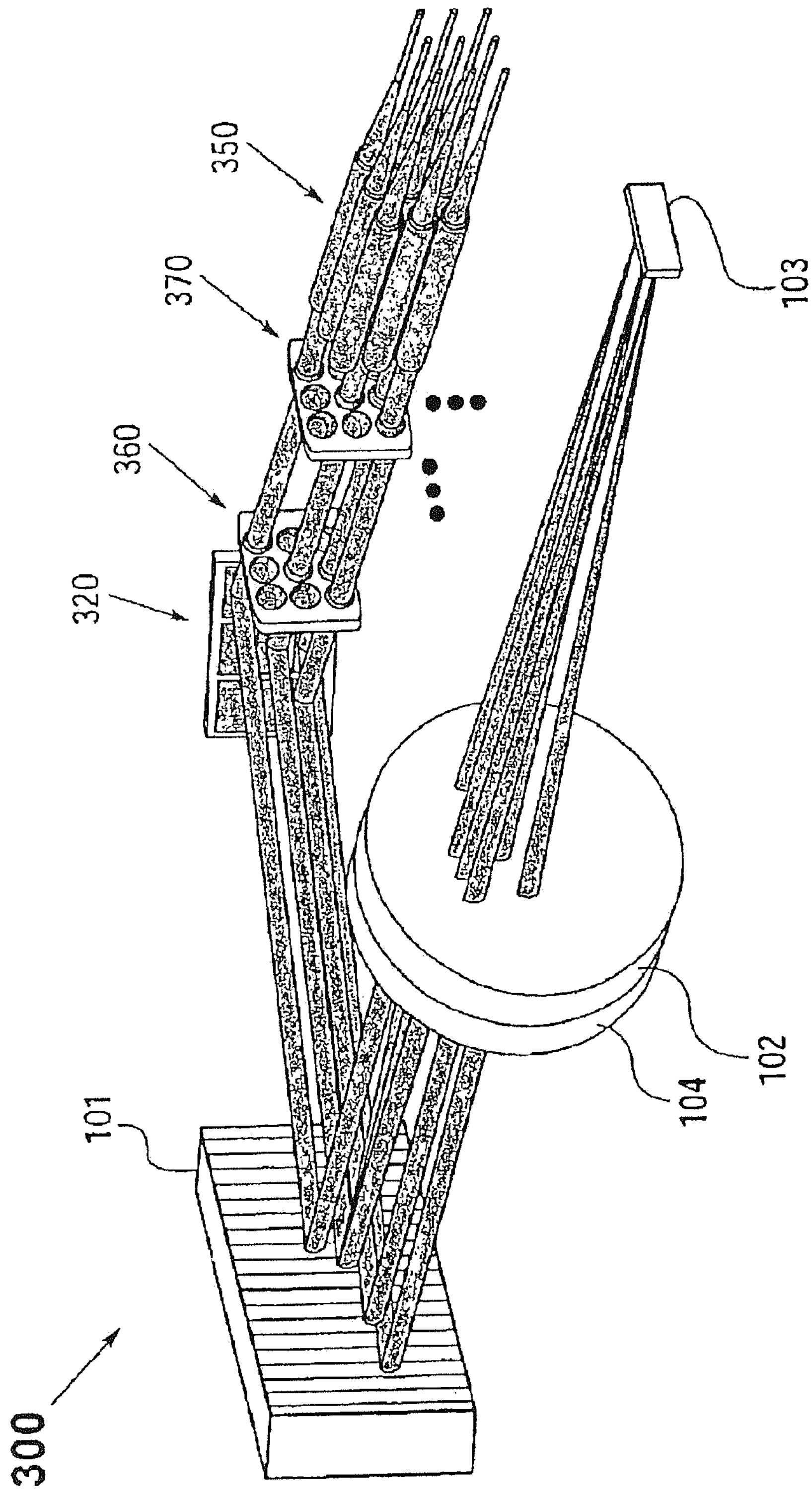
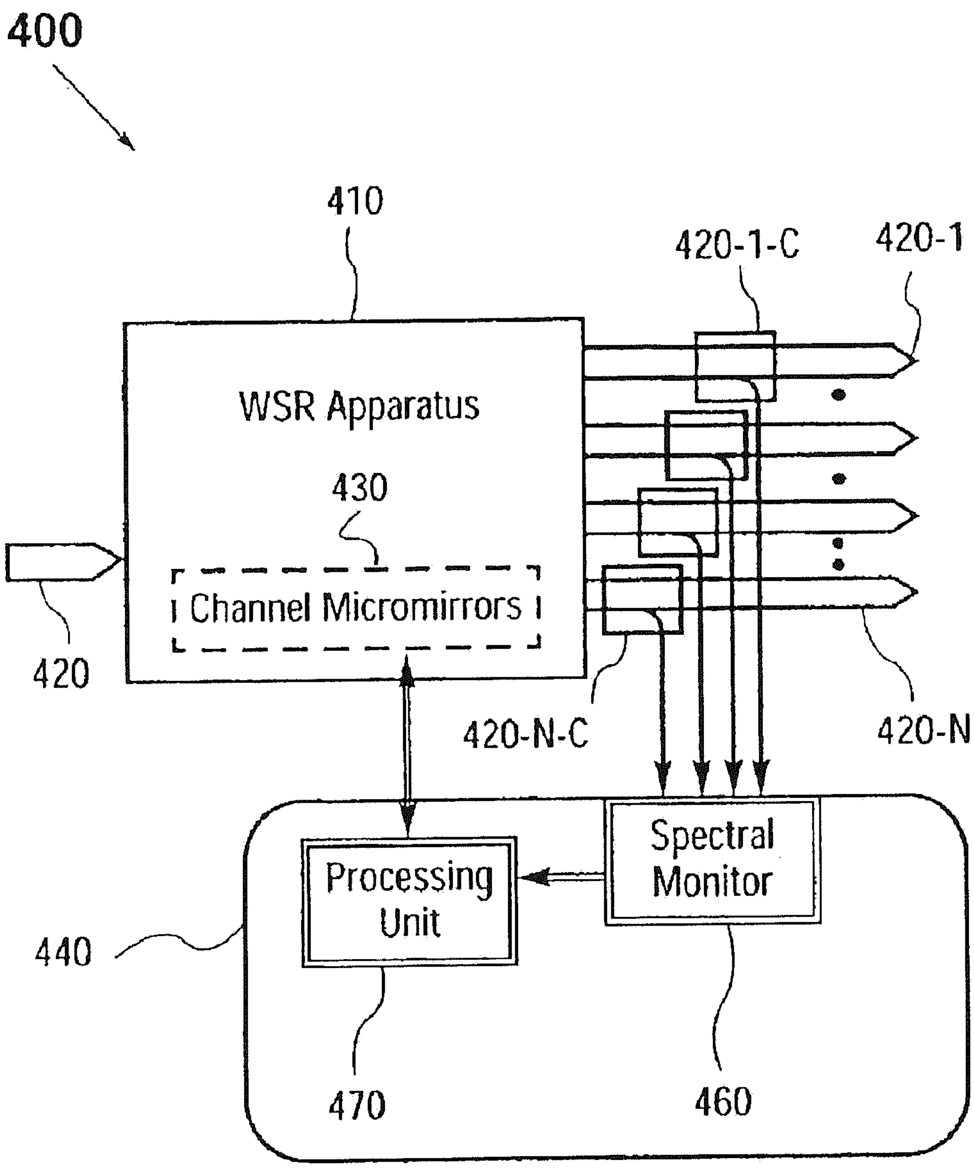


Fig. 3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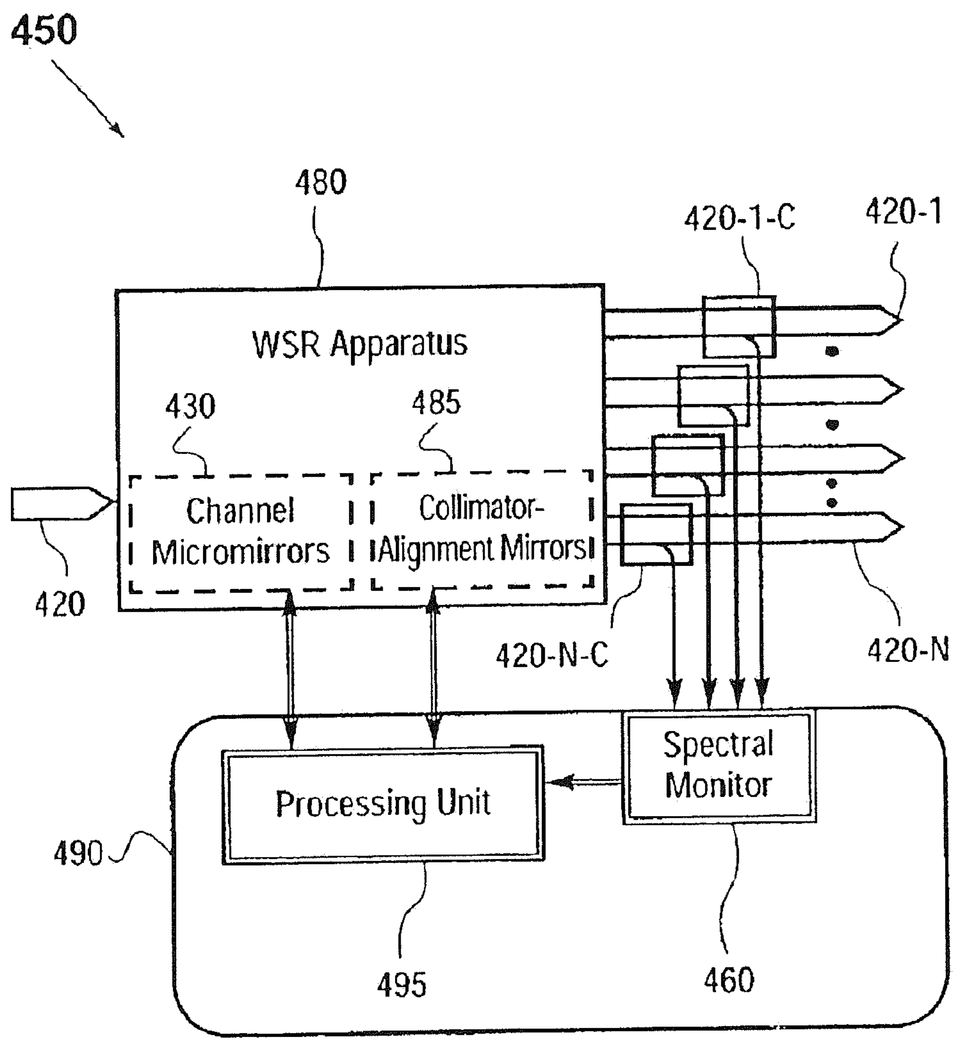
410
420-1-C
420-1
WSR Apparatus
430
Channel Micromirrors
420
420-N-C
420-N
Spectral Monitor
Processing Unit
440
470
460

Fig. 4A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480
420-1-C
420-1
WSR Apparatus
430
485
Channel Micromirrors
Collimator-Alignment Mirrors
420
420-N-C
420-N
Spectral Monitor
Processing Unit
490
495
460

Fig. 4B

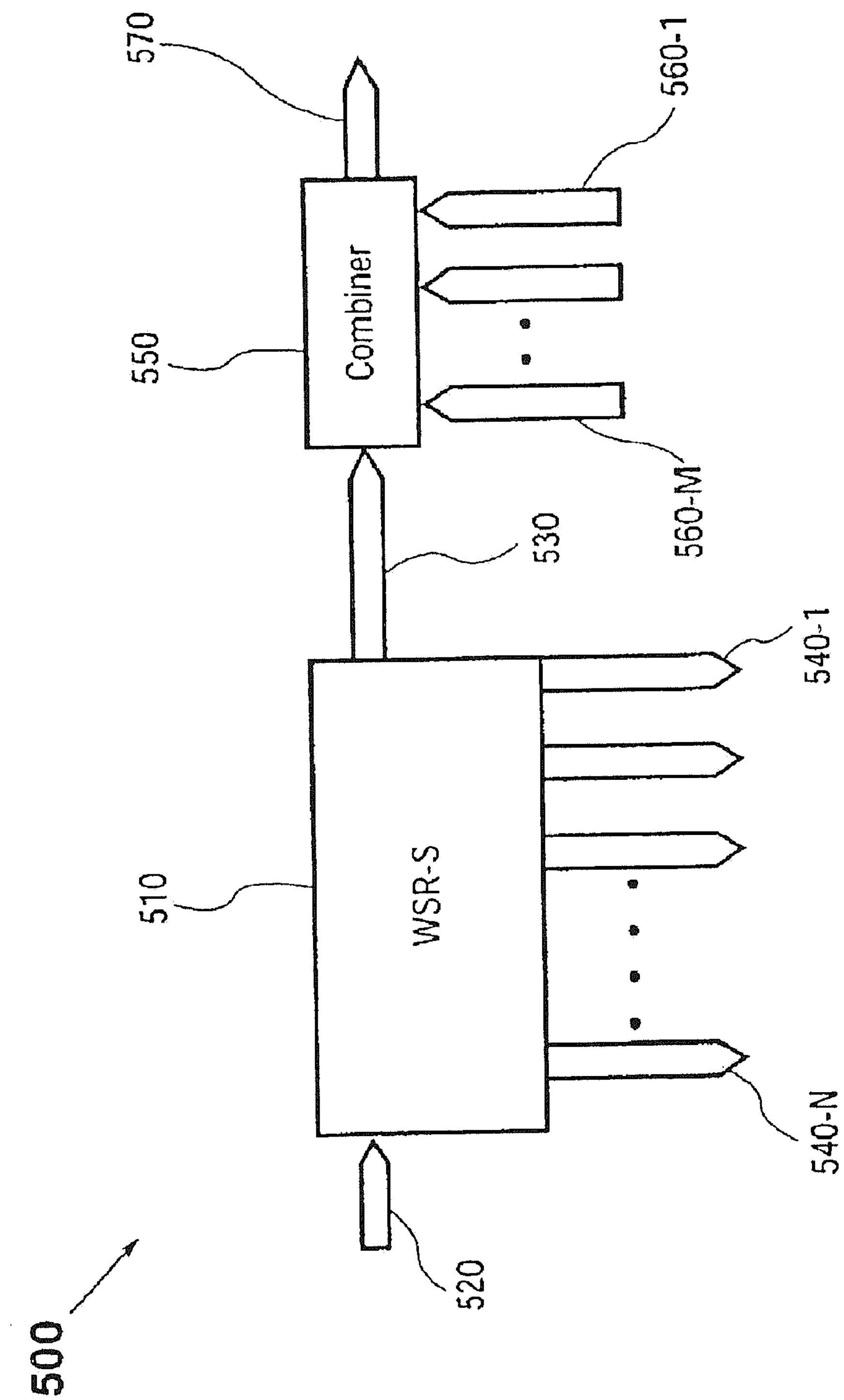

Fig. 5

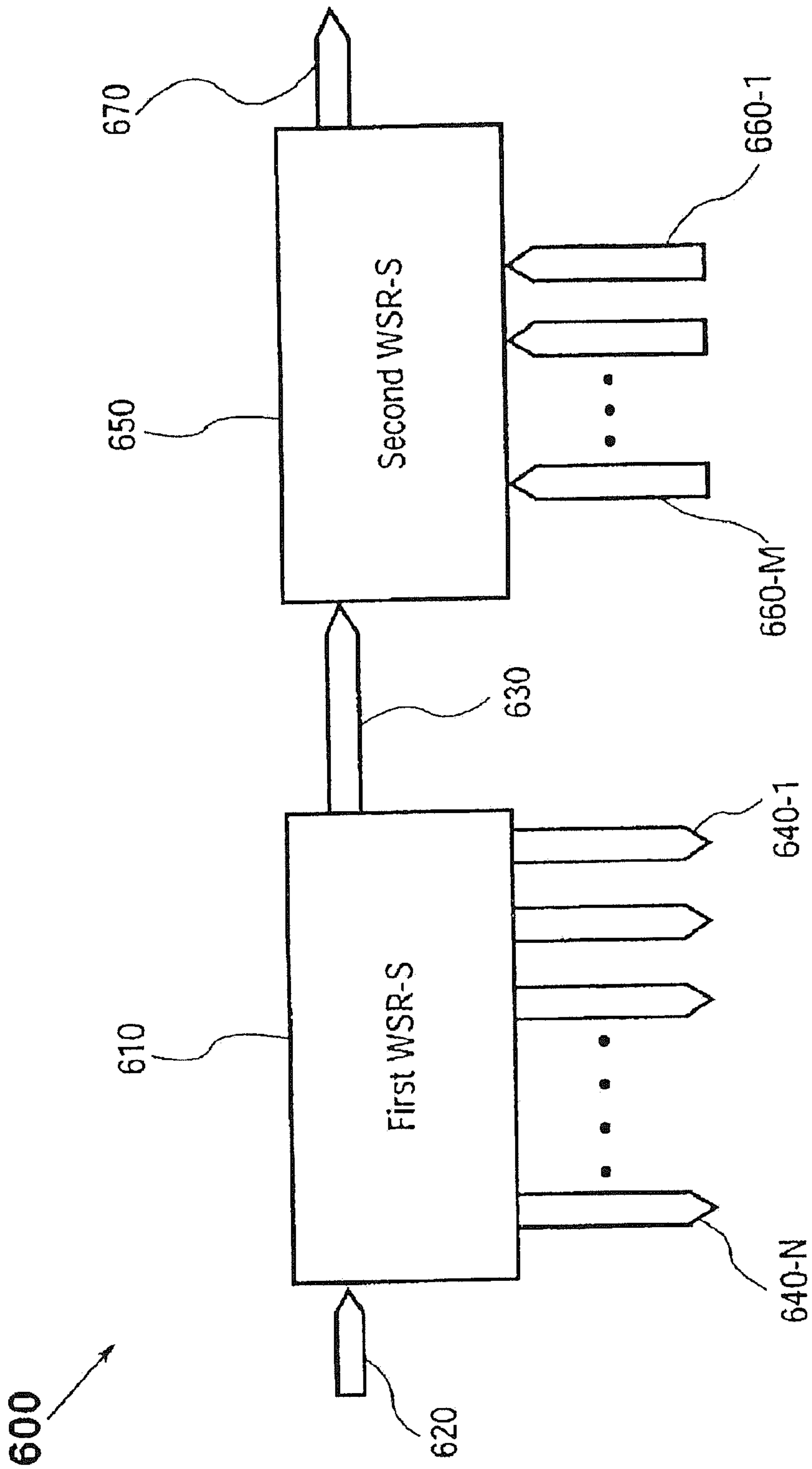
600
610
First WSR-S
620
630
640-1
640-N
650
Second WSR-S
660-1
660-M
670

Fig. 6

RECONFIGURABLE OPTICAL ADD-DROP MULTIPLEXERS WITH SERVO CONTROL AND DYNAMIC SPECTRAL POWER MANAGEMENT CAPABILITIES

Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue.

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. application Ser. No. 10/005,714, filed Nov. 7, 2001 now U.S. Pat. No. 6,687,431, which is a continuation of U.S. application Ser. No. 09/938,426, filed Aug. 23, 2001, now U.S. Pat No. 6,625,346 which claims the benefit of U.S. application Ser. No. 60/277,217, filed Mar. 19, 2001.

FIELD OF THE INVENTION

This invention relates generally to optical communication systems. More specifically, it relates to a novel class of dynamically reconfigurable optical add-drop multiplexers (OADMs) for wavelength division multiplexed optical networking applications.

BACKGROUND

As fiber-optic communication networks rapidly spread into every walk of modern life, there is a growing demand for optical components and subsystems that enable the fiber-optic communications networks to be increasingly scalable, versatile, robust, and cost-effective.

Contemporary fiber-optic communications networks commonly employ wavelength division multiplexing (WDM), for it allows multiple information (or data) channels to be simultaneously transmitted on a single optical fiber by using different wavelengths and thereby significantly enhances the information bandwidth of the fiber. The prevalence of WDM technology has made optical add-drop multiplexers indispensable building blocks of modern fiber-optic communication networks. An optical add-drop multiplexer (OADM) serves to selectively remove (or drop) one or more wavelengths from a multiplicity of wavelengths on an optical fiber, hence taking away one or more data channels from the traffic stream on the fiber. It further adds one or more wavelengths back onto the fiber, thereby inserting new data channels in the same stream of traffic. As such, an OADM makes it possible to launch and retrieve multiple data channels (each characterized by a distinct wavelength) onto and from an optical fiber respectively, without disrupting the overall traffic flow along the fiber. Indeed, careful placement of the OADMs can dramatically improve an optical communication network's flexibility and robustness, while providing significant cost advantages.

Conventional OADMs in the art typically employ multiplexers/demultiplexers (e.g, waveguide grating routers or arrayed-waveguide gratings), tunable filters, optical switches, and optical circulators in a parallel or serial architecture to accomplish the add and drop functions. In the parallel architecture, as exemplified in U.S. Pat. No. 5,974,207, a demultiplexer (e.g., a waveguide grating router) first separates a multi-wavelength signal into its constituent spectral components. A wavelength switching/routing means (e.g., a combination of optical switches and optical circulators) then serves to drop selective wavelengths and add others. Finally, a multiplexer combines the remaining (i.e., the pass-through) wavelengths into an output multi-wavelength optical signal. In the serial architecture, as exemplified in U.S. Pat. No. 6,205,269, tunable filters (e.g., Bragg fiber gratings) in combination with optical circulators are used to separate the drop wavelengths from the pass-through wavelengths and subsequently launch the add channels into the pass-through path. And if multiple wavelengths are to be added and dropped, additional multiplexers and demultiplexers are required to demultiplex the drop wavelengths and multiplex the add wavelengths, respectively. Irrespective of the underlying architecture, the OADMs currently in the art are characteristically high in cost, and prone to significant optical loss accumulation. Moreover, the designs of these OADMs are such that it is inherently difficult to reconfigure them in a dynamic fashion.

U.S. Pat. No. 6,204,946 to Askyuk et al. discloses an OADM that makes use of free-space optics in a parallel construction. In this case, a multi-wavelength optical signal emerging from an input port is incident onto a ruled diffraction grating. The constituent spectral channels thus separated are then focused by a focusing lens onto a linear array of binary micromachined mirrors. Each micromirror is configured to operate between two discrete states, such that it either retroreflects its corresponding spectral channel back into the input port as a pass-through channel, or directs its spectral channel to an output port as a drop channel. As such, the pass-through signal (i.e., the combined pass-through channels) shares the same input port as the input signal. An optical circulator is therefore coupled to the input port, to provide necessary routing of these two signals. Likewise, the drop channels share the output port with the add channels. An additional optical circulator is thereby coupled to the output port, from which the drop channels exit and the add channels are introduced into the output port. The add channels are subsequently combined with the pass-through signal by way of the diffraction grating and the binary micromirrors.

Although the aforementioned OADM disclosed by Askyuk et al. has the advantage of performing wavelength separating and routing in free space and thereby incurring less optical loss, it suffers a number of limitations. First, it requires that the pass-through signal share the same port/fiber as the input signal. An optical circulator therefore has to be implemented, to provide necessary routing of these two signals. Likewise, all the add and drop channels enter and leave the OADM through the same output port, hence the need for another optical circulator. Moreover, additional means must be provided to multiplex the add channels before entering the system and to demultiplex the drop channels after exiting the system. This additional multiplexing/demultiplexing requirement adds more cost and complexity that can restrict the versatility of the OADM thus-constructed. Second, the optical circulators implemented in this OADM for various routing purposes introduce additional optical losses, which can accumulate to a substantial amount. Third, the constituent optical components must be in a precise alignment, in order for the system to achieve its intended purpose. There are, however, no provisions provided for maintaining the requisite alignment; and no mechanisms implemented for overcoming degradation in the alignment owing to environmental effects such as thermal and mechanical disturbances over the course of operation.

U.S. Pat. No. 5,906,133 to Tomlinson discloses an OADM that makes use of a design similar to that of Aksyuk et al. There are input, output, drop and add ports implemented in this case. By positioning the four ports in a specific arrangement, each micromirror, notwithstanding switchable between two discrete positions, either reflects its corresponding channel (coming from the input port) to the output port, or concomitantly reflects its channel to the drop port and an incident add channel to the output port. As such, this OADM is able to perform both the add and drop functions without involving additional optical components (such as optical circulators used in the system of Aksyuk et al.). However, because a single drop port is designated for all the drop channels and a single add port is designated for all the add channels, the add channels would have to be multiplexed before entering the add port and the drop channels likewise need to be demutiplexed upon exiting from the drop port. Moreover, as in the case of Askyuk et al., there are no provisions provided for maintaining requisite optical alignment in the system, and no mechanisms implemented for combating degradation in the alignment due to environmental effects over the course of operation.

As such, the prevailing drawbacks suffered by the OADMs currently in the art are summarized as follows:

1) The wavelength routing is intrinsically static, rendering it difficult to dynamically reconfigure these OADMs.
2) Add and/or drop channels often need to be multiplexed and/or demultiplexed, thereby imposing additional complexity and cost.
3) Stringent fabrication tolerance and painstaking optical alignment are required. Moreover, the optical alignment is not actively maintained, rendering it susceptible to environmental effects such as thermal and mechanical disturbances over the course of operation.
4) In an optical communication network, OADMs are typically in a ring or cascaded configuration. In order to mitigate the interference amongst OADMs, which often adversely affects the overall performance of the network, it is essential that the power levels of spectral channels entering and exiting each OADM be managed in a systematic way, for instance, by introducing power (or gain) equalization at each stage. Such a power equalization capability is also needed for compensating for non-uniform gain caused by optical amplifiers (e.g., erbium doped fiber amplifiers) in the network. There lacks, however, a systematic and dynamic management of the power levels of various spectral channels in these OADMs.
5) The inherent high cost and heavy optical loss further impede the wide application of these OADMs.

In view of the foregoing, there is an urgent need in the art for optical add-drop multiplexers that overcome the aforementioned shortcomings in a simple, effective, and economical construction.

SUMMARY

The present invention provides a wavelength-separating-routing (WSR) apparatus and method which employ an array of fiber collimators serving as an input port and a plurality of output ports; a wavelength-separator; a beam-focuser; and an array of channel micromirrors.

In operation, a multi-wavelength optical signal emerges from the input port. The wavelength-separator separates the multi-wavelength optical signal into multiple spectral channels, each characterized by a distinct center wavelength and associated bandwidth. The beam-focuser focuses the spectral channels into corresponding spectral spots. The channel micromirrors are positioned such that each channel micromirror receives one of the spectral channels. The channel micromirrors are individually controllable and movable, e.g., continuously pivotable (or rotatable), so as to reflect the spectral channels into selected ones of the output ports. As such, each channel micromirror is assigned to a specific spectral channel, hence the name "channel micromirror". And each output port may receive any number of the reflected spectral channels.

A distinct feature of the channel micromirrors in the present invention, in contrast to those used in the prior art, is that the motion, e.g., pivoting (or rotation), of each channel micromirror is under analog control such that its pivoting angle can be continuously adjusted. This enables each channel micromirror to scan its corresponding spectral channel across all possible output ports and thereby direct the spectral channel to any desired output port.

In the WSR apparatus of the present invention, the wavelength-separator may be provided by a ruled diffraction grating, a holographic diffraction grating, an echelle grating, a curved diffraction grating, a dispersing prism, or other wavelength-separating means known in the art. The beam-focuser may be a single lens, an assembly of lenses, or other beam-focusing means known in the art. The channel micromirrors may be provided by silicon micromachined mirrors, reflective ribbons (or membranes), or other types of beam-deflecting means known in the art. And each channel micromirror may be pivotable about one or two axes. The fiber collimators serving as the input and output ports may be arranged in a one-dimensional or two-dimensional array. In the latter case, the channel micromirrors must be pivotable biaxially.

The WSR apparatus of the present invention may further comprise an array of collimator-alignment mirrors, in optical communication with the wavelength-separator and the fiber collimators, for adjusting the alignment of the input multi-wavelength signal and directing the spectral channels into the selected output ports by way of angular control of the collimated beams. Each collimator-alignment mirror may be rotatable about one or two axes. The collimator-alignment mirrors may be arranged in a one-dimensional or two-dimensional array. First and second arrays of imaging lenses may additionally be optically interposed between the collimator-alignment mirrors and the fiber collimators in a telecentric arrangement, thereby "imaging" the collimator-alignment mirrors onto the corresponding fiber collimators to ensure an optimal alignment.

The WSR apparatus of the present invention may further include a servo-control assembly, in communication with the channel micromirrors and the output ports. The servo-control assembly serves to monitor the power levels of the spectral channels coupled into the output ports and further provide control of the channel micromirrors on an individual basis, so as to maintain a predetermined coupling efficiency of each spectral channel in one of the output ports. As such, the servo-control assembly provides dynamic control of the coupling of the spectral channels into the respective output ports and actively manages the power levels of the spectral channels coupled into the output ports. (If the WSR apparatus includes an array of collimator-alignment mirrors as described above, the servo-control assembly may additionally provide dynamic control of the collimator-alignment mirrors.) Moreover, the utilization of such a servo-control assembly effectively relaxes the requisite fabrication tolerances and the precision of optical alignment during assembly of a WSR apparatus of the present invention, and further enables the system to correct for shift in optical alignment over the course of operation. A WSR apparatus incorporating a servo-control assembly thus described is termed a WSR-S apparatus, thereinafter in the present invention.

Accordingly, the WSR-S (or WSR) apparatus of the present invention may be used to construct a variety of optical devices, including a novel class of dynamically reconfigurable optical add-drop multiplexers (OADMs), as exemplified in the following embodiments.

One embodiment of an OADM of the present invention comprises an aforementioned WSR-S (or WSR) apparatus and an optical combiner. The output ports of the WSR-S apparatus include a pass-through port and one or more drop ports, each carrying any number of the spectral channels. The optical combiner is coupled to the pass-through port, serving to combine the pass-through channels with one or more add spectral channels. The combined optical signal constitutes an output signal of the system. The optical combiner may be an N×1 (N≧2) broadband fiber-optic coupler, for instance, which also serves the purpose of multiplexing a multiplicity of add spectral channels to be coupled into the system.

In another embodiment of an OADM of the present invention, a first WSR-S (or WSR) apparatus is cascaded with a second WSR-S (or WSR) apparatus. The output ports of the first WSR-S (or WSR) apparatus include a passthrough port and one or more drop ports. The second WSR-S (or WSR) apparatus includes a plurality of input ports and an exiting port. The configuration is such that the pass-through channels from the first WSR-S apparatus and one or more add channels are directed into the input ports of the second WSR-S apparatus, and consequently multiplexed into an output multi-wavelength optical signal directed into the exiting port of the second WSR-S apparatus. That is to say that in this embodiment, one WSR-S apparatus (e.g., the first one) effectively performs a dynamic drop function, whereas the other WSR-S apparatus (e.g., the second one) carries out a dynamic add function. And there are essentially no fundamental restrictions on the wavelengths that can be added or dropped, other than those imposed by the overall communication system. Moreover, the underlying OADM architecture thus presented is intrinsically scalable and can be readily extended to any number of the WSR-S (or WSR) systems, if so desired for performing intricate add and drop functions in a network environment.

Those skilled in the art will recognize that the aforementioned embodiments provide only two of many embodiments of a dynamically reconfigurable OADM according to the present invention. Various changes, substitutions, and alternations can be made herein, without departing from the principles and the scope of the invention. Accordingly, a skilled artisan can design an OADM in accordance with the present invention, to best suit a given application.

All in all, the OADMs of the present invention provide many advantages over the prior art devices, notably:

1) By advantageously employing an array of channel micromirrors that are individually and continuously controllable, an OADM of the present invention is capable of routing the spectral channels on a channel-by-channel basis and directing any spectral channel into any one of the output ports. As such, its underlying operation is dynamically reconfigurable, and its underlying architecture is intrinsically scalable to a large number of channel counts.
2) The add and drop spectral channels need not be multiplexed and demultiplexed before entering and after leaving the OADM respectively. And there are not fundamental restrictions on the wavelengths to be added or dropped.
3) The coupling of the spectral channels into the output ports is dynamically controlled by a servo-control assembly, rendering the OADM less susceptible to environmental effects (such as thermal and mechanical disturbances) and therefore more robust in performance. By maintaining an optimal optical alignment, the optical losses incurred by the spectral channels are also significantly reduced.
4) The power levels of the spectral channels coupled into the output ports can be dynamically managed according to demand, or maintained at desired values (e.g., equalized at a predetermined value) by way of the servo-control assembly. This spectral power-management capability as an integral part of the OADM will be particularly desirable in WDM optical networking applications.
5) The use of free-space optics provides a simple, low loss, and cost-effective construction. Moreover, the utilization of the servo-control assembly effectively relaxes the requisite fabrication tolerances and the precision of optical alignment during initial assembly, enabling the OADM to be simpler and more adaptable in structure, lower in cost and optical loss.
6) The underlying OADM architecture allows a multiplicity of the OADMs according to the present invention to be readily assembled (e.g., cascaded) for WDM optical networking applications.

The novel features of this invention, as well as the invention itself, will be best understood from the following drawings and detailed description.

BRIEF DESCRIPTION OF THE FIGURES

FIGS. **1A-1D** show a first embodiment of a wavelength-separating-routing (WSR) apparatus according to the present invention, and the modeling results demonstrating the performance of the WSR apparatus;

FIGS. **2A-2C** depict second and third embodiments of a WSR apparatus according to the present invention;

FIG. **3** shows a fourth embodiment of a WSR apparatus according to the present invention;

FIGS. **4A-4B** show schematic illustrations of two embodiments of a WSR-S apparatus comprising a WSR apparatus and a servo-control assembly, according to the present invention;

FIG. **5** depicts an exemplary embodiment of an optical add-drop multiplexer (OADM) according to the present invention; and

FIG. **6** shows an alternative embodiment of an OADM according to the present invention.

DETAILED DESCRIPTION

In this specification and appending claims, a "spectral channel" is characterized by a distinct center wavelength and associated bandwidth. Each spectral channel may carry a unique information signal, as in WDM optical networking applications.

FIG. **1A** depicts a first embodiment of a wavelength-separating-routing (WSR) apparatus according to the present invention. By way of example to illustrate the general principles and the topological structure of a wavelength-separating-routing (WSR) apparatus of the present invention, the WSR apparatus **100** comprises multiple input/output ports which may be in the form of an array of fiber collimators **110**, providing an input port **110-1** and a plurality of output ports **110-2** through **110-N** (N≧3); a wavelength-separator which in one form may be a diffraction grating **101**; a beam-focuser in the form of a focusing lens **102**; and an array of channel micromirrors **103**.

In operation, a multi-wavelength optical signal emerges from the input port **110-1**. The diffraction grating **101** angularly separates the multi-wavelength optical signal into multiple spectral channels, which are in turn focused by the focusing lens **102** into a spatial array of distinct spectral spots (not shown in FIG. **1A**) in a one-to-one correspondence. The channel micromirrors **103** are positioned in accordance with the spatial array formed by the spectral spots, such that each channel micromirror receives one of the spectral channels. The channel micromirrors **103** are individually controllable and movable, e.g., pivotable (or rotatable) under analog (or continuous) control, such that, upon reflection, the spectral channels are directed into selected ones of the output ports **110-2** through **110**-N by way of the focusing lens **102** and the diffraction grating **101**. As such, each channel micromirror is assigned to a specific spectral channel, hence the name "channel micromirror". Each output port may receive any number of the reflected spectral channels.

For purposes of illustration and clarity, only a selective few (e.g., three) of the spectral channels, along with the input multi-wavelength optical signal, are graphically illustrated in FIG. **1A** and the following figures. It should be noted, however, that there can be any number of the spectral channels in a WSR apparatus of the present invention (so long as the number of spectral channels does not exceed the number of channel mirrors employed in the system). It should also be noted that the optical beams representing the spectral channels shown in FIG. 1A and the following figures are provided for illustrative purpose only. That is, their sizes and shapes may not be drawn according to scale. For instance, the input beam and the corresponding diffracted beams generally have different cross-sectional shapes, so long as the angle of incidence upon the diffraction grating is not equal to the angle of diffraction, as is known to those skilled in the art.

In the embodiment of FIG. 1A, it is preferable that the diffraction grating **101** and the channel micromirrors **103** are placed respectively at the first and second (i.e., the front and back) focal points (on the opposing sides) of the focusing lens **102**. Such a telecentric arrangement allows the chief rays of the focused beams to be parallel to each other and generally parallel to the optical axis. In this application, the telecentric configuration further allows the reflected spectral channels to be efficiently coupled into the respective output ports, thereby minimizing various translational walk-off effects that may otherwise arise. Moreover, the input multi-wavelength optical signal is preferably collimated and circular in cross-section. The corresponding spectral channels diffracted from the diffraction grating **101** are generally elliptical in cross-section; they may be of the same size as the input beam in one dimension and elongated in the other dimension.

It is known that the diffraction efficiency of a diffraction grating is generally polarization-dependent. That is, the diffraction efficiency of a grating in a standard mounting configuration may be considerably higher for P-polarization that is perpendicular to the groove lines on the grating than for S-polarization that is orthogonal to P-polarization, especially as the number of groove lines (per unit length) increases. To mitigate such polarization-sensitive effects, a quarter-wave plate **104** may be optically interposed between the diffraction grating **101** and the channel micromirrors **103**, and preferably placed between the diffraction grating **101** and the focusing lens **102** as is shown in FIG. **1A**. In this way, each spectral channel experiences a total of approximately 90-degree rotation in polarization upon traversing the quarter-wave plate **104** twice. (That is, if a beam of light has P-polarization when first encountering the diffraction grating, it would have predominantly (if not all) S-polarization upon the second encountering, and vice versa.) This ensures that all the spectral channels incur nearly the same amount of round-trip polarization dependent loss.

In the WSR apparatus **100** of FIG. 1A, the diffraction grating **101**, by way of example, is oriented such that the focused spots of the spectral channels fall onto the channel micromirrors **103** in a horizontal array, as illustrated in FIG. 1B.

Depicted in FIG. 1B is a close-up view of the channel micromirrors **103** shown in the embodiment of FIG. 1A. By way of example, the channel micromirrors **103** are arranged in a one-dimensional array along the x-axis (i.e., the horizontal direction in the figure), so as to receive the focused spots of the spatially separated spectral channels in a one-to-one correspondence. (As in the case of FIG. 1A, only three spectral channels are illustrated, each represented by a converging beam.) Let the reflective surface of each channel micromirror lie in the x-y plane as defined in the figure and be movable, e.g., pivotable (or deflectable) about the x-axis in an analog (or continuous) manner. Each spectral channel, upon reflection, is deflected in the y-direction (e.g., downward) relative to its incident direction, so to be directed into one of the output ports **110-2** through **110**-N shown in FIG. **1A**.

As described above, a unique feature of the present invention is that the motion of each channel micromirror is individually and continuously controllable, such that its position, e.g., pivoting angle, can be continuously adjusted. This enables each channel micromirror to scan its corresponding spectral channel across all possible output ports and thereby direct the spectral channel to any desired output port. To illustrate this capability, FIG. 1C shows a plot of coupling efficiency as a function of a channel micromirror's pivoting angle θ, provided by a ray-tracing model of a WSR apparatus in the embodiment of FIG. 1A. As used herein, the coupling efficiency for a spectral channel is defined as the ratio of the amount of optical power coupled into the fiber core in an output port to the total amount of optical power incident upon the entrance surface of the fiber (associated with the fiber collimator serving as the output port). In the ray-tracing model, the input optical signal is incident upon a diffraction grating with 700 lines per millimeter at a grazing angle of 85 degrees, where the grating is blazed to optimize the diffraction efficiency for the "−1" order. The focusing lens has a focal length of 100 mm. Each output port is provided by a quarter-pitch GRIN lens (2 mm in diameter) coupled to an optical fiber (see FIG. 1D). As displayed in FIG. 1C, the coupling efficiency varies with the pivoting angle θ, and it requires about a 0.2-degree change in θ for the coupling efficiency to become practically negligible in this exemplary case. As such, each spectral channel may practically acquire any coupling efficiency value by way of controlling the pivoting angle of its corresponding channel micromirror. This is also to say that variable optical attenuation at the granularity of a single wavelength can be obtained in a WSR apparatus of the present invention. FIG. 1D provides ray-tracing illustrations of two extreme points on the coupling efficiency vs. θ curve of FIG. 1C: on-axis coupling corresponding to θ=0, where the coupling efficiency is maximum; and off-axis coupling corresponding to θ=0.2 degrees, where the representative collimated beam (representing an exemplary spectral channel) undergoes a significant translational walk-off and renders the coupling efficiency practically negligible. All in all, the exemplary modeling results thus described demonstrate the unique capabilities of the WSR apparatus of the present invention.

FIG. 1A provides one of many embodiments of a WSR apparatus according to the present invention. In general, the wavelength-separator is a wavelength-separating means that may be a ruled diffraction grating, a holographic diffraction grating, an echelle grating, a dispersing prism, or other types of spectral-separating means known in the art. The beam-focuser may be a focusing lens, an assembly of lenses, or other beam-focusing means known in the art. The focusing function may also be accomplished by using a curved diffraction grating as the wavelength-separator. The channel micromirrors may be provided by silicon micromachined mirrors, reflective ribbons (or membranes), or other types of beam-deflecting elements known in the art. And each micromirror may be pivoted about one or two axes. What is important is that the pivoting (or rotational) motion of each channel micromirror be individually controllable in an analog manner, whereby the pivoting angle can be continuously adjusted so as to enable the channel micromirror to scan a spectral channel across all possible output ports. The underlying fabrication techniques for micromachined mirrors and associated actuation mechanisms are well documented in the art, see U.S. Pat. No. 5,629,790 for example. Moreover, a fiber collimator is typically in the form of a collimating lens (such as a GRIN lens) and a ferrule-mounted fiber packaged together in a mechanically rigid stainless steel (or glass) tube. The fiber collimators serving as the input and output ports may be arranged in a one-dimensional array, a two-dimensional array, or other desired spatial pattern. For instance, they may be conveniently mounted in a linear array along a V-groove fabricated on a substrate made of silicon, plastic, or ceramic, as commonly practiced in the art. It should be noted, however, that the input port and the output ports need not necessarily be in close spatial proximity with each other, such as in an array configuration (although a close packing would reduce the rotational range required for each channel micromirror). Those skilled in the art will know how to design a WSR apparatus according to the present invention, to best suit a given application.

A WSR apparatus of the present invention may further comprise an array of collimator-alignment mirrors, for adjusting the alignment of the input multi-wavelength optical signal and facilitating the coupling of the spectral channels into the respective output ports, as shown in FIGS. 2A-2B and 3.

Depicted in FIG. 2A is a second embodiment of a WSR apparatus according to the present invention. By way of example, WSR apparatus **200** is built upon and hence shares a number of the elements used in the embodiment of FIG. 1A, as identified by those labeled with identical numerals. Moreover, a one-dimensional array **220** of collimator-alignment mirrors **220-1** through **220**-N is optically interposed between the diffraction grating **101** and the fiber collimator array **110**. The collimator-alignment mirror **220-1** is designated to correspond with the input port **110-1**, for adjusting the alignment of the input multi-wavelength optical signal and therefore ensuring that the spectral channels impinge onto the corresponding channel micromirrors. The collimator-alignment mirrors **220-2** through **220**-N are designated to the output ports **110-2** through **110**-N in a one-to-one correspondence, serving to provide angular control of the collimated beams of the reflected spectral channels and thereby facilitating the coupling of the spectral channels into the respective output ports according to desired coupling efficiencies. Each collimator-alignment mirror may be rotatable about one axis, or two axes.

The embodiment of FIG. 2A is attractive in applications where the fiber collimators (serving as the input and output ports) are desired to be placed in close proximity to the collimator-alignment mirror array **220**. To best facilitate the coupling of the spectral channels into the output ports, arrays of imaging lenses may be implemented between the collimator-alignment mirror array **220** and the fiber collimator array **110**, as depicted in FIG. 2B. By way of example, WSR apparatus **250** of FIG. 2B is built upon and hence shares many of the elements used in the embodiment of FIG. 2A, as identified by those labeled with identical numerals. Additionally, first and second arrays **260**, **270** of imaging lenses are placed in a 4-f telecentric arrangement with respect to the collimator-alignment mirror array **220** and the fiber collimator array **110**. The dashed box **280** shown in FIG. 2C provides a top view of such a telecentric arrangement. In this case, the imaging lenses in the first and second arrays **260**, **270** all have the same focal length f. The collimator-alignment mirrors **220-1** through **220**-N are placed at the respective first (or front) focal points of the imaging lenses in the first array **260**. Likewise, the fiber collimators **110-1** through **110**-N are placed at the respective second (or back) focal points of the imaging lenses in the second array **270**. And the separation between the first and second arrays **260**, **270** of imaging lenses is 2f. In this way, the collimator-alignment mirrors **220-1** through **220**-N are effectively imaged onto the respective entrance surfaces (i.e., the front focal planes) of the GRIN lenses in the corresponding fiber collimators **110-1** through **110**-N. Such a telecentric imaging system substantially eliminates translational walk-off of the collimated beams at the output ports that may otherwise occur as the mirror angles change.

FIG. 3 shows a fourth embodiment of a WSR apparatus according to the present invention. By way of example, WSR apparatus **300** is built upon and hence shares a number of the elements used in the embodiment of FIG. 2B, as identified by those labeled with identical numerals. In this case, the one-dimensional fiber collimator array **110** of FIG. 2B is replaced by a two-dimensional array **350** of fiber collimators, providing for an input-port and a plurality of output ports. Accordingly, the one-dimensional collimator-alignment mirror array **220** of FIG. 2B is replaced by a two-dimensional array **320** of collimator-alignment mirrors, and first and second one-dimensional arrays **260**, **270** of imaging lenses of FIG. 2B are likewise replaced by first and second two-dimensional arrays **360**, **370** of imagining lenses respectively. As in the case of the embodiment of FIG. 2B, the first and second two-dimensional arrays **360**, **370** of imaging lenses are placed in a 4-f telecentric arrangement with respect to the two-dimensional collimator-alignment mirror array **320** and the two-dimensional fiber collimator array **350**. The channel micromirrors **103** must be pivotable biaxially in this case (in order to direct its corresponding spectral channel to any one of the output ports). As such, the WSR apparatus **300** is equipped to support a greater number of the output ports.

In addition to facilitating the coupling of the spectral channels into the respective output ports as described above, the collimator-alignment mirrors in the above embodiments also serve to compensate for misalignment (e.g., due to fabrication and assembly errors) in the fiber collimators that provide for the input and output ports. For instance, relative misalignment between the fiber cores and their respective collimating lenses in the fiber collimators can lead to pointing errors in the collimated beams, which may be corrected for by the collimator-alignment mirrors. For these reasons, the collimator-alignment mirrors are preferably rotatable about two axes. They may be silicon micromachined mirrors, for fast rotational speeds. They may also be other types of mirrors or beam-deflecting elements known in the art.

To optimize the coupling of the spectral channels into the output ports and further maintain the optimal optical alignment against environmental effects such as temperature variations and mechanical instabilities over the course of operation, a WSR apparatus of the present invention may incorporate a servo-control assembly, for providing dynamic control of the coupling of the spectral channels into the respective output ports on a channel-by-channel basis. A WSR apparatus incorporating a servo-control assembly is termed a WSR-S apparatus, thereinafter in this specification.

FIG. **4**A depicts a schematic illustration of a first embodiment of a WSR-S apparatus according to the present invention. The WSR-S apparatus **400** comprises a WSR apparatus **410** and a servo-control assembly **440**. The WSR **410** may be in the embodiment of FIG. **1**A, or any other embodiment in accordance with the present invention. The servo-control assembly **440** includes a spectral monitor **460**, for monitoring the power levels of the spectral channels coupled into the output ports **420-1** through **420**-N of the WSR apparatus **410**. By way of example, the spectral monitor **460** is coupled to the output ports **420-1** through **420**-N by way of fiber-optic couplers **420-1-**C through **420**-N-C, wherein each fiber-optic coupler serves to tap off a predetermined fraction of the optical signal in the corresponding output port. The servo-control assembly **440** further includes a processing unit **470**, in communication with the spectral monitor **460** and the channel micromirrors **430** of the WSR apparatus **410**. The processing unit **470** uses the power measurements from the spectral monitor **460** to provide feedback control of the channel micromirrors **430** on an individual basis, so as to maintain a desired coupling efficiency for each spectral channel into a selected output port. As such, the servo-control assembly **440** provides dynamic control of the coupling of the spectral channels into the respective output ports on a channel-by-channel basis and thereby manages the power levels of the spectral channels coupled into the output ports. The power levels of the spectral channels in the output ports may be dynamically managed according to demand, or maintained at desired values (e.g., equalized at a predetermined value) in the present invention. Such a spectral power-management capability is essential in WDM optical networking applications, as discussed above.

FIG. **4**B depicts a schematic illustration of a second embodiment of a WSR-S apparatus according to the present invention. The WSR-S apparatus **450** comprises a WSR apparatus **480** and a servo-control assembly **490**. In addition to the channel micromirrors **430** (and other elements identified by the same numerals as those used in FIG. **4**A), the WSR apparatus **480** further includes a plurality of collimator-alignment mirrors **485**, and may be configured according to the embodiment of FIGS. **2**A, **2**B, **3**, or any other embodiment in accordance with the present invention. By way of example, the servo-control assembly **490** includes the spectral monitor **460** as described in the embodiment of FIG. **4**A, and a processing unit **495**. In this case, the processing unit **495** is in communication with the channel micromirrors **430** and the collimator-alignment mirrors **485** of the WSR apparatus **480**, as well as the spectral monitor **460**. The processing unit **495** uses the power measurements from the spectral monitor **460** to provide dynamic control of the channel micromirrors **430** along with the collimator-alignment mirrors **485**, so to maintain the coupling efficiencies of the spectral channels into the output ports at desired values.

In the embodiment of FIG. **4**A or **4**B, the spectral monitor **460** may be one of spectral power monitoring devices known in the art that is capable of detecting the power levels of spectral components in a multi-wavelength optical signal. Such devices are typically in the form of a wavelength-separating means (e.g., a diffraction grating) that spatially separates a multi-wavelength optical signal by wavelength into constituent spectral components, and one or more optical sensors (e.g., an array of photodiodes) that are configured such to detect the power levels of these spectral components. The processing unit **470** in FIG. **4**A (or the processing unit **495** in FIG. **4**B) typically includes electrical circuits and signal processing programs for processing the power measurements received from the spectral monitor **460** and generating appropriate control signals to be applied to the channel micromirrors **430** (and the collimator-alignment mirrors **485** in the case of FIG. **4**B), so to maintain the coupling efficiencies of the spectral channels into the output ports at desired values. The electronic circuitry and the associated signal processing algorithm/software for such processing unit in a servo-control system are known in the art. A skilled artisan will know how to implement a suitable spectral monitor along with an appropriate processing unit to provide a servo-control assembly in a WSP-S apparatus according to the present invention, for a given application.

The incorporation of a servo-control assembly provides additional advantages of effectively relaxing the requisite fabrication tolerances and the precision of optical alignment during initial assembly of a WSR apparatus of the present invention, and further enabling the system to correct for shift in the alignment over the course of operation. By maintaining an optimal optical alignment, the optical losses incurred by the spectral channels are also significantly reduced. As such, the WSR-S apparatus thus constructed is simpler and more adaptable in structure, more robust in performance, and lower in cost and optical loss. Accordingly, the WSR-S (or WSR) apparatus of the present invention may be used to construct a variety of optical devices and utilized in many applications.

For instance, by directing the spectral channels into the output ports in a one-channel-per-port fashion and coupling the output ports of a WSR-S (or WSR) apparatus to an array of optical sensors (e.g., photodiodes), or a single optical sensor that is capable of scanning across the output ports, a dynamic and versatile spectral power monitor (or channel analyzer) is provided, which would be highly desired in WDM optical networking applications. Moreover, a novel class of optical add-drop multiplexers (OADMs) may be built upon the WSR-S (or WSR) apparatus of the present invention, as exemplified in the following embodiments.

FIG. **5** depicts an exemplary embodiment of an optical add-drop multiplexer (OADM) according to the present invention. By way of example, OADM **500** comprises a WSR-S (or WSR) apparatus **510** and an optical combiner **550**. An input port **520** of the WSR-S apparatus **510** transmits a multi-wavelength optical signal. The constituent spectral channels are subsequently separated and routed into a plurality of output ports, including a pass-through port **530** and one or more drop ports **540-1** through **540**-N ($N \geqq 1$). The pass-through port **530** may receive any number of the spectral channels (i.e., the pass-through spectral channels). Each drop port may also receive any number of the spectral channels (i.e., the drop spectral channels). The pass-through port **530** is optically coupled to the optical combiner **550**, which serves to combine the pass-through spectral channels with one or more add spectral channels provided by one or more add ports **560-1** through **560**-M ($M \geqq 1$). The combined optical signal is then routed into an existing port **570**, providing an output multi-wavelength optical signal.

In the above embodiment, the optical combiner **550** may be a K×1 ($K \geqq 2$) broadband fiber-optic coupler, wherein there are K input-ends and one output-end. The pass-through spectral channels and the add spectral channels are fed into the K input-ends (e.g., in a one-to-one correspondence) and the combined optical signal exits from the output-end of the K×1 fiber-optic coupler as the output multi-wavelength optical signal of the system. Such a multiple-input coupler also serves the purpose of multiplexing a multiplicity of add spectral channels to be coupled into the OADM **500**. If the power levels of the spectral channels in the output multi-wavelength optical signal are desired to be actively managed, such as being equalized at a predetermined value, two spectral monitors may be utilized. As a way of example, the first spectral monitor may receive optical signals tapped off from the pass-through port **530** and the drop ports **540-1** through **540**-N (e.g., by way of fiber-optic couplers as depicted in FIG. **4**A or **4**B). The second spectral monitor receives optical signals tapped off from the exiting port **570**. A servo-control system may be constructed accordingly for monitoring and controlling the pass-through, drop and add spectral channels. As such, the embodiment of FIG. **5** provides a versatile optical add-drop multiplexer in a simple and low-cost assembly, while providing multiple physically separate drop/add ports in a dynamically reconfigurable fashion.

FIG. **6** depicts an alternative embodiment of an optical add-drop multiplexer (OADM) according to the present invention. By way of example, OADM **600** comprises a first WSR-S apparatus **610** optically coupled to a second WSR-S apparatus **650**. Each WSR-S apparatus may be in the embodiment of FIG. **4**A or **4**B. (A WSR apparatus of the embodiment of FIG. **1**A, **2**A, **2**B, or **3** may be alternatively implemented.) The first WSR-S apparatus **610** includes an input port **620**, a pass-through port **630**, and one or more drop ports **640-1** through **640**-N (N≧1). The pass-through spectral channels from the pass-through port **630** are further coupled to the second WSR-S apparatus **650**, along with one or more add spectral channels emerging from add ports **660-1** through **660**-M (M≧1). In this exemplary case, the pass-through port **630** and the add ports **660-1** through **660**-M constitute the input ports for the second WSR-S apparatus **650**. By way of its constituent wavelength-separator (e.g., a diffraction grating) and channel micromirrors (not shown in FIG. **6**), the second WSR-S apparatus **650** serves to multiplex the pass-through spectral channels and the add spectral channels, and route the multiplexed optical signal into an exiting port **770** to provide an output signal of the system.

In the embodiment of FIG. **6**, one WSR-S apparatus (e.g., the first WSR-S apparatus **610**) effectively performs dynamic drop function, whereas the other WSR-S apparatus (e.g., the second WSR-S apparatus **650**) carries out dynamic add function. And there are essentially no fundamental restrictions on the wavelengths that can be added or dropped (other than those imposed by the overall communication system). Moreover, the underlying OADM architecture thus presented is intrinsically scalable and can be readily extended to any number of cascaded WSR-S (or WSR) systems, if so desired for performing intricate add and drop functions. Additionally, the OADM of FIG. **6** may be operated in reverse direction, by using the input ports as the output ports, the drop ports as the add ports, and vice versa.

Those skilled in the art will recognize that the aforementioned embodiments provide only two of many embodiments of a dynamically reconfigurable OADM according to the present invention. Those skilled in the art will also appreciate that various changes, substitutions, and alternations can be made herein without departing from the principles and the scope of the invention as defined in the appended claims. Accordingly, a skilled artisan can design an OADM in accordance with the principles of the present invention, to best suit a given application.

Although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions, and alternations can be made herein without departing from the principles and the scope of the invention. Accordingly, the scope of the present invention should be determined by the following claims and their legal equivalents.

What is claimed is:

1. An optical add-drop apparatus comprising

an input port for an input multi-wavelength optical signal having first spectral channels;

one or more other ports for second spectral channels; an output port for an output multi-wavelength optical signal;

a wavelength-selective device for spatially separating said spectral channels; **[and]**

a spatial array of beam-deflecting elements positioned such that each element receives a corresponding one of said spectral channels, each of said elements being individually and continuously controllable *in two dimensions* to reflect its corresponding spectral channel to a selected one of said ports *and to control the power of the spectral channel reflected to said selected port.*

2. The optical add-drop apparatus of claim **1** further comprising a control unit for controlling each of said beam-deflecting elements.

3. The optical add-drop apparatus of claim **2**, wherein the control unit further comprises a servo-control assembly, including a spectral monitor for monitoring power levels of selected ones of said spectral channels, and a processing unit responsive to said power levels for controlling said beam-deflecting elements.

4. The optical add-drop apparatus of claim **3**, wherein said servo-control assembly maintains said power levels at predetermined values.

5. The optical add-drop apparatus of claim **2**, wherein the control unit controls said beam-deflecting elements to direct selected ones of said first spectral channels to one or more of said second ports to be dropped as second spectral channels from said output multi-wavelength optical signal.

6. The optical add-drop apparatus of claim **2**, wherein the control unit controls said beam-deflecting elements to direct selected ones of said second spectral channels to said output port to be added to said output multi-wavelength optical signal.

7. The optical add-drop apparatus of claim **1** further comprising alignment mirrors for adjusting alignment of said input and output multi-wavelength optical signals and said second spectral channels with said wavelength-selective device.

8. The optical add-drop apparatus of claim **7** further comprising collimators associated with said alignment mirrors, and imaging lenses in a telecentric arrangement with said alignment mirrors and said collimators.

9. The optical add-drop apparatus of claim **1**, wherein said wavelength selective device further combines selected ones of said spectral channels reflected from said beam-deflecting elements to form said output multi-wavelength optical signal.

10. The optical add-drop apparatus of claim **1**, wherein said one or more other ports comprise an add port and a drop port for respectively adding second and dropping first spectral channels.

11. The optical add-drop apparatus of claim **1** further comprising a beam-focuser for focusing said separated spectral channels onto said beam deflecting elements.

12. The optical add-drop apparatus of claim **1**, wherein said wavelength-selective device comprises a device selected from the group consisting of ruled diffraction gratings, holographic diffraction gratings, echelle gratings, curved diffraction gratings, and dispersing prisms.

13. The optical add-drop apparatus of claim 1, wherein said beam-deflecting elements comprise micromachined mirrors.

14. The optical add-drop apparatus of claim 1, wherein said beam-deflecting elements comprise reflective membranes.

15. An optical add-drop apparatus, comprising

an input port for an input multi-wavelength optical signal having multiple spectral channels;

an output port for an output multi-wavelength optical signal;

one or more drop ports for selected spectral channels dropped from said multi-wavelength optical signal;

a wavelength-selective device for spatially separating said multiple spectral channels; and

a spatial array of beam-deflecting elements positioned such that each element receives a corresponding one of said spectral channels, each of said elements being individually and continuously controllable *in two dimensions* to reflect its corresponding spectral channel to a selected one of said ports *and to control the power of the spectral channel reflected to said selected port*, whereby a subset of said spectral channels is directed to said drop ports.

16. An optical add-drop apparatus, comprising

an input port for an input multi-wavelength optical signal having multiple spectral channels;

an output port for an output multi-wavelength optical signal;

one or more add ports for selected spectral channels to be added to said output multi-wavelength optical signal;

a wavelength-selective device for reflecting said multiple and said selected spectral channels; and

a spatial array of beam-deflecting elements positioned such that each element receives a corresponding one of said spectral channels, each of said elements being individually and continuously controllable *in two dimensions* to reflect its corresponding spectral channel to a selected one of said ports *and to control the power of the spectral channel reflected to said selected port*, whereby said spectral channels from said add ports are selectively provided to said output port.

17. A method of performing dynamic add and drop in a WDM optical network, comprising

separating an input multi-wavelength optical signal into spectral channels;

imaging each of said spectral channels onto a corresponding beam-deflecting element; and

controlling dynamically and continuously said beam-deflecting elements *in two dimensions* so as to combine selected ones of said spectral channels into an output multi-wavelength optical signal *and to control the power of the spectral channels combined into said output multi-wavelength optical signal.*

18. The method of claim 17, wherein said selected ones of said spectral channels comprises a subset of said spectral channels, such that other non-selected ones of said spectral channels are dropped from said output multi-wavelength optical signal.

19. The method of claim 18, wherein said controlling comprises reflecting said non-selected ones of said spectral channels to one or more drop ports.

20. The method of claim 17 further comprising imaging other spectral channels onto other corresponding beam-deflecting elements, and controlling dynamically and continuously said other beam-deflecting elements so as to combine said other spectral channels with said selected ones of said spectral channels into said output multi-wavelength optical signal.

21. The method of claim 17, wherein said imaging comprises focusing said spectral channels onto said beam-deflecting elements.

22. The method of claim 17 further comprising monitoring a power level in one or more of said selected ones of said spectral channels, and controlling an alignment between said input multi-wavelength optical signal and corresponding beam-deflecting elements in response to said monitoring.

* * * * *

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(12) **Reissued Patent**
Wilde et al.

(10) **Patent Number: US RE42,678 E**
(45) **Date of Reissued Patent: Sep. 6, 2011**

(54) **RECONFIGURABLE OPTICAL ADD-DROP MULTIPLEXERS WITH SERVO CONTROL AND DYNAMIC SPECTRAL POWER MANAGEMENT CAPABILITIES**

(75) Inventors: **Jeffrey P. Wilde**, Morgan Hill, CA (US); **Joseph E. Davis**, Morgan Hill, CA (US)

(73) Assignee: **Capella Photonics, Inc.**, San Jose, CA (US)

(21) Appl. No.: **12/815,930**

(22) Filed: **Jun. 15, 2010**

Related U.S. Patent Documents

Reissue of:

(64) Patent No.: **Re. 39,397**
Issued: **Nov. 14, 2006**
Appl. No.: **11/027,586**
Filed: **Dec. 31, 2004**

Which is a Reissue of:

(64) Patent No.: **6,625,346**
Issued: **Sep. 23, 2003**
Appl. No.: **09/938,426**
Filed: **Aug. 23, 2001**

U.S. Applications:

(60) Provisional application No. 60/277,217, filed on Mar. 19, 2001.

(51) **Int. Cl.**
G02B 6/28 (2006.01)

(52) **U.S. Cl.** **385/24**; 385/11; 385/37; 385/34

(58) **Field of Classification Search** 385/24, 385/11, 37, 34
See application file for complete search history.

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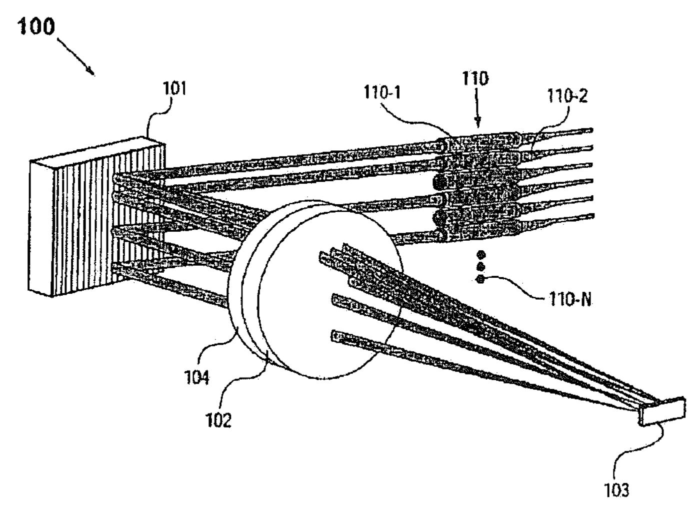
Primary Examiner — Brian M Healy
(74) *Attorney, Agent, or Firm* — Barry N. Young

(57) **ABSTRACT**

This invention provides a novel wavelength-separating-routing (WSR) apparatus that uses a diffraction grating to separate a multi-wavelength optical signal by wavelength into multiple spectral characters, which are then focused onto an array of corresponding channel micromirrors. The channel micromirrors are individually controllable and continuously pivotable to reflect the spectral channels into selected output ports. As such, the inventive WSR apparatus is capable of routing the spectral channels on a channel-by-channel basis and coupling any spectral channel into any one of the output ports. The WSR apparatus of the present invention may be further equipped with servo-control and spectral power-management capabilities, thereby maintaining the coupling efficiencies of the spectral channels into the output ports at desired values. The WSR apparatus of the present invention can be used to construct a novel class of dynamically reconfigurable optical add-drop multiplexers (OADMs) for WDM optical networking applications.

67 Claims, 12 Drawing Sheets



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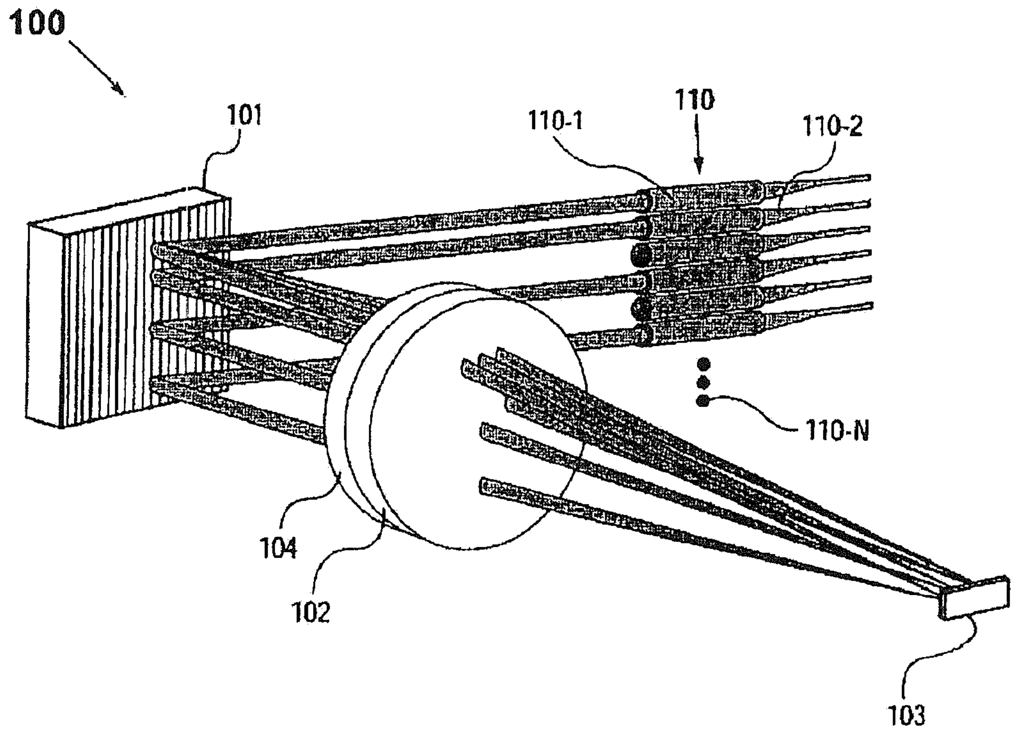

Fig. 1A

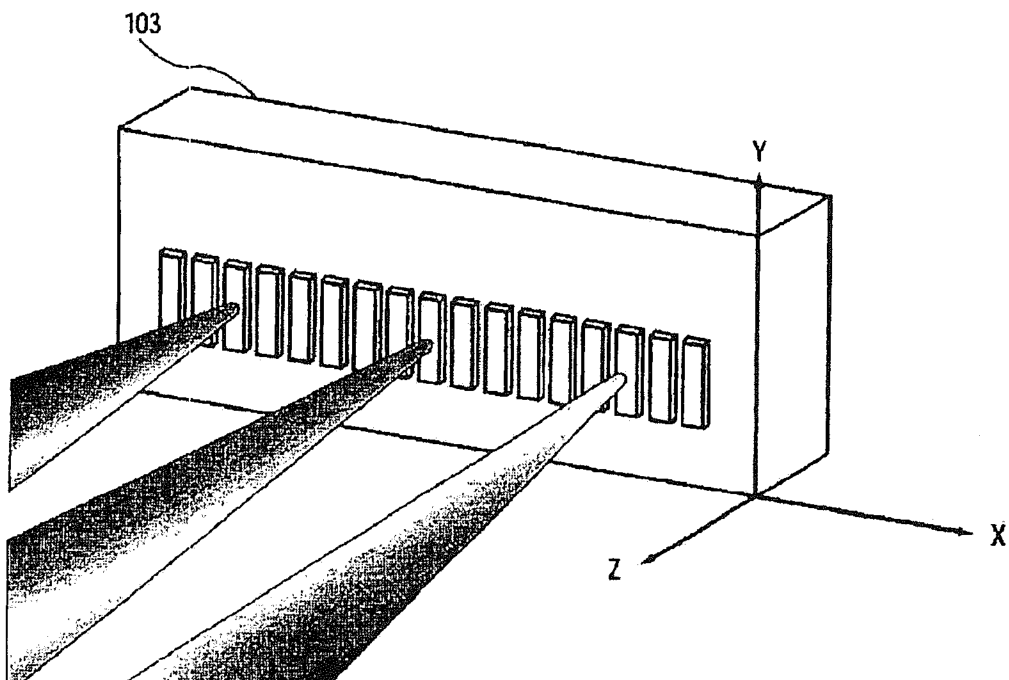

Fig. 1B

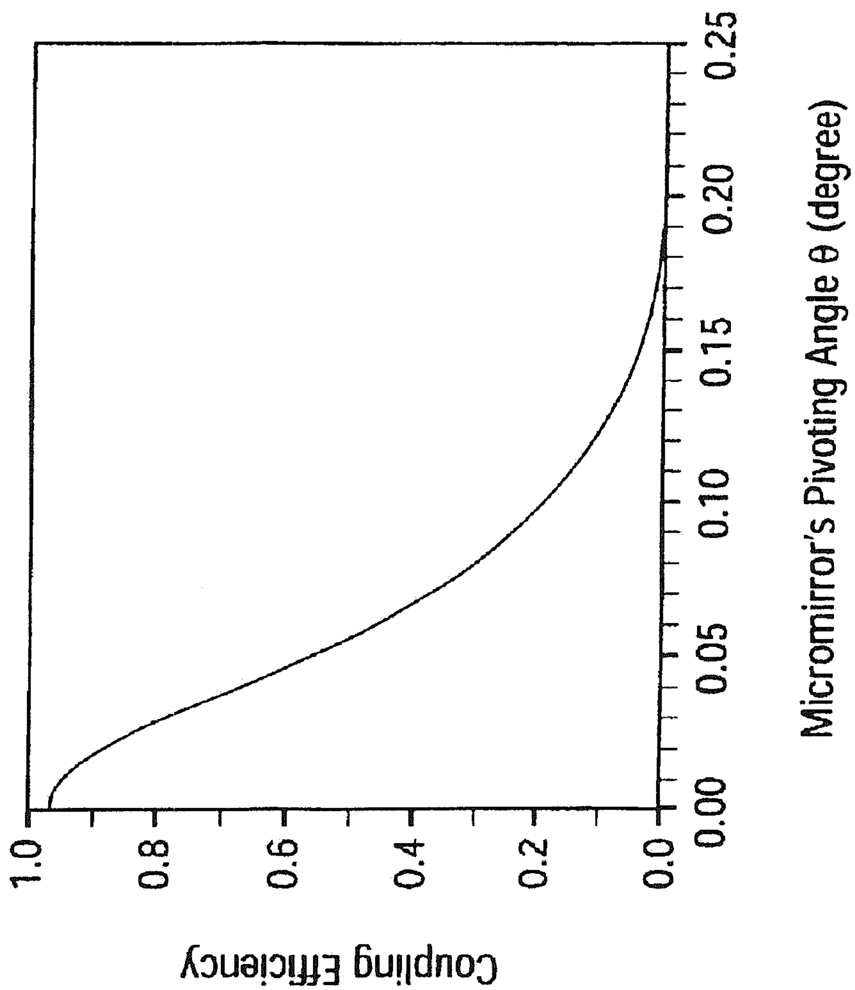
Coupling Efficiency
1.0
0.8
0.6
0.4
0.2
0.0
0.00
0.05
0.10
0.15
0.20
0.25
Micromirror's Pivoting Angle θ (degree)

Fig. 1C

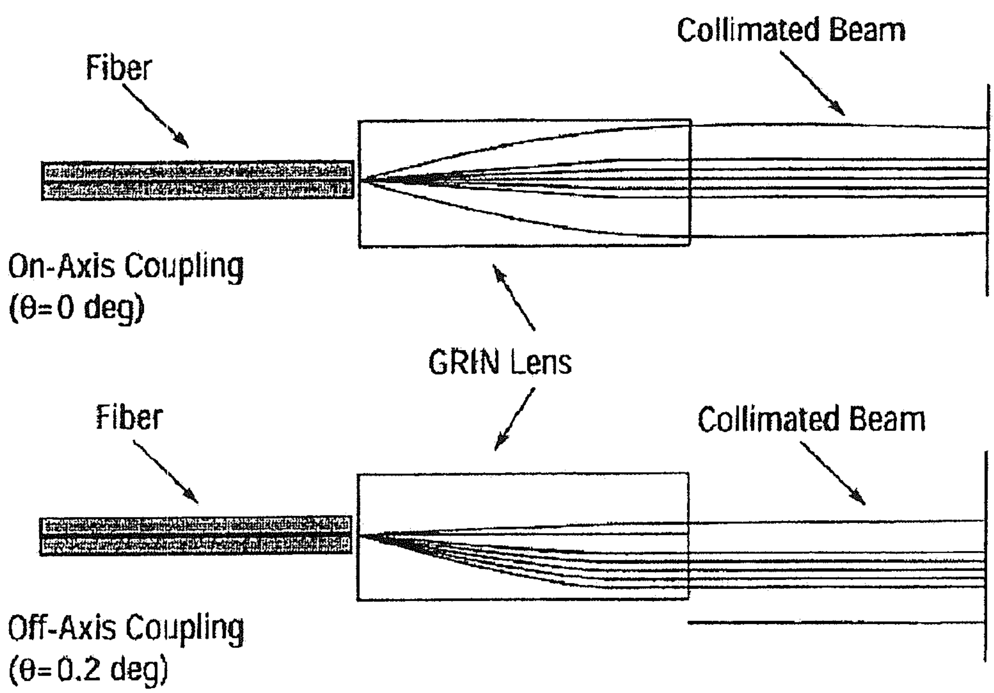
Collimated Beam
Fiber
On-Axis Coupling
(θ=0 deg)
GRIN Lens
Fiber
Collimated Beam
Off-Axis Coupling
(θ=0.2 deg)

Fig. 1D

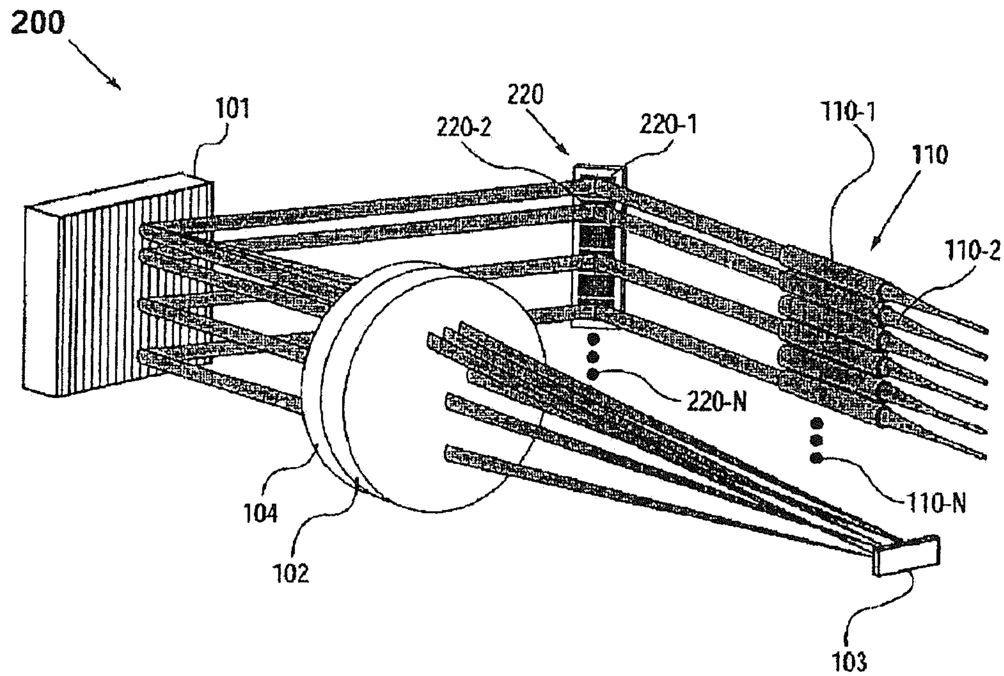

Fig. 2A

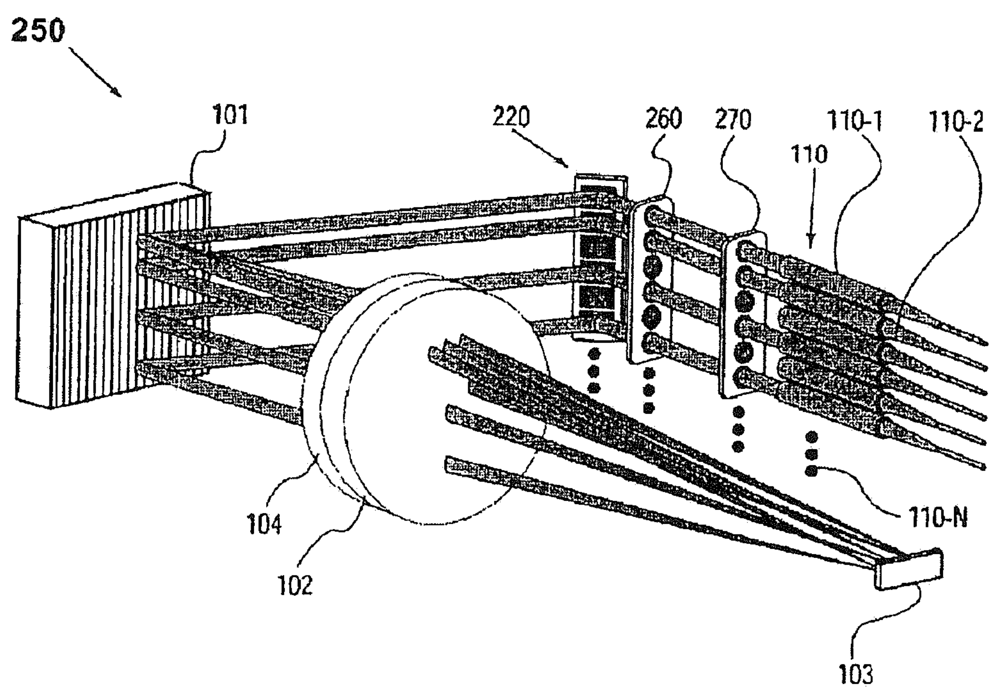

Fig. 2B

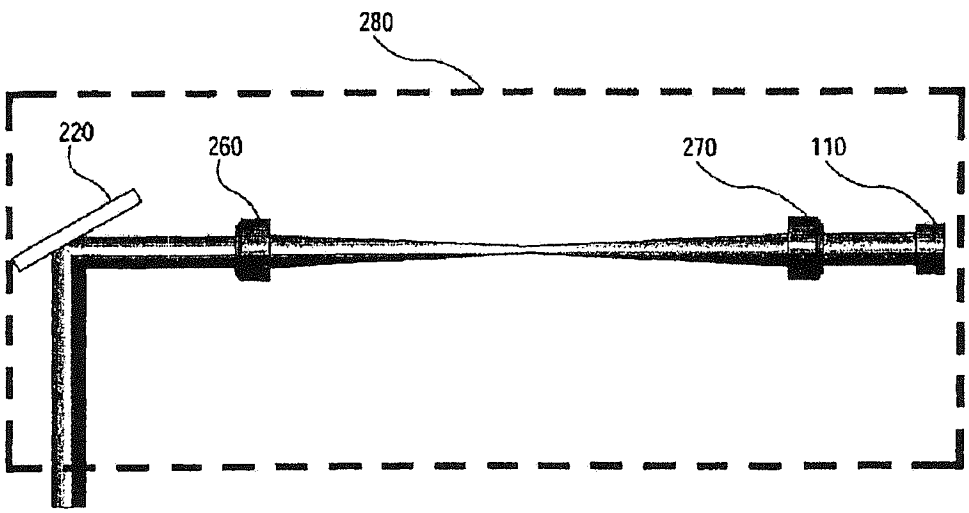

Fig. 2C

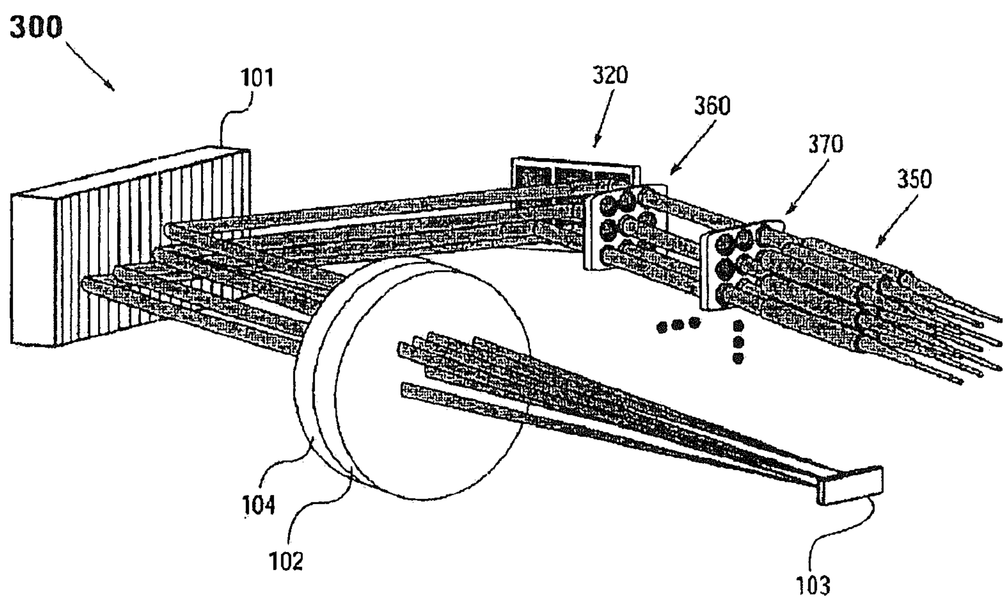

Fig. 3

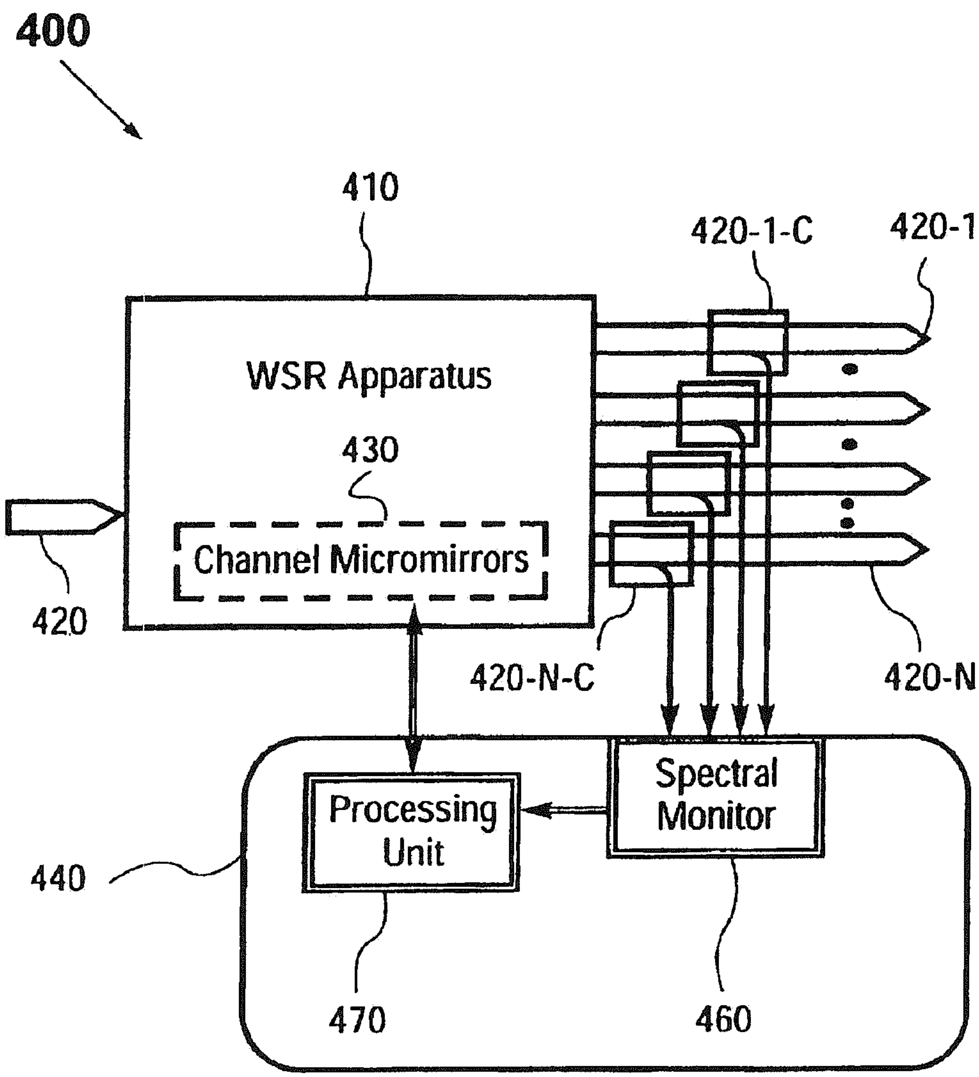
400
410
420-1-C
420-1
WSR Apparatus
430
Channel Micromirrors
420
420-N-C
420-N
Spectral Monitor
Processing Unit
440
470
460

Fig. 4A

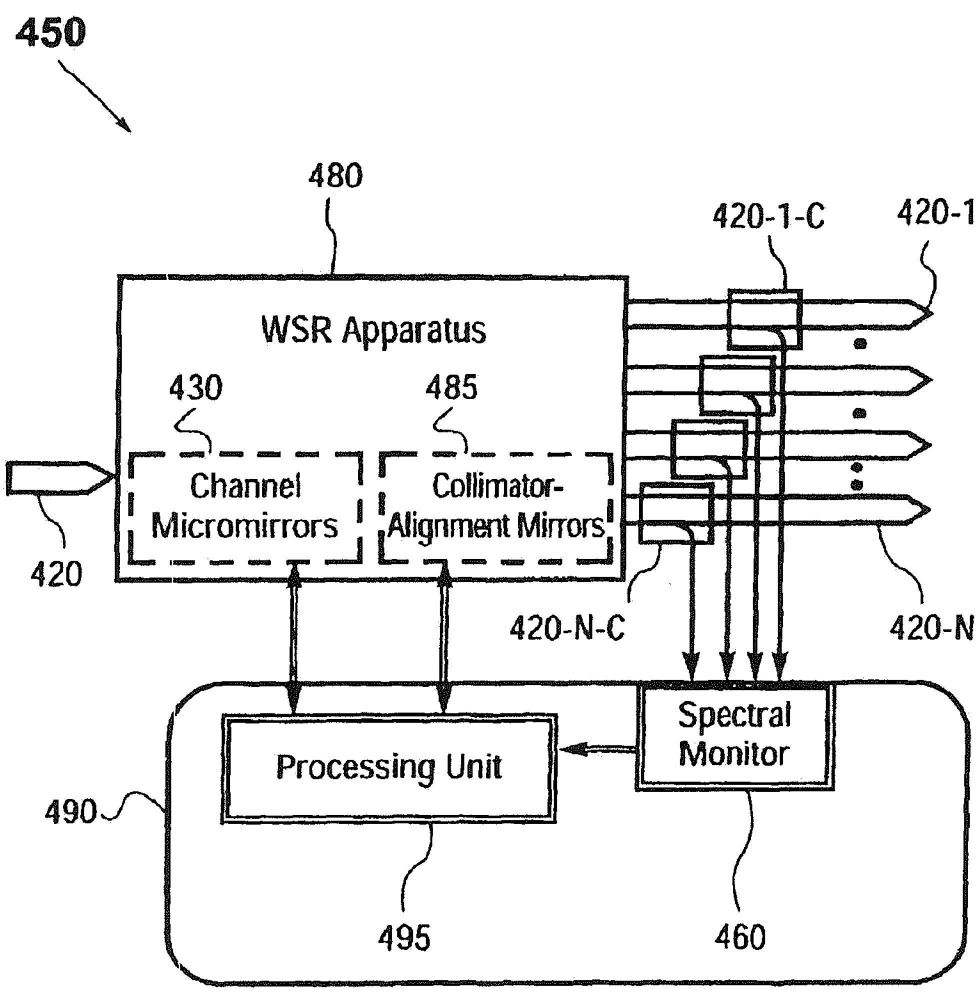
450
480
420-1-C
420-1
WSR Apparatus
430
485
Channel Micromirrors
Collimator-Alignment Mirrors
420
420-N-C
420-N
Processing Unit
Spectral Monitor
490
495
460

Fig. 4B

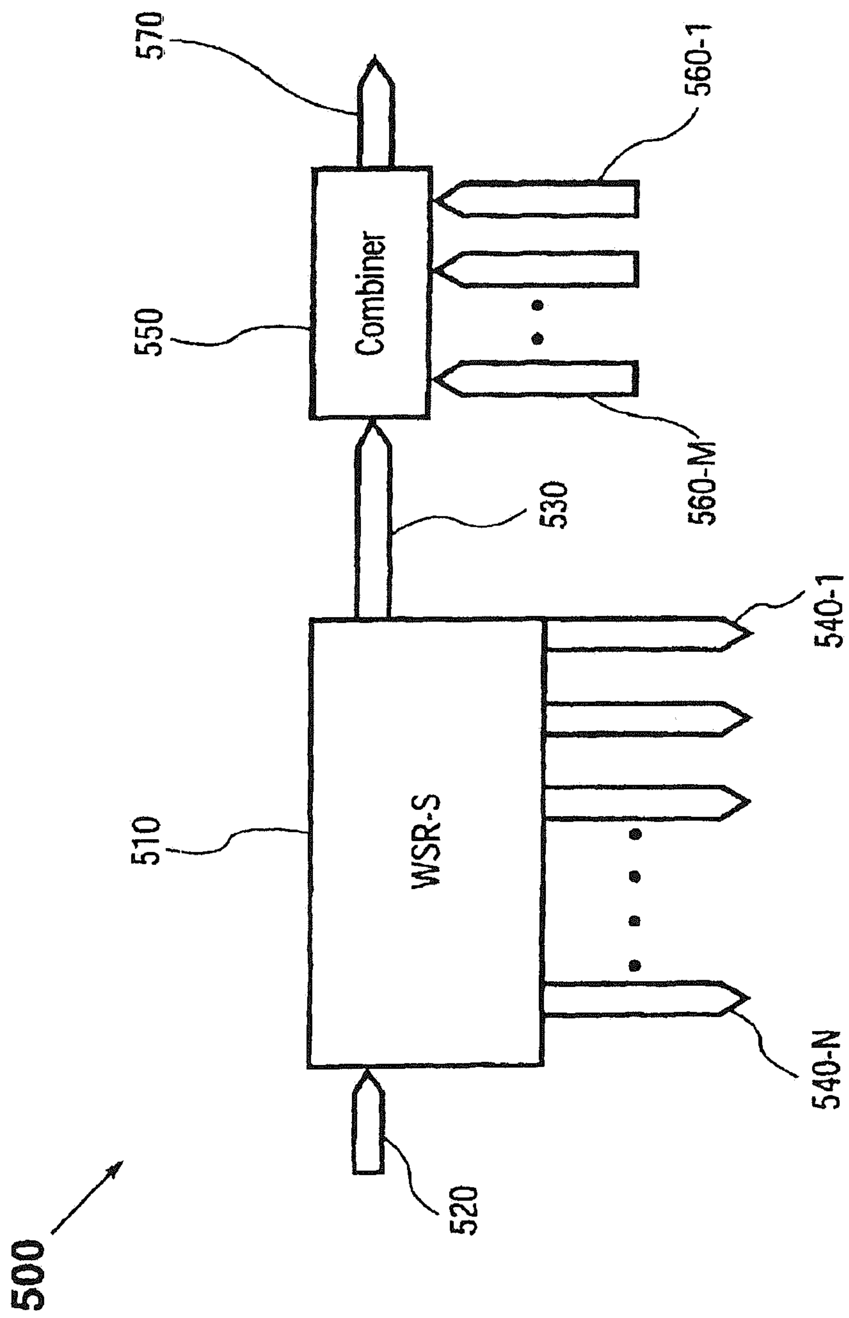

Fig. 5

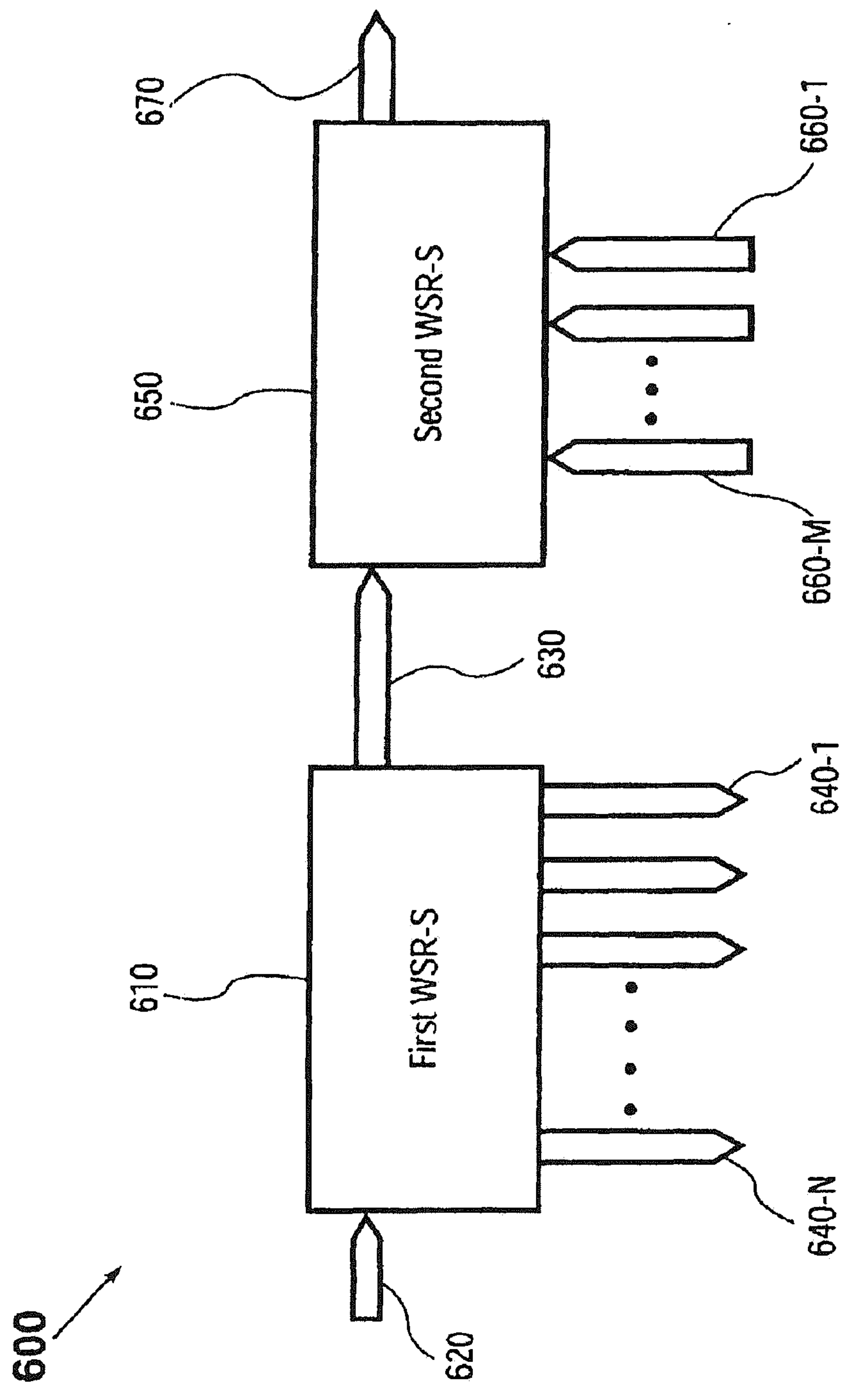
600
610
First WSR-S
620
630
640-1
640-N
650
Second WSR-S
660-1
660-M
670

Fig. 6

RECONFIGURABLE OPTICAL ADD-DROP MULTIPLEXERS WITH SERVO CONTROL AND DYNAMIC SPECTRAL POWER MANAGEMENT CAPABILITIES

Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of the first and this reissue specification; matter printed in italics indicates the additions made by the first reissue. Matter enclosed in double heavy brackets [[ ]] appears in the first reissue patent but forms no part of this reissue specification; matter printed in bold face indicates the additions made by this reissue.

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority of U.S. Provisional Patent Application No. 60/277,217, filed Mar. 19, 2001 which is incorporated herein by reference.

FIELD OF THE INVENTION

This invention relates generally to optical communication systems. More specifically, it relates to a novel class of dynamically reconfigurable optical add-drop multiplexers (OADMs) for wavelength division multiplexed optical networking applications.

BACKGROUND

As fiber-optic communication networks rapidly spread into every walk of modern life, there is a growing demand for optical components and subsystems that enable the fiber-optic communications networks to be increasingly scalable, versatile, robust, and cost-effective.

Contemporary fiber-optic communications networks commonly employ wavelength division multiplexing (WDM), for it allows multiple information (or data) channels to be simultaneously transmitted on a single optical fiber by using different wavelengths and thereby significantly enhances the information-bandwidth of the fiber. The prevalence of WDM technology has made optical add-drop multiplexers indispensable building blocks of modern fiber-optic communication networks. An optical add-drop multiplexer (OADM) serves to selectively remove (or drop) one or more wavelengths from a multiplicity of wavelengths on an optical fiber, hence taking away one or more data channels from the traffic stream on the fiber. It further adds one or more wavelength back onto the fiber, thereby inserting new data channels in the same stream of traffic. As such, an OADM makes it possible to launch and retrieve multiple data channels (each characterized by a distinct wavelength) onto and from an optical fiber respectively, without disrupting the overall traffic flow along the fiber. Indeed, careful placement of the OADMs can dramatically improve an optical communication network's flexibility and robustness, while providing significant cost advantages.

Conventional OADMs in the art typically employ multiplexers/demultiplexers (e.g. waveguide grating routers or arrayed-waveguide gratings), tunable filters, optical switches, and optical circulators in a parallel or serial architecture to accomplish the add and drop functions. In the parallel architecture, as exemplified in U.S. Pat. No. 5,974,207, a demultiplexer (e.g., a waveguide grating router) first separates a multi-wavelength signal into its constituent spectral components. A wavelength switching/routing means (e.g., a combination of optical switches and optical circulators) then serves to drop selective wavelengths and add others. Finally, a multiplexer combines the remaining (i.e., the pass-through) wavelengths into an output multi-wavelength optical signal. In the serial architecture, as exemplified in U.S. Pat. No. 6,205,269, tunable filters (e.g., Bragg fiber gratings) in combination with optical circulators are used to separate the drop wavelength from the pass-through wavelengths and subsequently launch the add channels into the pass-through path. And if multiple wavelengths are to be added and dropped, additional multiplexers and demultiplexers are required to demultiplex the drop wavelengths and multiplex the add wavelengths, respectively. Irrespective of the underlying architecture, the OADMs currently in the art are characteristically high in cost, and prone to significant optical loss accumulation. Moreover, the designs of these OADMs are such that it is inherently difficult to reconfigure them in a dynamic fashion.

U.S. Pat. No. 6,204,946 to Askyuk et al. discloses an OADM that makes use of free-space optics in a parallel construction. In this case, a multi-wavelength optical signal emerging from an input port is incident onto a ruled diffraction grating. The constituent spectral channels thus separated are then focused by a focusing lens onto a linear array of binary micromachined mirrors. Each micromirror is configured to operate between two discrete states, such that it either retrofits its corresponding spectral channel back into the input port as a pass-through channel, or directs its spectral channel to an output port as a drop channel. As such, the pass-through signal (i.e., the combined pass-through channels) shares the same input port as the input signal. An optical circulator is therefore coupled to the input port, to provide necessary routing of these two signals. Likewise, the drop channels share the output port with the add channels. An additional optical circulator is thereby coupled to the output port, from which the drop channels exit and the add channels are introduced into the output ports. The add channels are subsequently combined with the pass-through signal by way of the diffraction grating and the binary micromirrors.

Although the aforementioned OADM disclosed by Askyuk et al. has the advantage of performing wavelength separating and routing in free space and thereby incurring less optical loss, it suffers a number of limitations. First, it requires that the pass-through signal share the same port/fiber as the input signal. An optical circulator therefore has to be implemented, to provide necessary routing of these two signals. Likewise, all the add and drop channels enter and leave the OADM through the same output port, hence the need for another optical circulator. Moreover, additional means must be provided to multiplex the add channels before entering the system and to demultiplex the drop channels after exiting the system. This additional multiplexing/demultiplexing requirement adds more cost and complexity that can restrict the versatility of the OADM thus-constructed. Second, the optical circulators implemented in this OADM for various routing purposes introduce additional optical losses, which can accumulate to a substantial amount. Third, the constituent optical components must be in a precise alignment, in order for the system to achieve its intended purpose. There are, however, no provisions provided for maintaining the requisite alignment; and no mechanisms implemented for overcoming degradation in the alignment owing to environmental effects such as thermal and mechanical disturbances over the course of operation.

U.S. Pat. No. 5,906,133 to Tomlinson discloses an OADM that makes use of a design similar to that of Aksyuk et al. There are input, output, drop and add ports implemented in this case. By positioning the four ports in a specific arrangement, each micromirror, notwithstanding switchable between two discrete positions, either reflects its corresponding channel (coming from the input port) to the output port, or concomitantly reflects its channel to the drop port and an incident add channel to the output port. As such, this OADM is able to perform both the add and drop functions without involving additional optical components (such as optical circulators and in the system of the Aksyuk et al.). However, because a single drop port is designated for all the drop channels and a single add port is designated for all the add channels, the add channels would have to be multiplexed before entering the add port and the drop channels likewise need to be demultiplexed upon exiting from the drop port. Moreover, as in the case of Askyuk et al., there are no provisions provided for maintaining requisite optical alignment in the system, and no mechanisms implemented for combating degradation in the alignment due to environmental effects over the course of operation.

As such, the prevailing drawbacks suffered by the OADMs currently in the art are summarized as follows:

1) The wavelength routing is intrinsically static, rendering it difficult to dynamically reconfigure these OADMs.
2) Add and/or drop channels often need to be multiplexed and/or demultiplexed, thereby imposing additional complexity and cost.
3) Stringent fabrication tolerance and painstaking optical alignments are required. Moreover, the optical alignment is not actively maintained, rendering it susceptible to environmental effects such as thermal and mechanical disturbances over the course of operation.
4) In an optical communication network, OADMs are typically in a ring or cascaded configuration. In order to mitigate the interference amongst OADMs, which often adversely affects the overall performance of the network, it is essential that the power levels of spectral channels entering and exiting each OADM be managed in a systematic way, for instance, by introducing power (or gain) equalization at each stage. Such a power equalization capability is also needed for compensating for nonuniform gain caused by optical amplifiers (e.g., erbium doped fiber amplifiers) in the network. There lacks, however, a systematic and dynamic management of the power levels of various spectral channels in these OADMs.
5) The inherent high cost and heavy optical loss further impede the wide application of these OADMs.

In view of the foregoing, there is an urgent need in the art for optical add-drop multiplexers that overcome the aforementioned shortcomings, in a simple, effective, and economical construction.

SUMMARY

The present invention provides a wavelength-separating-routing (WSR) apparatus and method which employ an array of fiber collimators serving as an input port and a plurality of output ports; a wavelength-separator; a beam-focuser; and an array of channel micromirrors.

In operation, a multi-wavelength optical signal emerges from the input port. The wavelength-separator separates the multi-wavelength optical signal into multiple spectral channels, each characterized by a distinct center wavelength and associated bandwidth. The beam-focuser focuses the spectral channels into corresponding spectral spots. The channel micromirrors are positioned such that each channel micromirror receives one of the spectral channels. The channel micromirrors are individually controllable and movable, e.g., continuously pivotable (or rotatable), so as to reflect the spectral channels into selected ones of the output ports. As such, each channel micromirror is assigned to a specific spectral channel, hence the name "channel micromirror". And each output port may receive any number of the reflected spectral channels.

A distinct feature of the channel micromirrors in the present invention, in contrast to those used in the prior art, is that the motion, e.g., pivoting (or rotation), of each channel micromirror is under analog control such that its pivoting angle can be continouously adjusted. This enables each channel micromirror to scan its corresponding spectral channel across all possible output ports and thereby direct the spectral channel to any desired output ports.

In the WSR apparatus of the present invention, the wavelength-separator may be provided by a ruled diffraction grating, a holographic diffraction grating, an echelle grating, a curved diffraction grating, a dispersing prism, or other wavelength-separating means known in the art. The beam-focuser may be a single lens, an assembly of lenses, or other beam-focusing means known in the art. The channel micromirrors may be provided by silicon micromachined mirrors, reflective ribbons (or membranes), or other types of beam-deflecting means known in the art. And each channel micromirror may be pivotable about one or two axes. The fiber collimators serving as the input and output ports may be arranged in a one-dimensional or two-dimensional array. In the latter case, the channel micromirrors must be pivotable biaxially.

The WSR apparatus of the present invention may further comprise an array of collimator-alignment mirrors, in optical communication with the wavelength-separator and the fiber collimators, for adjusting the alignment of the input multi-wavelength signal and directing the spectral channels into the selected output ports by way of angular control of the collimated beams. Each collimator-alignment mirror may be rotatable about one or two axes. The collimator-alignment mirrors may be arranged in a one-dimensional or two-dimensional array. First and second arrays of imaging lenses may additionally be optically interposed between the collimator-alignment mirrors and the fiber collimators in a telecentric arrangement, thereby "imaging" the collimator-alignment mirrors onto the corresponding fiber collimators to ensure an optimal alignment.

The WSR apparatus of the present invention may further include a servo-control assembly, in communication with the channel micromirrors and the output ports. The servo-control assembly serves to monitor the power levels of the spectral channels coupled into the output ports and further provide control of the channel micromirrors on an individual basis, so as to maintain a predetermined coupling efficiency of each spectral channel in one of the output ports. As such, the servo-control assembly provides dynamic control of the coupling of the spectral channels into the respective output ports and actively manages the power levels of the spectral channels coupling into the output ports. (If the WSR apparatus includes an array of collimator-alignment mirrors as described above, the servo-control assembly may additionally provide dynamic control of the collimator-alignment mirrors.) Moreover, the utilization of such a servo-control assembly effectively relaxes the requisite fabrication tolerances and the precision of optical alignment during assembly of a WSR apparatus of the present invention, and further enables the system to correct for shift in optical alignment over the course of operation. A WSR apparatus incorporating a servo-control assembly thus described is termed a WSR-S apparatus, thereinafter in the present invention.

Accordingly, the WSR-S (or WSR) apparatus of the present invention may be used to construct a variety of optical devices, including a novel class of dynamically reconfigurable optical add-drop multiplexers (OADMs), as exemplified in the following embodiments.

One embodiment of an OADM of the present invention comprises an aforementioned WSR-S (or WSR) apparatus and an optical combiner. The output ports of the WSR-S apparatus include a pass-through port and one or more drop ports, each carrying any number of the spectral channels. The optical combiner is coupled to the pass-through port, serving to combine the pass-through channels with one or more add spectral channels. The combined optical signal constitutes an output signal of the system. The optical combiner may be an N×1 ($N \leqq 2$) broadband fiber-optic coupler, for instance, which also serves the purpose of multiplexing a multiplicity of add spectral channels to be coupled into the system.

In another embodiment of an OADM of the present invention, a first WSR-S (or WSR) apparatus is cascaded with a second WSR-S (or WSR) apparatus. The output ports of the first WSR-S (or WSR) apparatus include a pass-through port and one or more drop ports. The second WSR-S (or WSR) apparatus includes a plurality of input ports and an exiting port. The configuration is such that the pass-through channels from the first WSR-S apparatus and one or more add channels are directed into the input ports of the second WSR-S apparatus, and consequently multiplexed into an output multi-wavelength optical signal directed into the exiting port of the second WSR-S apparatus. That is to say that in this embodiment, one WSR-S apparatus (e.g., the first one) effectively performs a dynamic drop function, whereas the other WSR-R apparatus (e.g., the second one) carries out a dynamic add function. And there are essentially no fundamental restrictions on the wavelengths that can be added or dropped, other than those imposed by the overall communication system. Moreover, the underlying OADM architecture thus presented is intrinsically scalable and can be readily extended to any number of the WSR-S (or WSR) systems, if so desired for performing intricate add and drop functions in a network environment.

Those skilled in the art will recognize that the aforementioned embodiments provide only two of many embodiments of a dynamically reconfigurable OADM according to the present invention. Various changes, substitutions, and alternations can be made herein, without departing from the principles and the scope of the invention. Accordingly, a skilled artisan can design an OADM in accordance with the present invention, to best suit a given application.

All in all, the OADMs of the present invention provide many advantages over the prior art devices, notably:

1) By advantageously employing an array of channel micromirrors that are individually and continuously controllable, an OADM of the present invention is capable of routing the spectral channels on a channel-by-channel basis and directing any spectral channel into any one of the output ports. As such, its underlying operation is dynamically reconfigurable, and its underlying architecture is intrinsically scalable to a large number of channel counts.
2) The add and drop spectral channels need not be multiplexed and demultiplexed before entering and after leaving the OADM respectively. And there are not fundamental restrictions on the wavelengths to be added or dropped.
3) The coupling of the spectral channels into the output ports is dynamically controlled by a servo-control assembly, rendering the OADM less susceptible to environmental effects (such as thermal and mechanical disturbances) and therefore more robust in performance. By maintaining an optimal optical alignment, the optical losses incurred by the spectral channels are also significantly reduced.
4) The power levels of the spectral channels coupled into the output ports can be dynamically managed according to demand, or maintained at desired values (e.g., equalized at a predetermined value) by way of the servo-control assembly. This spectral power-management capability as an integral part of the OADM will be particularly desirable in WDM optical networking applications.
5) The use of free-space optics provides a simple, low loss, and cost-effective construction. Moreover, the utilization of the servo-control assembly effectively relaxes the requisite fabrication tolerances and the precision of optical alignment during initial assembly, enabling the OADM to be simpler and more adaptable in structure, lower in cost and optical loss.
6) The underlying OADM architecture allows a multiplicity of the OADMs according to the present invention to be readily assembled (e.g., cascaded) for WDM optical networking applications.

The novel features of this invention, as well as the invention itself, will be best understood from the following drawings and detailed description.

BRIEF DESCRIPTION OF THE FIGURES

FIGS. 1A-1D show a first embodiment of a wavelength-separating-routing (WSR) apparatus according to the present invention, and the modeling results demonstrating the performance of the WSR apparatus;

FIGS. 2A-2C depict second and third embodiments of a WSR apparatus according to the present invention;

FIG. 3 shows a fourth embodiment of a WSR apparatus according to the present invention;

FIGS. 4A-4B show schematic illustration of two embodiments of a WSR-S apparatus comprising a WSR apparatus and a servo-control assembly, according to the present invention;

FIG. 5 depicts an exemplary embodiment of an optical add-drop multiplexer (OADM) according to the present invention; and

FIG. 6 shows an alternative embodiment of an OADM according to the present invention.

DETAILED DESCRIPTION

In this specification and appending claims, a "spectral channel" is characterized by a distinct center wavelength and associated bandwidth. Each spectral channel may carry a unique information signal, as in WDM optical networking applications.

FIG. 1A depicts a first embodiment of a wavelength-separating-routing (WSR) apparatus according to the present invention. By way of example to illustrate the general principles and the topological structure of a wavelength-separating-routing (WSR) apparatus of the present invention, the WSR apparatus 100 comprises multiple input/output ports which may be in the form of an array of fiber collimators 110, providing an input port 110-1 and a plurality of output ports 110-2 through 110-N ($N \leqq 3$); a wavelength-separator which in one form may be a diffraction grating 101; a beam-focuser in the form of a focusing lens 102; and an array of channel micromirrors 103.

In operation, a multi-wavelength optical signal emerges from the input port 110-1. The diffraction grating 101 angularly separates the multi-wavelength optical signal into multiple spectral channels, which are in turn focused by the focusing lens 102 into a spatial array of distinct spectral spots (not shown in FIG. 1A) in a one-to-one correspondence. The channel micromirrors 103 are positioned in accordance with the spatial array formed by the spectral spots, such that each channel micromirror receives one of the spectral channels. The channel micromirrors 103 are individually controllable and movable, e.g., pivotable (or rotatable) under analog (or continuous) control, such that, upon reflection, the spectral channels are directed into selected ones of the output ports 110-2 through 110-N by way of the focusing lens 102 and the diffraction grating 101. As such, each channel micromirror is assigned to a specific spectral channel, hence the name "channel micromirror". Each output port may receive any number of the reflected spectral channels.

For purposes of illustration and clarity, only a selective few (e.g., three) of the spectral channels, along with the input multi-wavelength optical signal, are graphically illustrated in FIG. 1A and the following figures. It should be noted, however, that there can be any number of the spectral channels in a WSR apparatus of the present invention (so long as the number of spectral channels does not exceed the number of channel mirrors employed in the system). It should also be noted that the optical beams representing the spectral channels shown in FIG. 1A and the following figures are provided for illustrative purpose only. That is, their sizes and shapes may not be drawn according to scale. For instance, the input beam and the corresponding diffracted beams generally have different cross-sectional shapes, so long as the angle of incidence upon the diffraction grating is not equal to the angle of diffraction, as is known to those skilled in the art.

In the embodiment of FIG. 1A, it is preferable that the diffracting grating 101 and the channel micromirrors 103 are placed respectively at the first and second (i.e., the front and back) focal points (on the opposing sides) of the focusing lens 102. Such a telecentric arrangement allows the chief rays of the focused beams to be parallel to each other and generally parallel to the optical axis. In this application, the telecentric configuration further allows the reflected spectral channels to be efficiently coupled into the respective output ports, thereby minimizing various translational walk-off effects that may otherwise arise. Moreover, the input multi-wavelength optical signal is preferably collimated and circular in cross-section. The corresponding spectral channels diffracted from the diffraction grating 101 are generally elliptical in cross-section; they may be of the same size as the input beam in one dimension and elongated in the other dimension.

It is known that the diffraction efficiency of a diffraction grating is generally polarization-dependent. That is, the diffraction efficiency of a grating in a standard mounting configuration may be considerably higher for P-polarization that is perpendicular to the groove lines on the grating than for S-polarization that is orthogonal to P-polarization, especially as the number of groove lines (per unit length) increases. To mitigate such polarization-sensitive effects, a quarter-wave plate 104 may be optically interposed between the diffraction grating 101 and the channel micromirrors 103, and preferably placed between the diffraction grating 101 and the focusing lens 102 as is shown in FIG. 1A. In this way, each spectral channel experiences a total of approximately 90-degree rotation in polarization upon traversing the quarter-wave plate 104 twice. (That is, if a beam of light has P-polarization with first encountering the diffraction grating, it would have predominantly (if not all) S-polarization upon the second encountering, and vice versa.) This ensures that all the spectral channels incur nearly the same amount of round-trip polarization dependent loss.

In the WSR apparatus 100 of FIG. 1A, the diffraction grating 101, by way of example, is oriented such that the focused spots of the spectral channels fall onto the channel micromirrors 103 in a horizontal array, as illustrated in FIG. 1B.

Depicted in FIG. 1B is a close-up view of the channel micromirrors 103 shown in the embodiment of FIG. 1A. By way of example, the channel micromirrors 103 are arranged in a one-dimensional array along the x-axis (i.e., the horizontal direction in the figure), so as to receive the focused spots of the spatially separated spectral channels in a one-to-one correspondence. (As in the case of FIG. 1A, only three spectral channels are illustrated, each represented by a converging beam.) Let the reflective surface of each channel micromirror lie in the x-y plane as defined in the figure and be movable, e.g., pivotable (or deflectable) about the x-axis in an analog (or continuous) manner. Each spectral channel, upon reflection, is deflected in the y-direction (e.g., downward) relative to its incident direction, so to be directed into one of the output ports 110-2 through 110-N shown in FIG. 1A.

As described above, a unique feature of the present invention is that the motion of each channel micromirror is individually and continuously controllable, such that its position, e.g., pivoting angle, can be continuously adjusted. This enables each channel micromirror to scan its corresponding spectral channel across all possible output ports and thereby direct the spectral channel to any desired output port. To illustrate this capability, FIG. 1C shows a plot of coupling efficiency as a function of a channel micromirror's pivoting angle θ, provided by a ray-tracing model of a WSR apparatus in the embodiment of FIG. 1A. As used herein, the coupling efficiency for a spectral channel is defined as the ratio of the amount of optical power coupled into the fiber core in an output port to the total amount of optical power incident upon the entrance surface of the fiber (associated with the fiber collimator grating serving as the output port). In the ray-tracing model, the input optical signal is incident upon a diffraction grating with 700 lines per millimeter at a grazing angle of 85 degrees, where the grating is blazed to optimize the diffraction efficiency for the "−1" order. The focusing lens has a focal length of 100 mm. Each output port is provided by a quarter-pitch GRIN lens (2 mm in diameter) coupled to an optical fiber (see FIG. 1D). As displayed in FIG. 1C, the coupling efficiency varies with the pivoting angle θ, and it requires about a 0.2-degree change in θ for the coupling efficiency to become practically negligible in this exemplary case. As such, each spectral channel may practically acquire any coupling efficiency value by way of controlling the pivoting angle of its corresponding channel micromirror. This is also to say that variable optical attenuation at the granularity of a single wavelength can be obtained in a WSR apparatus of the present invention. FIG. 1D provides ray-tracing illustrations of two extreme points on the coupling efficiency vs. θ curve of FIG. 1C; on-axis coupling corresponding to $\theta=0$, where the coupling efficiency is maximum; and off-axis coupling corresponding to $\theta=0.2$ degrees, where the representative collimated beam (representing an exemplary spectral channel) undergoes a significant translational walk-off and renders the coupling efficiency practically negligible. All in all, the exemplary modeling results thus described demonstrate the unique capabilities of the WSR apparatus of the present invention.

FIG. 1A provides one of many embodiments of a WSR apparatus according to the present invention. In general, the wavelength-separator is a wavelength-separating means that may be a ruled diffraction grating, a holographic diffraction grating, an echelle grating, a dispersing prism, or other types of spectral-separating means known in the art. The beam-focuser may be a focusing lens, an assembly of lenses, or other beam-focusing means known in the art. The focusing function may also be accomplished by using a curved diffraction grating as the wavelength-separator. The channel micromirrors may be provided by silicon micromachined mirrors, reflective ribbons (or membranes), or other types of beam-deflecting elements known in the art. And each micromirror may be pivoted about one or two axes. What is important is that the pivoting (or rotational) motion of each channel micromirror be individually controllable in an analog manner, whereby the pivoting angle can be continuously adjusted so as to enable the channel micromirror to scan a spectral channel across all possible output ports. The underlying fabrication techniques for micromachined mirrors and associated actuation mechanism are well documented in the art, see U.S. Pat. No. 5,629,790 for example. Moreover, a fiber collimator is typically in the form of a collimating lens (such as a GRIN lens) and a ferrule-mounted fiber packaged together in a mechanically rigid stainless steel (or glass) tube. The fiber collimators serving as the input and output ports may be arranged in a one-dimensional array, a two-dimensional array, or other desired spatial pattern. For instance, they may be conveniently mounted in a linear array along a V-groove fabricated on a substrate made of silicon, plastic, or ceramic, as commonly practiced in the art. It should be noted, however, that the input port and the output ports need not necessarily be in close spatial proximity with each other, such as in an array configuration (although a close packing would reduce the rotational range required for each channel micromirror). Those skilled in the art will know how to design a WSR apparatus according to the present invention, to best suit a given application.

A WSR apparatus of the present invention may further comprise an array of collimator-alignment mirrors, for adjusting the alignment of the input multi-wavelength optical signal and facilitating the coupling of the spectral channels into the respective output ports, as shown in FIGS. 2A-2B and 3.

Depicted in FIG. 2A is a second embodiment of a WSR apparatus according to the present invention. By way of example, WSR apparatus 200 is built upon and hence shares a number of the elements used in the embodiment of FIG. 1A, as identified by those labeled with identical numerals. Moreover, a one-dimensional array 220 of collimator-alignment mirrors 220-1 through 220-N is optically interposed between the diffraction grating 101 and the fiber collimator array 110. The collimator-alignment mirror 220-1 is designated to correspond with the input port 110-1, for adjusting the alignment of the input multi-wavelength optical signal and therefore ensuring that the spectral channels impinge onto the corresponding channel micromirrors. The collimator-alignment mirrors 220-2 through 220-N are designated to the output ports 110-2 through 110-N in a one-to-one correspondence, serving to provide angular control of the collimator beams of the reflected spectral channels and thereby facilitating the coupling of the spectral channels into the respective output ports according to desired coupling efficiencies. Each collimator-alignment mirror may be rotatable about one axis, or two axes.

The embodiment of FIG. 2A is attractive in applications where the fiber collimators (serving as the input and output ports) are desired to be placed in close proximity to the collimator-alignment mirror array 220. To best facilitate the coupling of the spectral channels into the output ports, arrays of imaging lenses may be implemented between the collimator-alignment mirror array 220 and the fiber collimator array

110, as depicted in FIG. 2B. By way of example, WSR apparatus 250 of FIG. 2B is built upon and hence shares many of the elements used in the embodiment of FIG. 2A, as identified by those labeled with identical numerals. Additionally, first and second arrays 260, 270 of imaging lenses are placed in a 4-f telecentric arrangement with respect to the collimator-alignment mirror array 220 and the fiber collimator array 110. The dashed box 280 shown in FIG. 2C provides a top view of such a telecentric arrangement. In this case, the imaging lenses in the first and second arrays 260, 270 all have the same focal length f. The collimator-alignment mirrors 220-1 through 220-N are placed at the respective first (or front) focal points of the imaging lenses in the first array 260. Likewise, the fiber collimators 110-1 through 110-N are placed at the respective second (or back) focal points of the imaging lenses in the second array 270. And the separation between the first and second arrays 260, 270 of imaging lenses is 2f. In this way, the collimator-alignment mirrors 220-1 through 220-N are effectively imaged onto the respective entrance surfaces (i.e., the front focal planes) of the GRIN lenses in the corresponding fiber collimators 110-1 through 110-N. Such a telecentric imaging system substantially eliminates translational walk-off of the collimated beams at the output ports that may otherwise occur as the mirror angles change.

FIG. 3 shows a fourth embodiment of a WSR apparatus according to the present invention. By way of example, WSR apparatus 300 is built upon and hence shares a number of the elements used in the embodiment of FIG. 2B, as identified by those labeled with identical numerals. In this case, the one-dimensional fiber collimator array 110 of FIG. 2B is replaced by a two-dimensional array 350 of fiber collimators, providing for an input-port and a plurality of output ports. Accordingly, the one-dimensional collimator-alignment mirror array 220 of FIG. 2B is replaced by a two-dimensional array 320 of collimator-alignment mirrors, and first and second one-dimensional arrays 260, 270 of imaging lenses of FIG. 2B are likewise replaced by first and second two-dimensional arrays 360, 370 of imaging lenses respectively. As in the case of the embodiment of FIG. 2B, the first and second two-dimensional arrays 360, 370 of imaging lenses are placed in a 4-f telecentric arrangement with respect to the two-dimensional collimator-alignment mirror array 320 and the two-dimensional fiber collimator array 350. The channel micromirror 103 must be pivotable biaxially in this case (in order to direct its corresponding spectral channel to any one of the output ports). As such, the WSR apparatus 300 is equipped to a support a greater number of the output ports.

In addition to facilitating the coupling of the spectral channels into the respective output ports as described above, the collimator-alignment mirrors in the above embodiments also serve to compensate for misalignment (e.g., due to fabricated and assembly errors) in the fiber collimators that provide for the input and output ports. For instance, relative misalignment between the fiber cores and their respective collimating lenses in the fiber collimators can lead to pointing errors in the collimated beams, which may be corrected for by the collimator-alignment mirrors. For these reasons, the collimator-alignment mirrors are preferably rotatable about two axes. They may be silicon micromachined mirrors, for fast rotational speeds. They may also be other types of mirrors or beam-deflecting elements known in the art.

To optimize the coupling of the spectral channels into the output ports and further maintain the optimal optical alignment against environment effects such as temperature variations and mechanical instabilities over the course of operation, a WSR apparatus of the present invention may incorporate a servo-control assembly, for providing dynamic control of the coupling of the spectral channels into the respective output ports on a channel-by-channel basis. A WSR apparatus incorporating a servo-control assembly is termed a WSR-S apparatus, thereinafter in this specification.

FIG. 4A depicts a schematic illustration of a first embodiment of a WSR-S apparatus according to the present invention. The WSR-S apparatus 400 comprises a WSR apparatus 410 and a servo-control assembly 440. The WSR 410 may be in the embodiment of FIG. 1A, or any other embodiment in accordance with the present invention. The servo-control assembly 440 includes a spectral monitor 460, for monitoring the power levels of the spectral channels coupled into the output ports 420-1 through 420-N of the WSR apparatus 410. By way of example, the spectral monitor 460 is coupled to the output ports 420-1 through 420-N by way of fiber-optic couplers 420-1 through 420-N-C, wherein each fiber-optic coupler serves to tap off a predetermined fraction of the optical signal in the corresponding output port. The servo-control assembly 440 further includes a processing unit 470, in communication with the spectral monitor 460 and the channel micromirrors 430 of the WSR apparatus 410. The processing unit 470 uses the power measurements from the spectral monitor 460 to provide feedback control of the channel micromirrors 430 on an individual basis, so as to maintain a desired coupling efficiency for each spectral channel into a selected output port. As such, the servo-control assembly 440 provides dynamic control of the coupling of the spectral channels into the respective output ports on a channel-by-channel basis and thereby manages the power levels of the spectral channels coupled into the output ports. The power levels of the spectral channels in the output ports may be dynamically managed according to demand, or maintained at desired values (e.g., equalized at a predetermined value) in the present invention. Such a spectral power-management capability is essential in WDM optical networking applications, as discussed above.

FIG. 4B depicts a schematic illustration of a second embodiment of a WSR-S apparatus according to the present invention. The WSR-S apparatus 450 comprises a WSR apparatus 480 and a servo-control assembly 490. In addition to the channel micromirrors 430 (and other elements identified by the same numerals as those used in FIG. 4A), the WSR apparatus 480 further includes a plurality of collimator-alignment mirrors 485, and may be configured according to the embodiments of FIGS. 2A, 2B, 3, or any other embodiment in accordance with the present invention. By way of example, the servo-control assembly 490 includes the spectral monitor 460 as described in the embodiment of FIG. 4A, and a processing unit 495. In this case, the processing unit 495 is in communication with the channel micromirrors 430 and the collimator-alignment mirrors 485 of the WSR apparatus 480, as well as the spectral monitor 460. The processing unit 495 uses the power measurements from the spectral monitor 460 to provide dynamic control of the channel micromirrors 430 along with the collimator-alignment mirrors 485, so to maintain the coupling efficiencies of the spectral channels into the output ports at desired values.

In the embodiment of FIG. 4A or 4B, the spectral monitor 460 may be one of spectral power monitoring devices known in the art that is capable of detecting the power levels of spectral components in a multi-wavelength optical signal. Such devices are typically in the form of a wavelength-separating means (e.g., a diffraction grating) that spatially separates a multi-wavelength optical signal by wavelength into constituent spectral components, and one or more optical sensors (e.g., an array of photodiodes) that are configured such to detect the power levels of these spectral components. The processing unit 470 in FIG. 4A (or the processing unit 495 in FIG. 4B) typically includes electrical circuits and signal processing programs for processing the power measurements received from the spectral monitor 460 and generating appropriate control signals to be applied to the channel micromirrors 430 (and the collimator-alignment mirrors 485 in the case of FIG. 4B), so to maintain the coupling efficiencies of the spectral channels into the output ports at desired values. The electronic circuitry and the associated signal processing algorithm/software for such processing unit in a servo-control system are known in the art. A skilled artisan will know how to implement a suitable spectral monitor along with an appropriate processing unit to provide a servo-control assembly in a WSP-S apparatus according to the present invention, for a given application.

The incorporation of a servo-control assembly provides additional advantages of effectively relaxing the requisite fabrication tolerances and the precision of optical alignment during initial assembly of a WSR apparatus of the present invention, and further enabling the system to correct for shift in the alignment over the course of operation. By maintaining an optimal optical alignment, the optical losses incurred by the spectral channels are also significantly reduced. As such, the WSR-S apparatus thus constructed in simpler and more adaptable in structure, more robust in performance, and lower in cost and optical loss. Accordingly, the WSR-S (or WSR) apparatus of the present invention may be used to construct a variety of operable devices and utilized in many applications.

For instance, by directing the spectral channels into the output ports in a one-channel-per-port fashion and coupling the output ports of a WSR-S (or WSR) apparatus to an array of optical sensors (e.g., photodiodes), or a single optical sensor that is capable of scanning across the output ports, a dynamic and versatile spectral power monitor (or channel analyzer) is provided, which would be highly desired in WDM optical networking applications. Moreover, a novel class of optical add-drop multiplexers (OADMs) may be built upon the WSR-S (or WSR) apparatus of the present invention, as exemplified in the following embodiments.

FIG. 5 depicts an exemplary embodiment of an optical add-drop multiplexer (OADM) according to the present invention. By way of example, OADM 500 comprises a WSR-S (or WSR) apparatus 510 and an optical combiner 550. An input port 520 of the WSR-S apparatus 510 transmits a multi-wavelength optical signal. The constituent spectral channels are subsequently separated and routed into a plurality of output ports, including a pass-through port 530 and one or more drop ports 540-1 through 540-N ($N \geqq 1$). The pass-through port 530 may receive any number of the spectral channels (i.e., the pass-through spectral channels). Each drop port may also receive any number of the spectral channels (i.e., the drop spectral channels). The pass-through port 530 is optically coupled to the optical combiner 550, which serves to combine the pass-through spectral channels with one or more add spectral channels provided by one or more add ports 560-1 through 560-M ($M \geqq 1$). The combined optical signal is then routed into an existing port 570, providing an output multi-wavelength optical signal.

In the above embodiment, the optical combiner 550 may be a $K \times 1$ ($K \geqq 2$) broadband fiber-optic coupler, wherein there are K input-ends and one output-end. The pass-through spectral channels and the add spectral channels are fed into the K input-ends (e.g., in a one-to-one correspondence) and the combined optical signal exits from the output-end of the $K \times 1$ fiber-optic coupler as the output multi-wavelength optical signal of the system. Such a multiple-input coupler also serves the purpose of multiplexing a multiplicity of add spectral channels to be coupled into the OADM 500. If the power levels of the spectral channels in the output multi-wavelength optical signal are desired to be actively managed, such as being equalized at a predetermined value, two spectral monitors may be utilized. As a way of example, the first spectral monitor may receive optical signals tapped off from the pass-through port 530 and the drop ports 540-1 through 540-N (e.g., by way of fiber-optic couplers as depicted in FIG. 4A or 4B). The second spectral monitor receives optical signals tapped off from the exiting port 570. A servo-control system may be constructed accordingly for monitoring and controlling the pass-through, drop and add spectral channels. As such, the embodiment of FIG. 5 provides a versatile optical add-drop multiplexer in a simple and low-cost assembly, while providing multiple physically separate drop/add ports in a dynamically reconfigurable fashion.

FIG. 6 depicts an alternative embodiment of an optical add-drop multiplexer (OADM) according to the present invention. By way of example, OADM 600 comprises a first WSR-S apparatus 610 optically coupled to a second WSR-S apparatus 650. Each WSR-S apparatus may be in the embodiment of FIG. 4A or 4B. (A WSR apparats of the embodiment of FIG. 1A, 2A, 2B, or 3 may be alternatively implemented.) The first WSR-S apparatus 610 includes an input port 620, a pass-through port 630, and one or more drop ports 640-1 through 640-N (N≧1). The pass-through spectral channels from the pass-through port 630 are further coupled to the second WSR-S apparatus 650, along with one or more add spectral channels emerging from add ports 660-1 through 660-M (M≧1). In this exemplary case, the pass-through port 630 and the add ports 660-1 through 660-M constitute the input ports for the second WSR-S apparatus 650. By way of its constituent wavelength-separator (e.g., a diffraction grinding) and channel micromirrors (not shown in FIG. 6), the second WSR-R apparatus 650 serves to multiplex the pass-through spectral channels and the add spectral channels, and route the multiplexed optical signal into an exiting port 770 to provide an output signal of the system.

In the embodiment of FIG. 6, one WSR-S apparatus (e.g., the first WSR-S apparatus 610) effectively performs dynamic drop function, whereas the other WSR-S apparatus (e.g., the second WSR-S apparatus 650) carries out dynamic add function. And there are essentially no fundamental restrictions on the wavelengths that can be added or dropped (other than those imposed by the overall communication system). Moreover, the underlying OADM architecture thus presented is intrinsically scalable and can be readily extended to any number of cascaded WSR-S (or WSR) systems, if so desired for performing intricate add and drop functions. Additionally, the OADM of FIG. 6 may be operated in reverse direction, by using the input ports as the output ports, the drop ports as the add ports, and vice versa.

Those skilled in the art will recognize that the aforementioned embodiments provide only two of many embodiments of a dynamically reconfigurable OADM according to the present invention. Those skilled in the art will also appreciate that various changes, substitutions, and alternations can be made herein without departing from the principles and the scope of the invention as defined in the appended claims. Accordingly, a skilled artisan can design an OADM in accordance with the principles of the present invention, to best suit a given application.

Although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions, and alternations can be made herein without departing from the principles and the scope of the invention. Accordingly, the scope of the present invention should be determined by the following claims and their legal equivalents.

What is claimed is:

1. A wavelength-separating-routing apparatus, comprising:

a) multiple fiber collimators, providing an input port for a multi-wavelength optical signal and a plurality of output ports;

b) a wavelength-separator, for separating said multi-wavelength optical signal from said input port into multiple spectral channels;

c) a beam-focuser, for focusing said spectral channels into corresponding spectral spots; and

d) a spatial array of channel micromirrors positioned such that each channel micromirror receives one of said spectral channels, said channel micromirrors being **pivotal about two axes and being** individually and continuously controllable to reflect **[[**said**]] corresponding received** spectral channels into **any** selected ones of said output ports **and to control the power of said received spectral channels coupled into said output ports.**

2. The wavelength-separating-routing apparatus of claim 1 further comprising a servo-control assembly, in communication with said channel micromirrors and said output ports, for providing control of said channel micromirrors and thereby maintaining a predetermined coupling of each reflected spectral channel into one of said output ports.

3. The wavelength-separating-routing apparatus of claim 2 wherein said servo-control assembly comprises a spectral monitor for monitoring power levels of said spectral channels coupled into said output ports, and a processing unit responsive to said power levels for providing control of said channel micromirrors.

4. The wavelength-separating-routing apparatus of claim 3 wherein said servo-control assembly maintains said power levels at a predetermined value.

5. The wavelength-separating-routing apparatus of claim 1 further comprising an array of collimator-alignment mirrors, in optical communication with said wavelength-separator and said fiber collimators, for adjusting an alignment of said multi-wavelength optical signal from said input port and directing said reflected spectral channels into said output ports.

6. The wavelength-separating-routing apparatus of claim 5 wherein each collimator-alignment mirror is rotatable about one axis.

7. The wavelength-separating-routing apparatus of claim 5 wherein each collimator-alignment mirror is rotatable about two axes.

8. The wavelength-separating-routing apparatus of claim 5 further comprising first and second arrays of imaging lenses, in a telecentric arrangement with said collimator-alignment mirrors and said fiber collimators.

9. The wavelength-separating-routing apparatus of claim 1 wherein each channel micromirror is continuously pivotable about one axis.

10. The wavelength-separating-routing apparatus of claim 1 wherein each channel micromirror is pivotable about two axes.

11. The wavelength-separating-routing apparatus of claim 10 wherein said fiber collimators are arranged in a two-dimensional array.

12. The wavelength-separating-routing apparatus of claim 1 wherein each channel micromirror is a silicon micromachined mirror.

13. The wavelength-separating-routing apparatus of claim 1 wherein said fiber collimators are arranged in a one-dimensional array.

14. The wavelength-separating-routing apparatus of claim 1 wherein said beam-focuser comprises a focusing lens having first and second focal points.

15. The wavelength-separating-routing apparatus of claim 14 wherein said wavelength-separator and said channel micromirrors are placed respectively at said first and second focal points of said focusing lens.

16. The wavelength-separating-routing apparatus of claim 1 wherein said beam-focuser comprises an assembly of lenses.

17. The wavelength-separating-routing apparatus of claim 1 wherein said wavelength-separator comprises an element selected from the group consisting of ruled diffraction gratings, halographic diffraction gratings, echelle gratings, curved diffraction gratings, and dispersing gratings.

18. The wavelength-separating-routing apparatus of claim 1 further comprising a quarter-wave plate optically interposed between said wavelength-separator and said channel micromirrors.

19. The wavelength-separating-routing apparatus of claim 1 wherein each output port carries a single one of said spectral channels.

20. The wavelength-separating-routing apparatus of claim 19 further comprising one or more optical sensors, optically coupled to said output ports.

21. A servo-based optical apparatus comprising:

a) multiple fiber collimators, providing an input port for a multi-wavelength optical signal and a plurality of output ports;

b) a wavelength-separator, for separating said multi-wavelength optical signal from said input port into multiple spectral channels;

c) a beam-focuser, for focusing said spectral channels into corresponding spectral spots; and

d) a spatial array of channel micromirrors positioned such that each channel micromirror receives one of said spectral channels, said channel micromirrors being individually controllable to reflect said spectral channels into selected ones of said output ports; and

e) a servo-control assembly, in communication with said channel micromirrors and said output ports, for maintaining a predetermined coupling of each reflected spectral channel into one of said output ports.

22. The servo-based optical apparatus of claim 21 wherein said servo-control assembly comprises a spectral monitor for monitoring power levels of said spectral channels coupled into said output ports, and a processing unit responsive to said power levels for providing control of said channel micromirrors.

23. The servo-based optical apparatus of claim 22 wherein said servo-control assembly maintains said power levels at a predetermined value.

24. The servo-based optical apparatus of claim 21 further comprising an array of collimator-alignment mirrors, in optical communication with said wavelength-separator and said fiber collimators, for adjusting an alignment of said multi-wavelength optical signal from said input port and directing said reflected spectral channels into said output ports.

25. The servo-based optical apparatus of claim 24 further comprising first and second arrays of imaging lenses, in a telecentric arrangement with said collimator-alignment mirrors and said fiber collimators.

26. The servo-based optical apparatus of claim 24 wherein each collimator-alignment mirror is rotatable about at least one axis.

27. The servo-based optical apparatus of claim 21 wherein each channel micromirror is continuously pivotable about at least one axis.

28. The servo-based optical apparatus of claim 21 wherein each channel micromirror is a silicon micromachined mirror.

29. The servo-based optical apparatus of claim 21 wherein said wavelength-separator comprises an element selected from the group consisting of ruled diffraction gratings, holographic diffraction gratings, echelle gratings, curved diffraction gratings, and dispersing prisms.

30. The servo-based optical apparatus of claim 21 wherein said beam-focuser comprises one or more lenses.

31. An optical apparatus comprising:

a) an array of fiber collimators, providing an input port for a multi-wavelength optical signal and a plurality of output ports;

b) a wavelength-separator, for separating said multi-wavelength optical signal from said input port into multiple spectral channels;

c) a beam-focuser, for focusing said spectral channels into corresponding spectral spots;

d) a spatial array of channel micromirrors positioned such that each channel micromirror receives one of said spectral channels, said channel micromirrors being individually and continuously controllable to reflect said spectral channels into selected ones of said output ports; and

e) a one-dimensional array of collimator-alignment mirrors, for adjusting an alignment of said multi-wavelength optical signal from said input port and directing said reflected spectral channels into said output ports.

32. The optical apparatus of claim 31 further comprising a servo-control assembly, in communication with said channel micromirrors, said collimator-alignment mirrors, and said output ports, for providing control of said channel micromirrors along with said collimator-alignment mirrors and thereby maintaining a predetermined coupling of each reflected spectral channel into one of said output ports.

33. The optical apparatus of claim 32 wherein said servo-control assembly comprises a spectral monitor for monitoring power levels of said spectral channels coupled into said output ports, and a processing unit responsive to said power levels for providing control of said channel micromirrors and said collimator-alignment mirrors.

34. The optical apparatus of claim 31 wherein each channel micromirror is continuously pivotable about at least one axis.

35. The optical apparatus of claim 31 wherein each collimator-alignment mirror is rotatable about at least one axis.

36. The optical apparatus of claim 31 further comprising first and second arrays of imaging lenses, in a telecentric arrangement with said collimator-alignment mirrors and said fiber collimators.

37. An optical apparatus comprising:

a) an array of fiber collimators, providing an input port for a multi-wavelength optical signal and a plurality of output ports;

b) a wavelength-separator, for separating said multi-wavelength optical signal from said input port into multiple spectral channels;

c) a beam-focuser, for focusing said spectral channels into corresponding spectral spots;

d) a spatial array of channel micromirrors positioned such that each channel micromirror receives one of said spectral channels, said channel micromirrors being individually and continuously controllable to reflect said spectral channels into selected ones of said output ports; and

e) a two-dimensional array of collimator-alignment mirrors, for adjusting an alignment of said multi-wavelength optical signal from said input port and directing said reflected spectral channels into said output ports.

38. The optical apparatus of claim 37 further comprising a servo-control assembly, in communication with said channel micromirrors, and collimator-alignment mirrors, and said output ports, for providing control of said channel micromirrors along with said collimator-alignment mirrors and thereby maintaining a predetermined coupling of each reflected spectral channel into one of said output ports.

39. The optical apparatus of claim 38 wherein said servo-control assembly comprises a spectral monitor for monitoring power levels of said spectral channels coupled into said output ports, and a processing unit responsive to said power levels for providing control of said channel micromirrors and said collimator-alignment mirrors.

40. The optical apparatus of claim 37 wherein each collimator-alignment mirror is rotatable about at least one axis.

41. The optical apparatus of claim 37 wherein each channel micromirror is continuously pivotable about at least one axis.

42. The optical apparatus of claim 41 wherein each channel micromirrors is pivotable about two axes, and wherein said fiber collimators are arranged in a two-dimensional array.

43. The optical apparatus of claim 37 further comprising first and second arrays of imaging lenses, in a telecentric arrangement with said collimator-alignment mirrors and said fiber collimators.

44. An optical system comprising a wavelength-separating-routing apparatus, wherein said wavelength-separating-routing apparatus includes:

a) an array of fiber collimators, providing an input port for a multi-wavelength optical signal and a plurality of output ports including a pass-through port and one or more drop ports;

b) a wavelength-separator, for separating said multi-wavelength optical signal from said input port into multiple spectral channels;

c) a beam-focuser, for focusing said spectral channels into corresponding spectral spots; and

d) a spatial array of channel micromirrors positioned such that each channel micromirror receives one of said spectral channels, said channel micromirrors being **pivotal about two axes and being** individually and continuously [[pivotable]] **controllable** to reflect [[said]] **corresponding received** spectral channels into **any** selected ones of said output ports **and to control the power of said received spectral channels coupled into said output ports**, whereby said pass-through port receives a subset of said spectral channels.

45. The optical system of claim 44 further comprising a servo-control assembly, in communication with said channel micromirrors and said output ports, for providing control of said channel micromirrors and thereby maintaining a predetermined coupling of each reflected spectral channel into one of said output ports.

46. The optical system of claim 45 wherein said servo-control assembly comprises a spectral monitor for monitoring power levels of said spectral channels coupled into said output ports, and a processing unit responsive to said power levels for providing control of said channel micromirrors.

47. The optical system of claim 44 further comprising an array of collimator-alignment mirrors, in optical communication with said wavelength-separator and said fiber collimators, for adjusting an alignment of said multi-wavelength optical signal from said input port and directing said reflected spectral channels into said output ports.

48. The optical system of claim 47 further comprising first and second arrays of imaging lenses, in a telecentric arrangement with said collimator-alignment mirrors and said fiber collimators.

49. The optical system of claim 47 wherein each collimator-alignment mirror is rotatable about at least one axis.

50. The optical system of claim 44 wherein each channel micromirror is pivotable about at least one axis.

51. The optical system of claim 44 wherein each channel micromirror is a silicon micromachined mirror.

52. The optical system of claim 44 wherein said beam-focuser comprises a focusing lens having first and second focal points, and wherein said wavelength-separator and said channel micromirrors are placed respectively at said first and second focal points.

53. The optical system of claim 44 wherein said wavelength-separator comprises an element selected from the group consisting of ruled diffraction gratings, holographic diffraction gratings, echelle gratings, curved diffraction gratings, and dispersing prisms.

54. The optical system of claim 44 further comprising a quarter-wave plate optically interposed between said wavelength-separator and said channel micromirrors.

55. The optical system of claim 44 further comprising an auxiliary wavelength-separating-routing apparatus, including:

a) multiple auxiliary fiber collimators, providing a plurality of auxiliary input ports and an exiting port;

b) an auxiliary wavelength-separator;

c) an auxiliary beam-focuser; and

d) a spatial array of auxiliary channel micromirrors;

wherein said subset of said spectral channels in said pass-through port and one or more add spectral channels are directed into said auxiliary input ports, and multiplexed into an output optical signal directed into said exiting port by way of said auxiliary wavelength-separator, said auxiliary beam-focuser and said auxiliary channel micromirrors.

56. The optical system of claim 55 wherein said auxiliary channel micromirrors are individually pivotable.

57. The optical system of claim 55 wherein each auxiliary channel micromirror is pivotable continuously about at least one axis.

58. The optical system of claim 55 wherein each auxiliary channel micromirror is a silicon micromachined mirror.

59. The optical system of claim 55 wherein said auxiliary wavelength-separator comprises an element selected from the group consisting of ruled diffraction gratings, holographic diffraction gratings, echelle gratings, curved diffraction gratings, and dispersing prisms.

60. The optical system of claim 55 wherein said pass-through port constitutes one of said auxiliary input ports.

61. A method of performing dynamic wavelength separating and routing, comprising:

a) receiving a multi-wavelength optical signal from an input port;

b) separating said multi-wavelength optical signal into multiple spectral channels;

c) focusing said spectral channels onto a spatial array of corresponding beam-deflecting elements, whereby each beam-deflecting element receives one of said spectral channels; and

d) dynamically and continuously controlling said beam-deflecting elements[[, thereby directing]] **in two dimensions to direct** said spectral channels into [[a plurality]] **any selected ones** of **said** output ports **and to control the power of the spectral channels coupled into said selected output ports**.

62. The method of claim 61 further comprising the step of providing feedback control of said beam-deflecting elements[[, thereby maintaining]] **to maintain** a predetermining coupling of each spectral channel directed into one of said output ports.

63. The method of claim 62 further comprising the step of maintaining power levels of said spectral channels directed into said output ports at a predetermining value.

64. The method of claim 61 wherein each spectral channel is directed into a separate output port.

65. The method of claim 61 wherein a subset of said spectral channels is directed into one of said output ports, thereby providing one or more pass-through spectral channels.

66. The method of claim 65 further comprising the step of multiplexing said pass-through spectral channels with one or more add spectral channels, so as to provide an output optical signal.

67. The method of claim 61 wherein said beam-deflecting elements comprise an array of silicon micromachined mirrors.

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