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INVENTOR(S)

Given Name (first and middle [if any])	Family Name or Surname	Residence (City and either State or Foreign Country)
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☐ *Additional inventors are being named on the ___ separately numbered sheets attached hereto*

TITLE OF THE INVENTION (280 characters max)

Reconfigurable Optical Add-Drop Multiplexer with Dynamic Spectral Equalization Capability for DWDM Optical Networking Applications

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ENCLOSED APPLICATION PARTS *(check all that apply)*

☒ Specification *Number of Pages*	18	☐ CD(s), Number	
☒ Drawing(s) *Number of Sheets*	22	☐ Other (specify)	
☐ Application Data Sheet. See 37 CFR 1.76			

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Respectfully submitted,

SIGNATURE Jeffrey P. Wilde

Date 3/ 17 / 01

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PROVISIONAL PATENT APPLICATION OF

JEFFREY P. WILDE

for

RECONFIGURABLE OPTICAL ADD-DROP MULTIPLEXER WITH DYNAMIC SPECTRAL EQUALIZER CAPABILITY FOR DWDM OPTICAL NETWORKING APPLICATIONS

FIELD OF THE INVENTION

This invention relates generally to optical communication hardware, and more specifically to hardware designed for use in dense wavelength division multiplexed (DWDM) systems. The invention describes a new device design for providing two important functions of importance in emerging DWDM systems: (1) reconfigurable add-drop of individual wavelength channels, and (2) spectral equalization of wavelength channels.

SUMMARY & DETAILED DESCRIPTION

The more detailed disclosure of the present invention is contained in the following description and figures, as supplied by the attached appendices.

Appendix A: Design Concept for DWDM Multi-Channel Dynamic Add/Drop Module, by J. P. Wilde, 7/28/00
Appendix B: Modified Dynamic OADM Design, by J. P. Wilde, 11/28/00
Appendix C: Reconfigurable OADM with Dynamic Equalization, by J. P. Wilde, 12/28/00
Appendix D: Technical Specifications 1/9/2001, Dynamic Optical Add/Drop Multiplexer

Overview and Objective

Emerging DWDM communication systems are in need of a robust and low-cost device technology for providing dynamic optical add-drop of wavelength channels at node sites as shown in Figures 1 and 2. Such a device -- referred to as an optical add-drop multiplexer (OADM) -- should by remotely reconfigurable through software control. It is desirable to have complete control at the granularity of a single wavelength, meaning any individual wavelength channel can be added/dropped by the device.

Long-haul and ultra-long-haul applications require the OADM to support a large channel count (80 channels today, heading to 160 channels or more in the future). Therefore, a technology that is intrinsically scalable to such channel counts is needed. Moreover, it is important that the optical loss introduced by the device be independent (or only weakly dependent) on the number of channels. The device should also have low polarization dependent loss (PDL) and low polarization mode dispersion (PMD). A general set of device specifications is outlined in Appendix D.

Figures 3 and 4 illustrate two basic approaches, parallel and serial, to constructing a dynamic OADM. The parallel architecture is intrinsically scalable to large channel counts, and is the general approach taken in this invention. The serial scheme has various limitations as noted in Figure 4.

A parallel architecture based on free-space optics has been previously described in Ref. 1. A block diagram of this device is shown in Figure 5. It has four fiber ports: (1) input, (2) pass-through, (3) add, and (4) drop. One circulator is used to combine the input and pass-through ports onto one fiber, and another circulator combines the add and drop ports to a second fiber. Figure 6 shows a graphic of the optical system configuration of the OADM device described in Ref. 1. Two coupling lenses are implemented to convert the light paths from these two fibers to free space. Wavelength separation and routing are done in free space. The device utilizes a ruled diffraction grating to separate the input light into its constituent channels. A binary micromachined mirror array redirects each of the individual channels to one of two outputs. Each mirror in the linear array either retroreflects its corresponding channel back along the original input path towards the pass-through port, or it reflects its channel to the drop port.

While this architecture is attractive in the sense that it is compact and scalable to high channel count, it also has a number of limitations. First, the design requires precise alignment of components that makes assembly during fabrication complex and expensive. Second, no provisions are provided for maintaining the relative alignment of the optical components so that the system performance may degrade over time, or in the presence of shock and vibrations, or due to a temperature change. Third, it requires all the add and drop wavelengths to enter and leave the device on single fibers. In other words, additional means must be provided to multiplex the add channels onto a single fiber and to demultiplex the drop channels from the single fiber output from the device. This additional mux/demux requirement can lead to significant additional expense.

What is needed is an improved free-space architecture that overcomes these limitations.

Description of the Invention

The OADM device architecture disclosed here has all the positive attributes of a compact, parallel design, and also overcomes existing limitations by providing (1) a more versatile architecture with multiple physical add and drop ports, (2) analog mirrors under servo control that loosen fabrication tolerances and provide self-alignment to correct for component drift during operation, (3) additional optics to provide the servo feedback signal, and (4) a servo system scheme that provides for dynamic spectral equalization on a channel-by-channel basis.

OADM Architectures

Three different OADM architectures disclosed in the present invention are shown in Figures 7-9. All of these architectures provide for dynamic drop of one or more wavelength channels on any one of multiple drop ports. The "wavelength separation and routing" (WSR) function is common to all three architectures and is performed using free-space optics and silicon micromirrors. The optical loss of the WSR unit can be fairly low, its value being determined by the diffraction efficiency of a grating or similar dispersive device used for wavelength separation. A typical value is in the range from 2 - 4 dB. For the preferred case in which only one wavelength is dropped on each drop port, then no additional wavelength demultiplexing is required before the signals carried by the respective channels are received by photodetectors. The three approaches of Figs. 7-9 differ primarily in the way in which the add function is implemented.

The first of these (Fig. 7) is designed for one-way optical propagation. It uses a combiner (or 1xN coupler; e.g., the 1x16 broadband coupler sold by Newport Corp., Irvine, CA, product model number F-CPL-B16350) for injecting the add channels into the pass-through port. While use of a combiner is straightforward, the associated optical loss can be large (e.g., the 1x16 Newport coupler may have up to 14.5 dB of loss). For those situations where the loss can be tolerated, this is suitable approach.

The second architecture (Fig. 8) is designed for bi-directional operation and has better loss performance compared to the first embodiment. Two WSR units are utilized, with one unit providing dynamic drop and the other dynamic add. This architecture is very general, with no fundamental restrictions on the wavelengths that can be added or dropped (other than those restrictions imposed by the overall communication system).

The third architecture (Fig. 9) is also bi-directional, but uses only one WSR unit. Circulators are situated on all of the physical input/output ports, allowing for two-way optical propagation. This design has the restriction that at each of the add/drop ports, the add and drop wavelengths must be the same.

Free-Space Optical Embodiments

One embodiment of the present invention is shown in Figure 10. The input/output consists of a linear array of fiber collimators. Such collimators are well known in the art and are comprised of a collimating lens and ferrule-mounted fiber packaged together in a mechanically rigid stainless steel or glass tube (e.g., see collimators made by ADC Photonics, Inc., Minneapolis, MN, www.adc.com). The collimators can be positioned in a linear array by, for example, means of a V-groove array made out of any of a variety of materials including silicon, plastic, or ceramic. The top collimator is designated the input, the second collimator is designated the pass-through, and the remaining collimators are designated as drop ports.

Multi-wavelength light from the input collimator is directed to a ruled diffraction grating. The grating separates the different wavelength channels into different diffraction angles.

In the preferred embodiment, -1 order diffraction is assumed. A focusing lens receives the diffracted light and focuses it onto a linear micromirror array positioned in the back focal plane. The lens has the property that it brings the different wavelength channels to focus at separate spatial locations such that each channel is associated with a unique focused spot. Each wavelength channel is associated with a single mirror in the micromirror array. Figure 10 illustrates only three wavelengths for simplicity. Figure 11 shows a close-up view of the micromirror array, with each of the three wavelengths falling on its respective mirror.

Each of the mirrors in the micromirror array reflects its associated wavelength channel back through the focusing lens, to the grating, and back towards one of output ports. This requires the micromirrors to be dynamically adjustable with at least one axis of rotation. The rotational motion should be under analog control, so that the angles can be continuous adjusted to scan across all possible output collimator ports. Various types of micromachined mirrors and deflectors exist in the art. One prior art implementation is shown here in Figure 12. This is an array of reflective ribbons, the position of each ribbon being under electrostatic control (made by Silicon Light Machines, Inc., Sunnyvale, CA). An adaptation of such a ribbon array can be used in the present invention to provide the micromirror function, with each ribbon in the array acting as a separately controllable mirror.

In the preferred embodiment, the grating is placed in the front focal plane of the focusing lens, thereby producing a telecentric optical system. A telecentric system has the property that the chief rays of the focused beams are all parallel to each other and generally parallel to the optical axis. In this application, the telecentric design allows the reflected beams to efficiently couple back into the output collimators, with little translational walk-off error (perpendicular to the vertical collimator array plane). A quarter wave plate is placed in front of the focusing lens to provide the desired polarization properties as discussed in Ref. 1 (namely minimal PDL and PMD).

By controlling independently the angle of each micromirror, the system has the ability to direct each wavelength channel to any of the outputs (pass-through or drop). The presence of multiple drops ports allows for the possibility of putting only one wavelength on one drop port, thereby avoiding the additional demultiplexing (and the associated cost and complexity) that would otherwise be required with the prior art device of Figures 5 and 6. Feedback control of the mirror positions makes the system stable. More detail regarding the control system is provided in the following sections. This system can readily scale to large channel count by simply adding more mirrors to the mirror array.

The results of an optical ray trace model are shown in Figures 13-15. The collimated beam diameter is approximately 1 mm. The angle of incidence on the grating is 85 degrees, and the grating spatial frequency is 700 lines/mm. The grating is blazed to optimize the –1 order diffraction efficiency. An f=30 mm ideal focusing lens captures the diffracted light and focuses it to the micromirror plane (denoted as the spatial light modulator (SLM) plane in Figures 13-15). In this model, the grating is not placed in the front focal plane of the focusing lens, so this configuration does not represent the

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