

RECONFIGURABLE OPTICAL ADD-DROP MULTIPLEXERS

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CROSS-REFERENCE TO RELATED APPLICATIONS

10 This application claims priority to U.S. Provisional Patent Application No. 60/277,217, filed on March 19, 2001; U.S. Patent Application No. 09/938,426, filed on August 23, 2001; U.S. Patent Application No. 10/005,714, filed on November 7, 2001; U.S. Patent Application No. 10/060,493, filed on January 29, 2002; and U.S. Patent Application No. 10/076,145, filed on February 14, 2002, all of which are incorporated herein by reference.

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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.

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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

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traffic. As such, an OADM makes it possible to launch and retrieve multiple data channels 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. Patent Number 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. Patent Number 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. 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. Patent Number 6,204,946 of Askyyuk 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 coupled to the output port. The drop channels exit from the output port and the add channels are introduced into the output port by way of the additional optical circulator. 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 of the add and drop channels enter and leave the OADM through the same output port, hence the need for the additional 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. 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. Patent Number 5,960,133 of Tomlinson discloses an OADM that makes use of a design similar to that of Aksyuk et al. In one embodiment, there are input, output, drop and add beams arranged in a rectangular array. Each micromirror, being switchable between two discrete positions, either reflects its corresponding wavelength component from the input beam back to the output beam, or concomitantly reflects the wavelength component from the input beam back to the drop beam and the same wavelength component from the add beam back to the output beam. Alternative embodiments are also shown, where multiple add and drop beams, along with input and output beams, are arranged in a two-dimensional array. However, 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 mitigating degradation in the alignment due to environmental effects over the course of operation. Moreover, it may be difficult in some applications to align multiple optical beams in a two-dimensional configuration and further maintain the requisite alignment.

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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.
- 10 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
- 15 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 optical power levels of spectral channels entering and exiting each OADM be
- 20 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 optical power levels of various spectral channels in
- 25 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

30 multiplexers that overcome the aforementioned shortcomings in a simple, effective, and economical construction.

SUMMARY OF THE INVENTION

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
5 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.
10 The beam-focuser focuses the spectral channels into corresponding focused spots. The channel micromirrors are positioned such that each channel micromirror receives a unique one of the spectral channels. The channel micromirrors are individually controllable and movable (e.g., pivotable or rotatable), so as to reflect the spectral channels into selected output ports. As such, each channel micromirror is assigned to a specific spectral channel,
15 hence the name "channel micromirror". 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 pivoting (or rotational) motion of each channel micromirror
20 may be 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
25 by a ruled diffraction grating, a holographic diffraction grating, an echelle grating, a curved diffraction grating, a transmission grating, a dispersing prism, or other types of wavelength-separating means known in the art. The beam-focuser may be a single lens, an assembly of lenses, or other types of beam-focusing means known in the art. The channel micromirrors may be provided by silicon micromachined mirrors, reflective
30 ribbons (or membranes), or other types of beam-deflecting means known in the art. 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 are 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 multi-wavelength input signal and directing the reflected 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 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 optical 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 for each spectral channel into an output port. (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.) As such, the servo-control assembly provides dynamic control of the coupling of the spectral channels into the respective output ports and thereby actively manages the optical power levels of the spectral channels coupled into the output ports. For example, the optical power levels of the spectral channels coupled into the output ports can be equalized at a predetermined value. Moreover, the utilization of such a servo-control assembly effectively relaxes the fabrication tolerances and precision during assembly of a WSR apparatus of the present invention, and further enables the system to correct for shift in optical alignment that may arise over the course of operation. A WSR apparatus incorporating a servo-control assembly thus described is termed a WSR-S apparatus, in the following discussion.

The WSR apparatus of the invention may further employ a polarization diversity arrangement to overcome polarization-sensitive effects the constituent optical elements may possess. A polarization-displacing unit (e.g., one or more birefringent beam displacers) and a polarization-rotating unit (e.g., one or more half-wave plates) may be disposed along the optical path between the fiber collimators providing the input and

output ports and the wavelength-separator. The polarization-displacing unit serves to decompose the multi-wavelength input optical signal into first and second polarization components. The polarization-rotating unit may subsequently rotate the polarization of the second polarization component (e.g., by 90-degrees), so that its polarization is

5 substantially parallel to the first polarization component. The wavelength-separator separates the incident optical signals by wavelength into first and second sets of optical beams, respectively. The beam-focuser may focus the first and second sets of optical beams into corresponding focused spots, impinging onto the channel micromirrors. The first and second optical beams associated with the same wavelength may impinge onto

10 (and be manipulated by) the same channel micromirror. The channel micromirrors may be individually controlled such that the first and second sets of optical beams are deflected upon reflection. The reflected first set of optical beams may subsequently undergo a 90-degree rotation in polarization by the polarization-rotating unit. This enables the polarization-displacing unit to recombine the reflected first and second sets of optical

15 beams by wavelength respectively into reflected spectral channels, prior to being coupled into the output ports.

As such, the aforementioned polarization diversity arrangement effectively renders the polarization-sensitive effects inconsequential and thereby lowers the insertion loss and

20 polarization-dependent loss of the system.

Accordingly, the WSR (or WSR-S) 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).

25 In one embodiment of an OADM according to the present invention, a one-dimensional input-output-port array, including an input port, a pass-through port, a plurality of drop ports, and a plurality of add ports, may be implemented in a WSR of the present invention. The arrangement of the input-output-port array may be such that the input ports (i.e., the

30 input port and the add ports) transmitting the incoming optical signals and the output ports (i.e., the pass-through and the drop ports) carrying the outgoing optical signal are positioned in an alternating (or interleaved) fashion, whereby interposed between every two input ports is an output port, and vice versa. Such an arrangement warrants that if a spectral channel originating from the input port is to be routed to a drop port, an add

spectral channel with the same wavelength from an adjacent (or pairing) add port can be simultaneously directed into the pass-through port. This is due to the fact that the drop spectral channel and the corresponding add spectral channel are routed to their respective destinations by the same channel micromirror in the WSR apparatus.

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A notable advantage of the aforementioned OADM is the ability to add and drop multiple spectral channels in a dynamically reconfigurable fashion, without involving additional means. A servo-control assembly may be further incorporated in an OADM of the present invention, for monitoring and controlling the optical power levels of the spectral channels coupled into the output ports.

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An alternative embodiment of an OADM of the present invention comprises a WSR (or WSR-S) apparatus and an optical combiner. The output ports of the WSR 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 $N \times 1$ ($N \geq 2$) broadband fiber-optic coupler, for instance, which may also serve the purpose of multiplexing a multiplicity of add spectral channels to be coupled into the system.

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In yet another embodiment of an OADM of the present invention, a first WSR (or WSR-S) apparatus is cascaded with a second WSR (or WSR-S) apparatus. The output ports of the first WSR apparatus include a pass-through port and one or more drop ports. The second 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 apparatus and one or more add channels are directed into the input ports of the second WSR apparatus, and consequently multiplexed into an output multi-wavelength optical signal directed into the exiting port of the second WSR apparatus. That is to say that in this embodiment, one WSR apparatus (e.g., the first one) effectively performs a dynamic drop function, whereas the other WSR 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

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OADM architecture thus presented is intrinsically scalable and can be readily extended to any number of the WSR (or WSR-S) systems, if so desired for performing intricate add and drop functions in a network environment.

5 The OADM's of the present invention provide many advantages over the prior 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
10 directing any spectral channel into any one of multiple output ports. As such, its underlying operation is dynamically reconfigurable, and its underlying architecture is intrinsically scalable to a large number of channel counts, as well as to multiple input and output ports.
- 2) The add and drop spectral channels need not be multiplexed and demultiplexed
15 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
20 more robust in performance. By maintaining an optimal optical alignment, the optical losses incurred by the spectral channels are also significantly reduced.
- 4) The optical power levels of the spectral channels coupled into the pass-through port may be dynamically managed according to demand, or maintained at desired values (e.g., equalized at a predetermined value) by way of the servo-control
25 assembly. The optical power levels of the spectral channels coupled into the drop ports may also be monitored by 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
30 construction. Moreover, the utilization of the servo-control assembly effectively relaxes the fabrication tolerances and precision during initial assembly, enabling the OADM to be simpler and more adaptable in structure, and 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.

5 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;

FIG. **2A** depicts a second embodiment of a WSR apparatus according to the present invention;

FIGS. **2B-2C** show a third embodiment of a WSR apparatus according to the present invention;

FIG. **3** depicts 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;

FIGS. **5A-5B** depict a first embodiment of an optical add-drop multiplexer (OADM) according to the present invention;

FIGS. **5C-5D** show a second embodiment of an OADM according to the present invention;

FIG. **5E** shows an exemplary embodiment of an OADM employing a servo-control assembly, according to the present invention;

FIG. **6A** depicts a third embodiment of an OADM according to the invention;

FIG. **6B** shows a fourth embodiment of an OADM according to the invention;

FIGS. **7A-7B** depict a fifth embodiment of a WSR apparatus according to the present invention, employing a polarization diversity arrangement;

FIGS. **7C-7D** depict two exemplary embodiments of a polarization-displacing unit that may be used in the WSR apparatus shown in FIGS. **7A-7B**;

FIG. **8A** shows a sixth embodiment of a WSR apparatus according to the present invention, employing a polarization diversity arrangement;

FIG. **8B** depicts a seventh embodiment of a WSR apparatus according to the present invention, employing a polarization diversity arrangement; and
FIG. **8C** shows an eighth embodiment of a WSR apparatus according to the present invention, employing a polarization diversity arrangement.

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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.

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FIG. **1A** depicts a perspective view of 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
15 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** ($N \geq 3$); 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**.

20 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 corresponding focused spots (not shown in FIG. **1A**). The channel micromirrors **103** are positioned in accordance with the spatial array formed by the
25 spectral channels, such that each channel micromirror receives a unique 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
30 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 select 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
5 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 may have different
10 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 in the first and second (i.e., the front and
15 back) focal planes (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
20 otherwise arise. Moreover, the multi-wavelength input 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, e.g., 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. For instance, the diffraction efficiency of a grating in a standard mounting configuration may be considerably higher for p (or TM) polarization (perpendicular to the groove lines on the grating) than for s (or TE) polarization (orthogonal to p-polarization), or vice versa. To mitigate such polarization-sensitive effects, a quarter-wave plate **104**
25 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 rotation in polarization of approximately 90-degrees upon traversing the quarter-wave plate **104** twice. (That is, if an optical beam has p-polarization when first
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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.

- 5 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
10 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.) The reflective surface of each channel
15 micromirror lies in the x-y plane as defined in the figure and may be movable, e.g., pivotable (or deflectable) about an axis along the x-direction 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 as to be directed into one of the output ports 110-2 through 110-N shown in FIG. 1A.

20 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
25 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
30 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
5 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
10 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. The exemplary modeling results thus described demonstrate the
15 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
20 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
25 types of beam-deflecting elements known in the art. Each micromirror may be pivoted about one or two axes. It is important 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
30 techniques for micromachined mirrors and associated actuation mechanisms are well documented in the art, see U.S. Patent Number 5,629,790 for example, which is fully and completely incorporated herein by reference. 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,
5 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
10 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
15 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
20 elements 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 multi-wavelength input optical signal and therefore ensuring that the
25 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
30 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, 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
5 shares many of the elements used in the embodiment of FIG. **2A**, as identified by those elements 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 the “4- f ” telecentric arrangement. In this
10 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**. The separation
15 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 “4- f ” imaging system substantially eliminates translational walk-off of the collimated beams at the output ports
20 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 elements labeled with
25 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
30 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 substantially identical “4- f ” telecentric arrangement with respect to the two-dimensional collimator-alignment mirror array **320** and the two-dimensional fiber

collimator array **350**. Each of the channel micromirrors **103** may 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 output ports.

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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
10 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-
15 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
20 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 in this specification.

25 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 apparatus **410** may be substantially similar to the WSR apparatus **100** of FIG. 1A, or any other embodiment in accordance with the present invention. The servo-control assembly **440** includes a spectral
30 power monitor **460**, for monitoring the optical 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 power monitor **460** may be 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 power monitor **460** and the channel micromirrors **430** of the WSR apparatus **410**. The processing unit **470** uses the optical power measurements from the spectral power 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.

By way of example, the processing unit **470** may apply an appropriate alternating (or “dither”) control signal to a channel micromirror, in superposition with the dc control signal for maintaining the channel micromirror at a particular pivoting position. This enables both the optical power level of the corresponding spectral channel and the rate of change in the optical power level (or the time derivative of the optical power level) at the instant micromirror’s pivoting angle to be obtained. In view of the exemplary coupling efficiency curve depicted in FIG. **1C**, the rate of change in the optical power level is proportional to the slope of the coupling efficiency curve, and is therefore useful in locating the micromirror’s pivoting angle corresponding to the measured optical power level. It is also useful in determining the magnitude of the feedback control signal to be applied to the channel micromirror, so as to achieve the desired coupling efficiency in a most effective manner. From the teachings of the present invention, a skilled artisan will know how to devise an appropriate servo control scheme, to best suit a given application.

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 optical power levels of the spectral channels coupled into the output ports. The optical 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 embodiment of FIG. 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 power 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 power monitor 460. The processing unit 495 uses the optical power measurements from the spectral power monitor 460 to provide dynamic control of the channel micromirrors 430 along with the collimator-alignment mirrors 485, so as to maintain the coupling efficiencies of the spectral channels into the output ports at desired values. The underlying operating principle of the processing unit 495 may be substantially similar to that of processing unit 470, as described above.

In the embodiment of FIG. 4A or 4B, the spectral power monitor 460 may be one of spectral power monitoring devices known in the art that is capable of detecting the optical 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 optical 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 optical power measurements received from the spectral power 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 as 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 a processing unit in a servo-control system are known in the art. Those skilled in the art will know how to implement a suitable spectral power 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 that may arise 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, including a novel class of optical add-drop multiplexers (OADMs) for WDM optical networking applications.

FIGS. 5A-5B depict a first embodiment of an optical add-drop multiplexer (OADM) of the present invention. Shown in FIG. 5A is a schematic view of OADM 500A according to the present invention, which only illustrates the input and output ports of a WSR apparatus, along with a plurality of add ports. The remainder of the WSR apparatus is schematically represented by a dashed box 510, for purpose of simplicity and clarity. The WSR apparatus in this case may be constructed according to the embodiment of FIG. 1A, 2A, 2B, 3, or any other configuration in accordance with the present invention. By way of example, an input port 520, a pass-through port 530, and a plurality of drop ports 540-1 through 540-N may be arranged, along with a plurality of add ports 560-1 through 560-N, in a one-dimensional input-output-port array 570. The arrangement of the input-output-port array 570 may be such that the input ports (e.g., the input port 520 and the add ports) transmitting the incoming optical signals and the output ports (e.g., the pass-through 530 and the drop ports) carrying the outgoing optical signals are positioned in an alternating (or interleaved) fashion, whereby interposed between every two input ports is an output port, and vice versa. Such an arrangement warrants that if a spectral channel λ_i originating from the input port 520 is to be routed to a drop port, such as the drop port 540-2, by way of the optical system in the dashed box 510, an add spectral channel with the same wavelength λ_i emerging from an adjacent add port 560-2 can be directed into the pass-through port 530 by the same optical system in the dashed box 510. This is due to the fact that the drop spectral channel and the corresponding add spectral channel are routed to their respective destinations by the same channel micromirror in the dashed box 510, as to be shown in further detail in FIG. 5B. (Note: in view of the functionality thus described,

the add port **560-2** is intrinsically paired with the drop port **540-2**; likewise, the add port **560-i** is paired with the drop port **540-i**, where $i = 1$ through N .)

By way of example, FIG. **5B** depicts an exemplary channel micromirror **580** (e.g., the
5 channel micromirror **103-i** shown in FIG. **1B**) in a magnified schematic view. A first
incident beam **581** represents the spectral channel λ_i originating from the input port **520** in
FIG. **5A**, and a first reflected beam **582** represents the reflected spectral channel λ_i from
the channel micromirror **580**. A second incident beam **583** represents the add spectral
channel λ_j coming from the add port **560-2** in FIG. **5A**, and a second reflected beam **584**
10 represents the reflected add channel λ_j from the channel micromirror **580**. Line **585**
indicates the normal direction to the reflective surface of the channel micromirror **580**.
Because the angle of incidence θ_1 for the first incident beam **581** is equal to the angle of
reflection θ_1' for the first reflected beam **582**, and the angle of incidence θ_2 for the second
incident beam **583** is likewise the same as the angle of reflection θ_2' for the second
15 reflected beam **584**, the spatial arrangement by which the input, pass-through, drop, and
add ports are positioned in FIG. **5A** enables the first reflected beam **582** to be routed into
the drop port **540-2** and the second reflected beam **584** to be directed into the pass-through
port **530**.
20 Moreover, by undergoing pivoting (or rotational) motion, e.g., about an axis **586** (e.g.,
along the x -direction shown in FIG. **1B**) perpendicular to the plane of the paper, the
channel micromirror **580** is further able to direct the spectral channel λ_i into any other drop
port in the input-output-port array **570**, along with routing an add spectral channel (with
the same wavelength) from a pairing add port to the pass-through port **530**, as governed by
25 the same operation principle illustrated in FIG **5B**. The channel micromirror **580** may also
direct the spectral channel λ_i to the pass-through port **530**, as described in the embodiment
of FIG. **1A**, **2A**, **2B**, or **3**.

One skilled in the art will appreciate that the exemplary embodiment of FIG. **5B** and the
30 operation principle thus illustrated are applicable to any channel micromirror in the
OADM **500A**. As such, the OADM **500A** is capable of inserting (or “adding”) add
spectral channels from multiple add ports to the pass-through port **530**, while
simultaneously routing the spectral channels from the input port **520** into the appropriate

drop ports, thereby performing both add and drop functions in a dynamically reconfigurable way.

It should be noted that the exemplary embodiment of FIG. 5A is provided, by way of example, to illustrate the general principles of the present invention. Various elements and features are shown for illustrative purpose only, and therefore not drawn to scale. For instance, the input, pass-through, drop and add ports in the input-output-port array 570 are generally not evenly spaced, although they may be approximately evenly spaced in a paraxial approximation. From the teachings of the present invention, those skilled in the art will also appreciate that there are many alternative ways of arranging the input ports and output ports in the input-output-port array 570 of FIG. 5A that would achieve substantially the same functionality as described above. By way of example, the input port 520 and the pass-through port 530 may be placed near the middle of, at the bottom of, or at any other desired location along the input-output-port array, so long as the drop ports and add ports are accordingly arranged so that interposed between every two input ports is an output port, and vice versa. This enables each channel micromirror to perform a dual function of “dropping” a spectral channel from the input port to a drop port and “adding” an add spectral channel (with the same wavelength) from a pairing add port to the pass-through port, in a manner as depicted in FIG. 5B. Furthermore, the input-output-port array 570 may be embodied by an array of fiber collimators, which may be conveniently mounted in a V-groove fabricated on a substrate made of silicon, plastic, or ceramic, as commonly practiced in the art.

The underlying principle and operation of the embodiments of FIGS. 5A-5B may be readily extended to devise an OADM equipped with a two-dimensional array of input and output ports, as illustrated in FIGS. 5C-5D. Shown in FIG. 5C is a schematic top view of a second embodiment of an OADM according to the present invention. (The schematic views shown in FIG. 5C and the following figures are presented with respect to the perspective view of FIG. 1A.) By way of example, the OADM 500B makes use of the general architecture of and hence a number of elements used in the embodiment of FIG. 1A, as identified by those elements labeled with identical numerals. In addition, a two-dimensional input-output-port array 575 is implemented (where only a top view of the input-output-port array 575 is explicitly shown), in lieu of the fiber collimator array 110 in FIG. 1A.

FIG. 5D depicts a schematic front view of the input-output-port array 575 of FIG. 5C. By way of example, the input-output-port array 575 comprises an input-port column 575A having an input port 525 and a plurality of add ports 565-1 through 565-N, and an output-port column 575B including a pass-through port 535 and a plurality of drop ports 545-1 through 545-N. In this arrangement, each input port (e.g., add port 565-i) forms a “pair” with its adjacent output port (e.g., drop port 545-i, where $i = 1$ through N), in such a way to enable each channel micromirror to route a spectral channel from the input port 525 to a drop port (e.g., the drop port 545-i) and to direct an add spectral channel (with the same wavelength) from a pairing add port (e.g., the add port 565-i) to the pass-through port 535, as the arrows in the figure indicate.

Referring to both FIGS. 5C and 5D, in operation, the input port 525 transmits a multi-wavelength optical signal. The wavelength-separator in the form of the diffraction grating 101 separates the multi-wavelength optical signal by wavelength into multiple “incoming spectral channels”. (Note: the “incoming spectral channels” herein refer to the spectral channels originating from the input port 525, in contrast with the add spectral channels to be described later). The beam-focuser in the form of the focusing lens 102 focuses the incoming spectral channels into corresponding focused spots, impinging onto the channel micromirrors 103. As a way of example, each channel micromirror may be configured such that in a “nominal position”, it reflects the corresponding incoming spectral channel to the pass-through port 535, as illustrated in FIG. 5C. Furthermore, the diffraction grating 101, along with the focusing lens 102, may direct add spectral channels emerging from the add ports in the input-output-port array 575 onto corresponding ones of the channel micromirrors 103. By pivoting each channel micromirror about an appropriate axis (e.g., along the x -direction shown in FIG. 1B), the channel micromirror is further able to direct the incoming spectral channel into a drop port (e.g., the drop port 545-i) in the input-output-port array 575 and an impinging add spectral channel from a pairing add port (e.g., the add port 565-i) into the pass-through port 535, as illustrated in FIG. 5D.

One skilled in the art will recognize that the input-output-port array 575 may be alternatively implemented in any other WSR apparatus according to the present invention (e.g., by appropriately modifying the embodiment of FIG. 2A, 2B, or 3). Those skilled in the art will also appreciate that the exemplary embodiment of FIGS. 5C-5D is provided, by way of example, to illustrate the general principles of the present invention. Various elements and features are shown for illustrative purpose only, and therefore not drawn to

scale. For instance, the input port **525** and the pass-through port **535** as a pair may be alternatively placed near the middle of, at the bottom of, or at any other desired location along the input-output-port array **575**, so long as the input ports and the output ports are separately grouped in two columns and paired accordingly. The input-output-port array
5 **575** may also be embodied by two columns of fiber collimators, wherein the input-port and output-port columns may be mounted in two V-grooves on a substrate, for example. From the teachings of the present invention, a skilled artisan will know how to implement various input and output ports in an OADM according to the present invention, to best suit a given application.

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Furthermore, a two-dimensional array of collimator-alignment mirrors (along with first and second arrays of imaging lenses) may be additionally implemented between the input-output-port array **575** and the diffraction grating **101** in the embodiment of FIG. **5C** (e.g., in a manner as illustrated in FIG. **3**), such that each collimator-alignment mirror
15 corresponds to either an input port or an output port. The collimator-alignment mirror array may be used for controlling the alignment of the multi-wavelength optical signal from the input port and the add spectral channels from the add ports, as well as for directing the reflected spectral channels into the output ports.

20 As such, a notable advantage of the aforementioned OADMs is the ability to perform both add and drop functions in a dynamically reconfigurable fashion, without involving additional components such as optical circulators and/or optical combiners.

A servo-control assembly may be further incorporated in an OADM of the present
25 invention, for monitoring and controlling the optical power levels of the spectral channels coupled into the output ports. By way of example, FIG. **5E** depicts an optical apparatus **500C** including a servo-control assembly **590** integrated in an OADM **518**, according to the present invention. The OADM **518** may be substantially identical to the embodiment of FIG. **5A**, **5C**, or any other embodiment according to the present invention. For purpose
30 of simplicity and clarity, only the output ports of the OADM **518** are explicitly shown, including a pass-through port **538** and a plurality of drop ports **548-1** through **548-N**. (For example, these output ports may be the pass-through port **530** and the drop ports **540-1** through **540-N** of FIG. **5A**, or the constituents of the output-port column **575B** in FIG. **5D**). The servo-control assembly **590** may include a spectral power monitor **591** and a

processing unit 592. The spectral power monitor 591 may be optically coupled to the pass-through port 538, so as to monitor the optical power levels of the spectral channels coupled into the pass-through port 538. The coupling of the spectral power monitor 591 to the pass-through port 538 may be accomplished by way of a fiber-optic coupler 538-C via an optical switch 595, for instance. The processing unit 592, in communication with the spectral power monitor 591 and the channel micromirrors (not shown in FIG. 5E) in the OADM 518, uses the optical power measurements from the spectral power monitor 591 to provide feedback control of the channel micromirrors on an individual basis, so as to maintain the optical power levels of the spectral channels coupled into the pass-through port 538 at desired values. For example, the optical power levels of the spectral channels in the pass-through port 538 may be equalized at a predetermined value, as might be desired in an optical networking application. (Note: if the OADM 518 also includes the collimator-alignment mirrors as depicted in FIG. 2A, 2B, or 3, the processing unit 592 may additionally provide control of the collimator-alignment mirrors, in a manner as illustrated in FIG. 4B.)

In the embodiment of FIG. 5E, the spectral power monitor 591 may additionally measure the optical power levels of the spectral channels in the drop ports 548-1 through 548-N, if so desired in a practical application. This may be accomplished by using fiber-optic couplers 548-1-C through 548-N-C to “tap off” predetermined fractions of the optical signals in the drop ports 548-1 through 548-N, respectively. The tapped-off optical signals may be combined by an optical combiner 596, whose output may in turn be coupled to the optical switch 595. The configuration may be such that during normal operation, the optical switch 595 is set in a first switching state (1) that allows the optical signal diverted from the pass-through port 538 to pass into the spectral power monitor 591 (while blocking off the combined optical signal diverted from the drop ports), thereby enabling the optical power levels of the spectral channels in the pass-through port 538 to be monitored and further controlled (e.g., equalized). On an occasional or regular basis, the optical switch 595 may be set in a second switching state (2) that allows the combined optical signal tapped off from the drop ports to pass into the spectral power monitor 591 (while blocking off the optical signal diverted from the pass-through port 538), thereby allowing the optical power levels of the drop spectral channels to be measured. Note that the processing unit 592 need not provide feedback control of the channels micromirrors in

the OADM 518, while the optical power levels of the drop spectral channels are being measured.

One skilled in the art will recognize that rather than operating the spectral power monitor 591 in a time-division-multiplexed fashion by way of the optical switch 595, an auxiliary spectral power monitor may be additionally employed in the embodiment of FIG. 5E, dedicated for monitoring the optical power levels of the spectral channels in the drop ports. (The optical switch 595 need not be utilized, in this case.) In either scenario, the processing unit, the spectral power monitor(s) and the fiber-optic couplers of FIG. 5E may be substantially similar to those described in the embodiment of FIG. 4A (or 4B) in configuration and operation. The optical combiner 596 may be an $N \times 1$ fiber-optic coupler, or any other suitable optical combining means known in the art. The optical switch 595 may be a 2×1 switch. Those skilled in the art will further appreciate that in lieu of the combination of the optical combiner 596 and the optical switch 595, an $(N+1) \times 1$ optical switch may be alternatively implemented in FIG. 5E, where the $(N+1)$ input ends of the switch may be coupled to the pass-through port 538 and the drop ports 548-1 through 548-N, respectively, and the output end of the switch may be coupled to the spectral power monitor 591.

FIG. 6A depicts a third embodiment of an OADM according to the invention. By way of example, OADM 600A comprises a WSR-S (or WSR) apparatus 610 and an optical combiner 650. An input port 620 of the WSR-S apparatus 610 receives a multi-wavelength optical signal. The constituent spectral channels of this optical signal are subsequently separated and routed into a plurality of output ports, including a pass-through port 630 and one or more drop ports 640-1 through 640-N ($N \geq 1$). The pass-through port 630 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 630 is optically coupled to the optical combiner 650, which serves to combine the pass-through spectral channels with one or more add spectral channels provided by one or more add ports 660-1 through 660-M ($M \geq 1$). The combined optical signal is then routed into an existing port 670, providing an output multi-wavelength optical signal.

In the above embodiment, the optical combiner **650** may be a $K \times 1$ ($K \geq 2$) 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 **600A**. If the optical 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 power monitors may be utilized. As a way of example, the first spectral power monitor may receive optical signals tapped off from the pass-through port **630** and the drop ports **640-1** through **640-N**, e.g., by way of fiber-optic couplers as depicted in FIG. **4A** or **4B**. The second spectral power monitor receives optical signals tapped off from the exiting port **670**. 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. **6A** provides a versatile optical add-drop multiplexer in a simple and low-cost assembly, while providing multiple drop/add ports in a dynamically reconfigurable fashion.

FIG. **6B** depicts a fourth embodiment of an OADM according to the invention. By way of example, OADM **600B** comprises a first WSR-S apparatus **610** optically coupled to a second WSR-S apparatus **680**. Each WSR-S apparatus may be substantially identical to the embodiment of FIG. **4A** or **4B**. (A WSR apparatus 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** ($N \geq 1$). The pass-through spectral channels from the pass-through port **630** are further coupled to the second WSR-S apparatus **680**, along with one or more add spectral channels emerging from add ports **660-1** through **660-M** ($M \geq 1$). 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 **680**. By way of its constituent wavelength-separator (e.g., a diffraction grating) and channel micromirrors (both not shown in FIG. **6B**), the second WSR-S apparatus **680** serves to multiplex the pass-through spectral channels and the add spectral channels, and route the multiplexed optical signal into an exiting port **670** to provide an output signal of the system.

In the embodiment of FIG. **6B**, one WSR-S apparatus, e.g., the first WSR-S apparatus **610**, effectively performs a dynamic drop function, whereas the other WSR-S apparatus (e.g., the second WSR-S apparatus **680**) carries out a dynamic add function. There are
5 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. **6B** may be
10 operated in reverse direction, by using the input ports as the output ports, and the drop ports as the add ports.

As discussed above, the diffraction efficiency of a diffraction grating is polarization-sensitive, and such polarization-sensitive effects may give rise to significant insertion loss
15 and polarization-dependent loss (PDL) in an optical system. The situation is exacerbated in WDM optical networking applications, where the polarization state of a WDM signal is typically indeterminate and may vary with time. This can produce an undesirable time-varying insertion loss that may cause the optical signals to fall below acceptable power levels, or render them unusable. Thus, it is desirable to avoid such polarization-sensitive
20 effects. The present invention affords a polarization diversity scheme that addresses this issue, as will now be described.

FIG. **7A** depicts a schematic top view and FIG. **7B** depicts a schematic side view of a fifth embodiment of a WSR apparatus of the present invention, employing a polarization
25 diversity arrangement that minimizes polarization-sensitive effects. WSR apparatus **700** may make use of the general architecture and a number of the elements used in the embodiment of FIG. **1A**, as indicated by those elements labeled with the same numerals. The input port **110-1** provides a multi-wavelength optical signal (which may contain wavelengths λ_1 through λ_M , for instance) to a polarization-displacing unit **720**. The multi-
30 wavelength optical signal may be of indeterminate and/or time-varying polarization. The polarization-displacing unit **720** may be disposed along the optical path between the array of fiber collimators **110** (including the input port **110-1** and the output ports **110-2** through **110-N**, as shown in FIG. **7B** below) and the diffraction grating **101**. The polarization-

displacing unit **720** serves to separate (or decompose) the input multi-wavelength optical signal into a first p-polarization component and a second s-polarization component that is orthogonal to the p-polarization component. Assuming that p-polarization is the “preferred” polarization direction of the diffraction grating **101** (i.e., the diffraction efficiency is higher for the p-polarization component than for the s-polarization component), the p-polarization component of the input optical signal may be output as a first optical signal **722** from the polarization displacing unit **720**. The s-polarization component of the input optical signal may undergo a 90-degree rotation in polarization by a polarization-rotating unit **730** to produce a second optical signal **732** also having p-polarization. Thus, the two optical signals **722**, **732** incident onto the diffraction grating **101** both possess p-polarization.

The first and second polarization components (optical signals **722**, **732**) emerging respectively from the polarization-displacing unit **720** and the polarization-rotating unit **730** may further undergo an anamorphic beam magnification by a beam-modifying unit **740**, and thereafter emerge as spatially separated and magnified beams **742**, **744** which impinge upon the diffraction grating **101**. The configuration may be such that the beam-modifying unit **740** preferentially enlarges the beam size in the direction perpendicular to the groove lines on the diffraction grating **101**, whereby the focused beams produced by the focusing lens **102** are narrower in this direction (i.e., perpendicular to the groove lines). This enables rectangular shaped micromirrors to be implemented, for instance. The diffraction grating **101** subsequently separates the magnified first and second polarization components **742**, **744** by wavelength respectively into first and second sets of diffracted optical beams. Each set of optical beams may contain multiple wavelengths λ_1 through λ_M , diffracted from the diffraction grating at different angles. The focusing lens **102** in turn focuses the diffracted optical beams into corresponding focused spots, impinging onto the channel micromirrors **103**. Each focused spot may be elliptical in cross-section. Further, the first and second diffracted optical beams having the same wavelength (e.g., λ_i) are arranged to impinge onto the same channel micromirror (e.g., the channel micromirror **103-i** shown in FIG. **7B** below). In this way, each channel micromirror concurrently handles two optical beams characterized by the same wavelength (and polarization).

FIG. 7B depicts a schematic side view of the WSR apparatus 700, where only the second polarization component (represented by optical signals 732, 744 in FIG. 7A) on the forward path), along with the reflected first set of optical beams on the return path, are explicitly shown. For purposes of illustration and clarity, several channel micromirrors are explicitly identified in this figure, while the array of channel micromirrors as a whole is also indicated by the numeral 103. As described above with respect to FIGS. 1A-1B, the channel micromirrors 103 are individually controllable and movable, e.g., pivotable about an axis 750 (which may be parallel to the x -axis shown in FIG. 1B and perpendicular to the plane of FIG. 7B). Hence, each channel micromirror is capable of directing its corresponding optical beams into any one of the output ports 110-2 through 110-N by way of its pivoting motion. By way of example, the channel micromirror 103-k may be controlled to direct the first and second optical beams with wavelength λ_k into the first output port 110-2; the channel micromirror 103-j may be controlled to direct the first and second optical beams with wavelength λ_j into the second output port 110-3; the channel micromirror 103-i may be controlled to direct the first and second optical beams with wavelength λ_i into the third output port 110-4, and so on. Note that a plurality of the channel micromirrors may be individually controlled to direct their corresponding optical beams into the same output port.

Referring to FIG. 7A, the first and second sets of optical beams reflected from the respective channel micromirrors 103 are deflected out of the plane of the figure (as indicated by the side view of FIG. 7B), hence not explicitly shown in the top view of FIG. 7A. With reference to FIG. 7B, it will be apparent to those skilled in the art that the reflected first and second sets of optical beams each undergo an anamorphic beam demagnification by way of the beam-modifying unit 740, thereby resuming the beam size of the input optical signal. The reflected first set of optical beams subsequently undergoes a 90-degree rotation in polarization by the polarization-rotating unit 730, whereby the reflected first and second sets of optical beams are polarized in two orthogonal directions upon entering the polarization-displacing unit 720. This enables the polarization-displacing unit 720 to recombine the reflected first and second sets of optical beams by wavelength respectively into reflected spectral channels, prior to being coupled into selected ones of the output ports 110-2 through 110-N.

It should be appreciated that the rotation in polarization produced by a polarization-rotating element (e.g., the polarization-rotating unit 730) may have slight variations about a prescribed angle (e.g., 90-degrees), due to imperfections that may exist in a practical system. Such variations, however, will not significantly affect the overall performance of the invention.

In the embodiment of FIGS. 7A-7B, the polarization-displacing unit 720 may be in the form of a single polarization-displacing element, corresponding to the array of fiber collimators 110. FIG. 7C shows two schematic views of an exemplary embodiment of a polarization-displacing element 720A which may be a birefringent beam displacer well known in the art. The first schematic represented by dashed box 761 of FIG. 7C illustrates a top view of the polarization-displacing element 720A, where an incident optical beam 770 (e.g., the multi-wavelength input optical signal in the embodiment of FIGS. 7A-7B) is decomposed into first and second polarization components 772, 774 polarized in two orthogonal directions, as illustrated in the figure. Notice that the two polarization components are spatially displaced and propagate in parallel, upon emerging from the polarization-displacing element 720A. The second schematic represented by dashed box 762 of FIG. 7C depicts an exemplary cross-sectional top view of the polarization-displacing element 720A, where two parallel optical beams 776, 778 polarized in two orthogonal directions (e.g., the first and second reflected optical beams associated with wavelength λ_i in the embodiment of FIGS. 7A-7B) are recombined by way of traversing the polarization-displacing element 720A into a single optical beam 780 (e.g., the reflected spectral channel with wavelength λ_i in the embodiment of FIGS. 7A-7B). As such, the polarization-displacing element 720A acts as a polarization-separating element for optical beams propagating in one direction; and serves as a polarization-combining element for optical beams traversing in the opposite direction.

Those skilled in the art will appreciate that rather than using a birefringent beam displacer, the polarization-displacing element 720A may alternatively be provided by a suitable polarizing-beam-splitting element, e.g., a polarizing beam splitter commonly used in the art in conjunction with an appropriate beam-deflector or prism (such that the two emerging polarization components propagate in parallel). Such a polarizing-beam-splitting element provides a substantially similar function to the aforementioned birefringent beam

displacer. In general, a polarization-displacing element in the present invention may be embodied by any optical element that provides a dual function of polarization separating and combining, e.g., in a manner as depicted in FIG. 7C.

5 Likewise, the polarization-rotating unit **730** may comprise a single polarization-rotating element, e.g., a half-wave plate, a liquid crystal rotator, a Faraday rotator, or any other means known in the art that is capable of rotating the polarization of an optical beam by a prescribed angle (e.g., 90 degrees).

10 Alternatively, the polarization-displacing unit **720** may comprise a plurality of polarization-displacing elements, each corresponding to one or more fiber collimators **110** in the embodiment of FIGS. 7A-7B. By way of example, FIG. 7D depicts a schematic side view of a polarization-displacing unit **720B** which may comprise an array of polarization-displacing elements **720-1** through **720-N**. Each polarization-displacing
15 element may be a birefringent beam displacer, a polarizing-beam-splitting element, or any other suitable means known in the art, as described above with respect to FIG. 7C. In this case, the polarization-rotating unit **730** may include one or more polarization-rotating elements, each as described above. As a way of example, FIG. 7D also shows a schematic side view of a polarization-rotating unit **730B** as an array of polarization-rotating elements
20 **730-1** through **730-N**, which may be in a one-to-one correspondence with the polarization-displacing elements **720-1** through **720-N**. As such, the polarization-displacing unit **720B**, along with the polarization-rotating unit **730B**, may be implemented in the embodiment of FIGS. 7A-7B so that the polarization-displacing elements **720-1** through **720-N** are in a one-to-one correspondence with the fiber collimators **110** that provide the input port **110-1**
25 and the output ports **110-2** through **110-N**.

Those skilled in the art will appreciate that the exemplary embodiments of FIGS. 7C-7D are provided as an example to illustrate how a polarization-displacing unit, along with a polarization-rotating unit, may be configured and operated in the present invention.

30 Various changes and modifications may be made herein to perform the designated functions in a substantially equivalent manner. For example, the polarization-displacing unit **720** along with the polarization-rotating unit **730** may alternatively be configured such that the first and second polarization components are spatially separated along a vertical direction that is substantially perpendicular to the plane of the paper in the schematic top

view of FIG. 7A, as opposed to being separated horizontally in a manner as illustrated in FIG. 7A. As will be appreciated from the teachings of the invention, one skilled in the art would know how to implement an appropriate polarization-displacing unit, along with a suitable polarization-rotating unit, in a WSR apparatus according to the present invention,
5 for a given application.

Moreover, the beam-modifying unit 740 may comprise an assembly of cylindrical lenses or prisms, in optical communication with the polarization-displacing unit 720 along with the polarization-rotating unit 730 and the diffraction grating 101. In general, a beam-
10 modifying unit may be embodied by any optical means that is capable of magnifying the input optical signal and de-magnifying the reflected optical beams according to a predetermined ratio. Such a beam-modifying unit may be particularly useful in applications that call for a refined spectral resolution, such as DWDM optical networking applications.

15 The WSR apparatus 700 of FIGS. 7A-7B is substantially similar to the WSR apparatus 100 of FIG. 1A in operation and function and hence achieves the advantages thereof. Furthermore, the aforementioned polarization diversity arrangement renders the polarization sensitivity of the diffraction grating 101 inconsequential in the WSR
20 apparatus 700. This enables the WSR apparatus 700 to minimize the insertion loss. It also allows the WSR apparatus 700 to enhance the spectral resolution in a simple and cost-effective construction (e.g., by making use of high-dispersion holographic diffraction gratings commonly available in the art). Another notable feature of the polarization diversity arrangement is that the first and second optical beams associated with each
25 wavelength (corresponding to the two polarization components of each spectral channel) effectively “exchange” their respective optical paths, upon reflection from the micromirror (e.g., the return path of the second optical beam is substantially similar to the forward path of the first optical beam, and vice versa). This has the important consequence of substantially equalizing the overall optical paths of the two polarization components for
30 each spectral channel, thereby minimizing polarization-dependent loss (PDL) and polarization-mode dispersion (PMD). Such attributes are highly desirable in many applications.

Those skilled in the art will appreciate that the WSR apparatus **700** of FIGS. **7A-7B** may be further modified in various ways according to the teachings of the present invention. For example, the WSR apparatus may include an array of collimator-alignment mirrors, e.g., in a manner as described with respect to the embodiment of FIG. **2A**, **2B**, or **3** above.

5 FIG. **8A** shows a schematic top view of a sixth embodiment of a WSR apparatus **800A** of the present invention, which employs an array of collimator-alignment mirrors **220** in a polarization diversity arrangement. By way of example, the WSR apparatus **800A** may be built upon the embodiments of FIGS. **2A** and **7A**, hence similar elements are labeled with the same numerals. In FIG. **8A**, the array of collimator-alignment mirrors **220** (which may
10 include the collimator-alignment mirrors **220-1** through **220-N**, as shown in FIG. **2A**) may be disposed along the optical path between the fiber collimators **110** and the polarization-displacing unit **720**, such that there is a one-to-one correspondence between the collimator-alignment mirrors **220** and the fiber collimators **110** providing the input and output ports. As described with respect to FIG. **2A**, the collimator-alignment mirrors **220**
15 may be controlled to adjust the alignment of the multi-wavelength input optical signal and to further provide angular control of the collimated beams of the reflected spectral channels. This facilitates the coupling of the reflected spectral channels into the respective output ports according to desired coupling efficiencies.

20 In the embodiment of FIG. **8A**, the collimator-alignment mirrors **220** are disposed between the fiber collimators **110** and the polarization-displacing unit **720**, and control the angular position of the (un-split) multi-wavelength input optical signal as well as the (combined) reflected spectral channels. There may be applications where it is desired to provide separate control to the first and second polarization components (on the forward path), as
25 well as to the reflected first and second sets of optical beams (on the return path). FIG. **8B** depicts a schematic top view of a seventh embodiment of a WSR apparatus **800B** of the present invention, pertaining to this situation. The WSR apparatus **800B** may be built upon the embodiment of FIG. **8A**, hence similar elements are labeled with the same numerals. In this case, a polarizing-beam-splitting unit **820** may be employed (in lieu of
30 the polarization-displacing unit **720** of FIG. **8A**), to decompose the multi-wavelength input optical signal into first and second polarization components **822**, **824** that are propagating in two orthogonal directions. The second polarization component **824** may be subsequently incident onto and reflected by a first beam-deflecting unit **222**, whereby it propagates parallel to the first polarization component **822**. The ensuing operation

thereafter is substantially similar to that of FIG. 8A. On the return path, the reflected first set of optical beams is incident onto and reflected by the first beam-deflecting unit 222, so as to enable the polarizing-beam-splitting unit 820 to recombine the reflected first and second sets of optical beams by wavelength respectively into reflected spectral channels.

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In the embodiment of FIG. 8B, the polarizing-beam-splitting unit 820 may be a single polarizing beam splitter known in the art, in optical communication with the array of fiber collimators 110 via the collimator-alignment mirrors 220. It may also comprise an array of polarizing beam splitters, e.g., in a one-to-one correspondence with the collimator-
10 alignment mirrors 220. The first beam-deflecting unit 222 may comprise an array of first mirrors, e.g., in a one-to-one correspondence with the collimator-alignment mirrors 220. The first mirrors 222 may be individually adjustable, so as to control the relative alignment and thereby ensure the requisite beam parallelism between the first and second polarization components on the forward path, which in turn causes the first and second
15 diffracted optical beams associated with each wavelength to substantially coincide on the same channel micromirror. On the return path, the first mirrors 222 may likewise adjust the relative alignment between the reflected first and second sets of optical beams respectively, thereby ensuring that the reflected first and second sets of optical beams are properly recombined into the respective spectral channels by way of the polarizing-beam-
20 splitting unit 820. The first mirrors 222 may be controlled on a dynamic basis. Alternatively, the first mirrors 222 may be adjusted to predetermined positions to enable the polarizing-beam-splitting unit 820 to achieve the requisite beam parallelism. The first mirrors 222 may be subsequently fixed in respective positions over the course of operation. (In this way, the tolerances required for the polarizing-beam-splitting unit 820
25 may be relaxed.) It should be further appreciated that the first beam-deflecting unit 222 may also be a static mirror, or any other beam-deflecting means known in the art, configured such that the combination of the polarizing-beam-splitting unit 820 and the first beam-deflecting unit 222 effectively constitutes a polarization-displacing unit as described above.

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FIG. 8C depicts a schematic top view of an eighth embodiment of a WSR apparatus 800C of the present invention. The WSR apparatus 800C may include the elements employed in the embodiment of FIG. 8B, along with second and third beam-deflecting units 224, 226. The second beam-deflecting unit 224 may comprise an array of second mirrors that are

individually adjustable, e.g., in a one-to-one correspondence with the constituent mirrors in the first beam-deflecting unit 222. The third beam-deflecting unit 226 may simply be a static mirror, or other known beam-deflecting device. In this way, the first and second polarization components 822, 824 (on the forward path) may be independently controlled
5 by the first and second beam-deflecting units 222, 224, which may also control the reflected first and second sets of optical beams (on the return path), respectively. The collimator-alignment mirrors 220 may further facilitate the coupling of the (combined) reflected spectral channels into the desired output ports.

10 The WSR apparatus 700 (or any one of the embodiments of FIGS. 8A-8C) of the present invention may further incorporate a servo-control assembly, e.g., in a manner as described with respect to FIG. 4A (or 4B) above. The servo-control assembly may dynamically manage the optical power levels of the reflected spectral channels coupled into the output ports. The servo-control assembly may also be configured such to minimize PDL
15 associated with the spectral channels.

[0001] Furthermore, a dynamically reconfigurable OADM may be built upon the WSR apparatus 700, 800A, 800B or 800C (along with an associated servo-control assembly), e.g., in a manner similar to that described above. The thus-constructed OADMs will have important advantages of low insertion loss, low PDL, and enhanced spectral resolution,
20 which would be particularly suitable for WDM optical networking applications.

Those skilled in the art will recognize that the aforementioned embodiments are provided by way of example to illustrate the general principles of the invention. Various changes, substitutions, and alternations can be made without departing from the principles and the
25 scope of the invention as defined in the appended claims.

CLAIMS

What is claimed is:

- 5 1. An 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 that separates said multi-wavelength optical signal by wavelength into multiple spectral channels; and
 - 10 c) an array of channel micromirrors positioned such that each channel micromirror receives a unique one of said spectral channels, said channel micromirrors being individually and continuously pivotable to reflect said spectral channels into selected output ports.
- 15 2. The optical 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 a unique one of said output ports.
- 20 3. The optical apparatus of claim 2 wherein said servo-control assembly comprises a spectral power monitor for monitoring optical power levels of said spectral channels coupled into said output ports, and a processing unit responsive to said optical power levels for providing control of said channel micromirrors.
- 25 4. The optical apparatus of claim 3 wherein said servo-control assembly is adapted to maintain said optical power levels at a predetermined value.
5. The optical 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 for directing said reflected spectral channels into said output ports.
- 30 6. The optical apparatus of claim 5 wherein each collimator-alignment mirror is rotatable about at least one axis.
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7. The optical 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.
- 5 8. The optical apparatus of claim 1 wherein each channel micromirror is pivotable about at least one axis.
9. The optical apparatus of claim 1 further comprising a beam focuser that focuses
10 said spectral channels into corresponding focused spots.
10. The optical apparatus of claim 9 wherein said beam-focuser comprises one or more focusing lenses.
11. The optical apparatus of claim 1 wherein said wavelength-separator comprises an
15 element selected from the group consisting of ruled diffraction gratings, holographic diffraction gratings, echelle gratings, transmission gratings, curved diffraction gratings, and dispersing prisms.
12. The optical apparatus of claim 1 further comprising a quarter-wave plate optically
20 interposed between said wavelength-separator and said channel micromirrors.
13. The optical apparatus of claim 1 wherein said output ports include a pass-through port and one or more drop ports, wherein said channel mirrors direct a subset of said spectral channels into said pass-through port to provide for a pass-through
25 signal, and wherein said optical apparatus further comprises an optical combiner for combining said pass-through signal with one or more add spectral channels.
14. The optical apparatus of claim 1 wherein said fiber collimators are arranged in a one-dimensional input-output-port array, including said input port for said multi-
30 wavelength optical signal and a plurality of add ports, and multiple output ports providing a pass-through port and a plurality of drop ports, wherein said input-output-port array is configured such that each drop port has a pairing add port, whereby each channel micromirror is able to reflect a spectral channel from said multi-wavelength optical signal into a drop port and an add spectral channel from a
35 pairing add port into said pass-through port.

15. The optical apparatus of claim 14 wherein said input-output-port array comprises alternating input and output ports.
- 5 16. The optical apparatus of claim 1 further comprising a polarization-displacing unit that decomposes said multi-wavelength optical signal into first and second polarization components, and a polarization-rotating unit that rotates a polarization of the second polarization component to be substantially parallel to a polarization of the first polarization component, wherein said wavelength-separator separates said first and second polarization components by wavelength respectively into first and second sets of optical beams, and wherein said channel micromirrors are positioned to reflect said first and second sets of optical beams, such that said reflected first and second sets of optical beams are recombined by wavelength respectively into reflected spectral channels by way of said polarization-rotating unit and said polarization-displacing unit.
- 10 17. The optical apparatus of claim 16 wherein said polarization-displacing unit comprises at least one polarization-displacing element in optical communication with said input port and said output ports.
- 15 18. The optical apparatus of claim 17 wherein said at least one polarization-displacing element comprises at least one element selected from the group consisting of birefringent beam displacers and polarizing-beam-splitting elements.
- 20 19. The optical apparatus of claim 16 wherein said polarization-rotating unit comprises at least one polarization-rotating element, in optical communication with said polarization-displacing unit.
- 25 20. The optical apparatus of claim 19 wherein said at least one polarization-rotating element comprises at least one element selected from the group consisting of half-wave plates, Faraday rotators, and liquid crystal rotators.
- 30 21. The optical apparatus of claim 16 further comprising a beam-modifying unit for providing anamorphic beam magnification of said first and second polarization components and anamorphic beam demagnification of said reflected first and second sets of optical beams.
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22. The optical apparatus of claim 21 further comprising a beam focuser for focusing said first and second sets of optical beams into corresponding focused spots.
23. The optical apparatus of claim 21 wherein said beam-modifying unit comprises one or more cylindrical lenses.
24. The optical apparatus of claim 21 wherein said beam-modifying unit comprises one or more prisms.
25. The optical apparatus of claim 16 further comprising an array of collimator-alignment mirrors in optical communication with said fiber collimators and said polarization-displacing unit for adjusting an alignment of said multi-wavelength optical signal from said input port and for directing said reflected spectral channels into said output ports.
26. 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 by wavelength into multiple spectral channels;
 - c) impinging said spectral channels onto an array of channel micromirrors, such that each channel micromirror receives a unique one of said spectral channels; and
 - d) dynamically and continuously controlling said channel micromirrors, thereby directing said spectral channels into a plurality of output ports.
27. The method of claim 26 further comprising the step of providing feedback control of said channel micromirrors, thereby maintaining a predetermined coupling of each spectral channel directed into a unique one of said output ports.
28. A method of dynamic routing of a multi-wavelength optical signal in a polarization diversity arrangement, comprising:
- a) decomposing said multi-wavelength optical signal into first and second polarization components;
 - b) rotating a polarization of said second polarization component to be substantially parallel to a polarization of the first polarization component;

- c) separating said first and second polarization components by wavelength respectively into first and second sets of optical beams;
 - d) focusing said first and second sets of optical beams onto an array of micromirrors;
 - 5 e) dynamically controlling said micromirrors to reflect said first and second sets of optical beams into selected output ports;
 - f) rotating a polarization of said reflected first set of optical beams by approximately 90-degrees; and
 - 10 g) recombining said reflected first and second sets of optical beams by wavelength respectively into reflected spectral channels.
29. The method of claim 28 further comprising the step of providing an anamorphic beam magnification to said first and second polarization components, respectively.
- 15 30. The method of claim 29 further comprising the step of providing an anamorphic beam demagnification to each of said first and second sets of optical beams.