♦ Wavelength Selective Switching for Optical Bandwidth Management

David T. Neilson, Christopher R. Doerr, Dan M. Marom, Roland Ryf, and Mark P. Earnshaw

Optical transport capacities have grown significantly in the last decade to meet the increased demands on communications networks. This growth has been achieved both by increases in individual channel rates, which are based on time division multiplexing (TDM), and by increased channel counts, through the use of dense wavelength division multiplexing (DWDM). Yet increasing optical transport capacity alone is insufficient to scale the network; the underlying data needs to be delivered from numerous geographically diverse originating locations to similarly diverse terminating locations, requiring increasing switching capacity to facilitate this networking need. Since the growth in the individual TDM channel rates is driven by the capabilities of electronics, it is reasonable to expect that the switching capacity of electronics will tend to track this trend, although because of the challenges in high data rate interconnects it is unlikely to exceed it. This leaves the challenge of managing the increased bandwidth attained through the use of DWDM. Management of this bandwidth in the optical layer is an attractive proposition if eliminating unnecessary high-speed electronics in the path of an optical signal can reduce the complexity of the network and the associated equipment costs. These optical bandwidth management elements are classified according to the degree of switching, as either reconfigurable optical add/drop multiplexers (ROADM) or wavelength selective cross-connects (WSXC), analogous to the add/drop multiplexers and digital cross-connects of the TDM domain. We generalize these elements and describe whether the switching provides functions that are multicolored, colorless, or colored, and whether the channels are fixed data rate or rateless. We review the wavelength selective switch (WSS) components that perform the necessary switching function and present two successful technology platforms that can be used to construct them: planar lightwave circuits (PLC) and micro-electro-mechanical systems (MEMS). We also discuss future directions for WSS technologies and device functionality to more flexibly manage bandwidth in the optical layer. © 2006 Lucent Technologies Inc.

Bell Labs Technical Journal 11(2), 105–128 (2006) © 2006 Lucent Technologies Inc. Published by Wiley Periodicals, Inc. Published online in Wiley InterScience (www.interscience.wiley.com). • DOI: 10.1002/bltj.20164

Introduction

Dense wavelength division multiplexing (DWDM) has provided greatly enhanced data transport capacity on a single fiber, with today's state-of-the-art systems capable of carrying multiple terabits per second. The economic basis behind DWDM is the sharing of the fiber resources, components, and optical amplifiers across many time domain multiplexed (TDM) channels. Innovations in optical transport systems, including the addition of Raman amplification as a way of achieving distributed amplification inside the fiber itself, has greatly increased the reach of these systems to thousands of kilometers in terrestrial systems.

The increased capacity and reach of optical transport systems now poses a challenge to efficiently utilize and manage the diverse data flows that must be carried in a real network. In general, a network supports a set of data paths having unique ingress points, transmission routes, and egress points distributed across the network. Typically there are more data paths with shorter length than longer length, which is merely a manifestation of Rent's rule for interconnection lengths [12] applied to the networking domain, and has been observed in real synchronous digital hierarchy (SDH) networks [63]. While some networks appear to have a lower bound to the link length, this is an artifact of the divisions between the classifications of networks as access, metro, regional, or long haul. If the collection of networks is treated as a single network, then a monotonically increasing number of links with decreasing link length would be seen. This distribution in data path lengths poses a dilemma: to take advantage of DWDM we need to aggregate as many of these paths on a fiber as possible; to take advantage of the reach we want to go as far as possible between optical to electronic to optical (OEO) regeneration sites where data can be aggregated and disaggregated form the DWDM system. This dilemma can be resolved by providing the capability to aggregate and disaggregate data paths in the optical domain, allowing the remaining data paths to continue in the optical domain as far as required or practical. This function, referred to as wavelength add-drop (WAD) or optical add-drop multiplexing (OADM), has been considered for some time, though initially it was little more than a set of optical demultiplexers and multiplexers with a fiber patch panel between them. Today greater functionality and performance is expected of the OADM in support of higher networking hierarchy layers, including the ability to provide remote provisioning, protection and restoration functions. This added flexibility is referred to as reconfigurable optical add-drop multiplexing (ROADM). These reconfigurable devices have performance enhancements necessary for meeting the physical layer requirements, such as wide, flat pass bands to ensure maximal bandwidth utilization of the optical system. In addition, ROADMs typically incorporate dynamic capabilities [70] such as providing power equalizations to improve system optical signal to noise ratio (OSNR) and maximize reach. The transition from an optically amplified line system with optical to electrical to optical (OEO)-based add-drop multiplexing (ADM), to the use of reconfigurable optical add-drop multiplexing (ROADM) with transparent transport and ultimately to transparent networking using wavelength selective cross connects (WSXC) is illustrated in **Figure 1**.

Panel 1. Abbreviations, Acronyms, and Terms

ADM—Add-drop multiplexing
AR—Anti-reflection
AWG—Arrayed waveguide grating
CMOS—Complementary metal oxide semiconductor
DWDM—Dense wavelength division multiplexing
MEMS—Micro-Electro-Mechanical Systems
OADM—Optical add-drop multiplexing
OEO—Optical to electronic to optical
OSNR—Optical signal-to-noise ratio
PHASAR—Phased-array
PLC—Planar light wave circuits
ROADM—Reconfigurable optical add/drop multiplexer
SDH—Synchronous digital hierarchy
TDM—Time-division multiplexing
TPA—Two-photon absorption
WAD—Wavelength add-drop multiplexing
WDM—Wavelength division multiplexing
WGR—Waveguide grating router
WSS—Wavelength selective switch
WSXC—Wavelength selective cross-connect

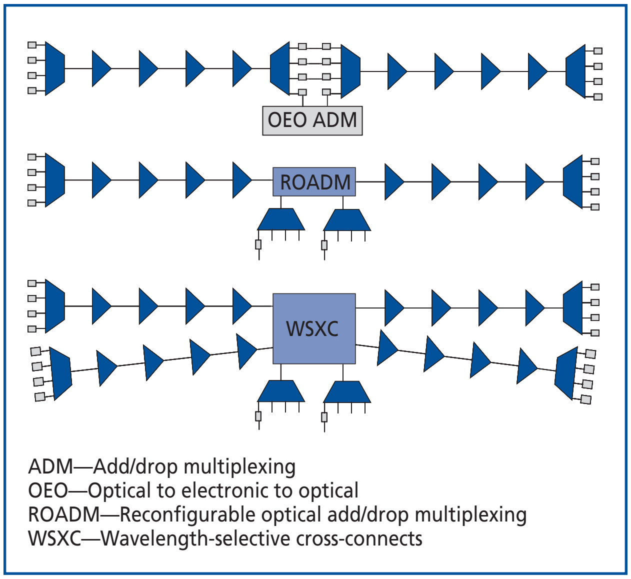


Figure 1.
Evolution of optical line systems.

In the simple picture of a line system with add-drop nodes, all added and dropped traffic goes to OEO interfaces, which are local to the add-drop node. However it is unlikely that traffic truly terminates at these nodes, rather it may enter some other optical transport system. In the same way that the OEO was eliminated in the primary transport path by using a ROADM, the OEO at the drop and the add sites might also be eliminated allowing the optical system to be extended.

Figure 1 also illustrates that there can be multiple branches at a node and multiple branching nodes on a system. Now that traffic between multiple line systems is being managed in the optical domain, the function that is required at the nodes is that of providing a wavelength selective cross-connect (WSXC).

In this paper, we describe in detail the functions that ROADM and WSXC nodes play in bandwidth management. We describe how a basic building block for these devices is the wavelength selective switch (WSS), though it comes in many functional forms and can be constructed with a variety of technologies. We focus on detailed implementations based on free space optics coupled with switching using micro mirror arrays, and on integrated optics using planar lightwave circuits (PLC), which have been most successful to date in demonstrating this functionality. We describe the subsystems that have been demonstrated in the different technologies and highlight the advantages and limitations of each technology. Finally we discuss the prospect for future wavelength switches that could enable packet-based functionality.

Optical Bandwidth Management

We should first consider the granularity of the switching that can be performed in the optical domain. The basic unit of bandwidth is the TDM data rate (e.g., 2.5 Gb/s, 10 Gb/s or 40 Gb/s) modulated on each of the carrier wavelengths corresponding to each of the DWDM channels. While it is possible to switch integer multiples of this bandwidth as a single entity using a banded approach, the flexibility to switch channels individually provides the greatest bandwidth management flexibility and capability. These functions need to be provided in a fashion that is as transparent as possible to minimize the impact on the physical layer performance of the optical system in terms of distorting the data stream due to limitations in the shape or flatness of the data pass band or due to degrading the optical signal-to-noise ratio (OSNR), which might negate the reach of the transport system and therefore the justification for managing bandwidth in the optical domain.

Wavelength selective switches (WSS) are transparent optical subsystems, which can switch single wavelength channels or wavelength bands between multiple ports. A wavelength selective switch, shown schematically in **Figure 2** is a subsystem containing some means of separating or demultiplexing the wavelength channels at the ingress ports, some kind of optical switch fabric and means of recombining or multiplexing some or all of the wavelengths into one or more egress ports, following the switching function. The switch fabric can have a variety of levels of connectivity and also may have input and output ports which are not multiplexed. There is no wavelength conversion or OEO inside a WSS, so the switch is optically transparent for the photons carrying the data. The switch fabric can also have add and drop ports which are not connected to the multiplexers. The number and type of ports determine the type of

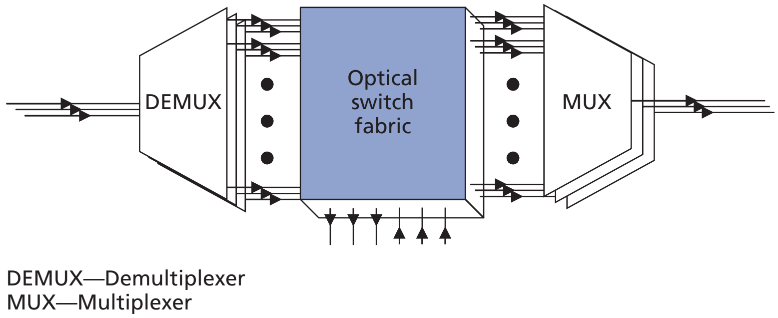


Figure 2.
Schematic of a generalized wavelength selective switch.

switching function and network functionality supported. Since the physical fiber ports on a WSS can have different capabilities, we will primarily characterize the WSS by the connectivity degree of the switching elements, which is equivalent to the potential number of network paths (K), which may be interconnected by the device.

In a transparent switching environment care must be taken in defining the number of ports and the functionality that each port supports. In this paper we will consider three types of ports: colored, colorless and multicolored. A colored port is one in which the wavelength channel of the light that can enter or leave it is predefined and has one unique value. A colorless port is one in which the wavelength channel of the light that can enter or leave it can be varied remotely but can only have one unique value at a time. A multicolored port is one which can support multiple wavelength channels of light that enter or leave it, and the wavelengths can be varied by the switching function of the device. In the following, we will use the parameter K to describe the degree of the switch and the parameter N to define the number of channels in the underlying DWDM system. The number of physical ports will depend on the degree of the switch and whether the ports are colored, colorless, or multicolored and logically could be in the range of one to the product of K and N.

Of particular interest is the $1 \times K$ WSS, which is shown schematically in **Figure 3** and comprises a single demultiplexer and a switch fabric, which consists of N units of conventional $1 \times K$ switches (one per wavelength). There are K multiplexers attached to the output ports of the switches. The $1 \times K$ or alternatively

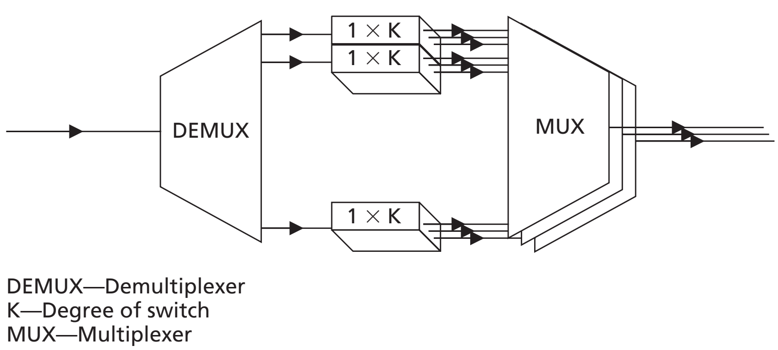


Figure 3.
1 × K wavelength selective switch.

the reverse K × 1 port arrangement is more attractive than the more generalized K × K WSXC since it maintains robustness to failures. This is often referred to as "east-west separable" functionality and it will be discussed in later sections.

WSS are typically designed for a fixed wavelength channel plan; with a given channel's spacing and passband requirements derived from the intended maximum transmission rates. Since the lifetime of optical network equipment can exceed 10 years, and development and adoption of new transmission formats and data rates is difficult to predict over such a time scale, a rateless WSS, with programmable bandwidth and channel plan could be of great interest since it would allow support for different data rates without having to sacrifice spectral efficiency and non uniformly spaced channels. **Figure 4** provides a view of both conventional and high-resolution wavelength selective switches. Figure 4a shows the principle of conventional resolution WSS, with one channel per mirror. Support for different data rates by utilizing a high-resolution WSS is illustrated in Figure 4b, and non-uniformly spaced channels are shown in Figure 4c. Each switching element of channel bandwidth is shown. In the conventional device (top) there is one switching element per predefined channel. Flexible bandwidth is typically achieved by combining contiguous WDM channels into single and wider channels [9, 58, 59].

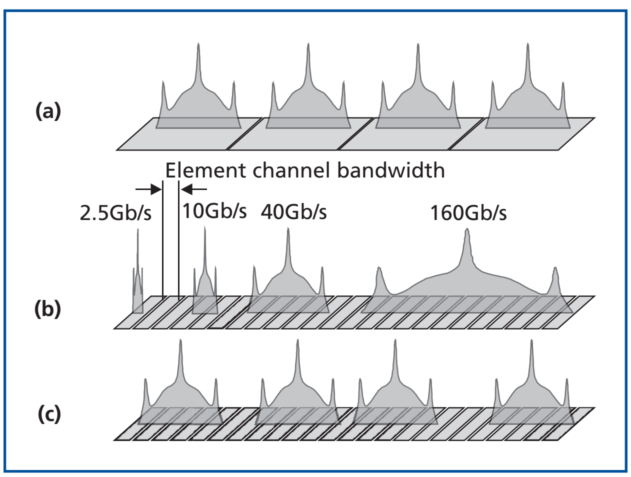


Figure 4.
Conventional and high-resolution wavelength selective switches.

For example, one could use two channels of a WSS with 50 GHz channel spacing and combine or bundle them to provide a 100 GHz wide channel, capable of supporting higher data rates [58]; however, even greater flexibility can be achieved if the presented channel bundling is combined with a WSS, which has very high spectral resolution [9]. This requires control of the phase and amplitude of the edge of the passband so the adjacent channels can be added coherently in phase. For the MEMS WSS for instance, the micromirror corresponding to the adjacent channels would have to be aligned so that they would appear as a single wider mirror. Although most WSS are not currently intended to provide this capability, many devices implemented using MEMS, liquid crystal, or PLC technology would actually support it. A drawback of the high resolution WSS approach is that the physical size of such a switch will be larger than a WSS meeting the system requirements at deployment.

Reconfigurable Optical Add/Drop Multiplexer (ROADM)

The ROADM is a device that can selectively drop channels from and add channels to a WDM system, while allowing the remaining channels to continue in the optical domain without the need for OEO regeneration. The traffic on one side of the ROADM node has to be independent of the traffic on the other, or "east-west separable," to ensure protection of traffic. This requires that the elements forming the system that manages traffic coming from or going towards a given direction (for example east) must be capable of continuing to function if the other direction (west) fails or if it is being replaced or undergoing maintenance. This allows a node at an add-drop site to maintain a connection to the network even if one of the fiber pairs to it is cut or part of the add-drop multiplexer fails. The practical consequence of this is that the add and the drop functions for a given path in the network cannot be performed using the same device nor can they even reside on the same circuit pack. However, the add for one path and the drop for a different path can be on the same device and/or circuit pack. The separation typically occurs in the ROADM at the through (THRU) channels point illustrated in **Figure 5**, where the boxes indicate the separation of

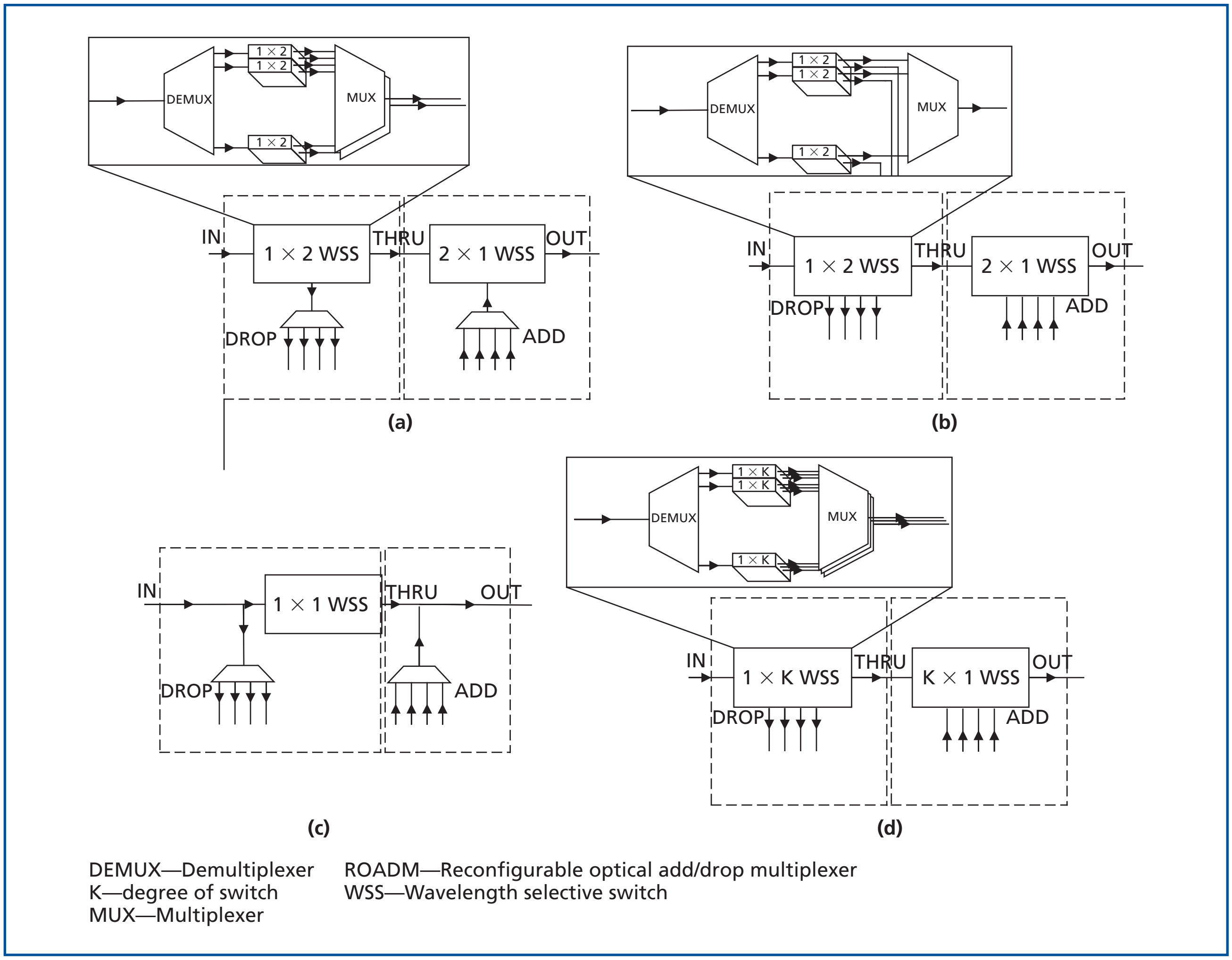


Figure 5.
ROADM configurations for producing drop and add ports.

the add and drop functions to allow for east-west separation.

Before adding new traffic to the line system, we must ensure that the selected DWDM channel bandwidth is clear. The drop function must sufficiently extinguish the data to avoid coherent cross talk penalty [27]. An extinction ratio of >35 dB is typically required for this function, to account for power diversity in the signal levels.

Since the drop function selects which channels go to the drop port and which go to the through port, the most obvious configuration for implementing the ROADM is that of the 1 × 2 WSS. Thus, the switch will independently route each of the incoming wavelength channels to one of the output ports. Similarly, for the add function, where the selection is between the through port and the add port, a 2 × 1 WSS switch could be used. This architecture has the attractive feature that both 1 × 2 WSS and 2 × 1 WSS contribute to the extinction of the dropped channels on the through path. If the intention is to add and drop multiple channels per node, a mechanism to demultiplex and multiplex the channels is required. Again the straightforward addition of a multiplexer to the add and drop ports leads to the system illustrated in Figure 5a. While the output from the 1×2 switch is a multicolored port capable of supporting any wavelength in the system, the outputs of the demultiplexer are colored ports which require that either receivers be prepositioned for each wavelength which may be dropped, or a new receiver must be physically added at the time of reconfiguration. A similar argument holds for the transmitting lasers for the add ports.

The basic way of building a ROADM outlined above may be modified to incorporate different functionality and technology capabilities. A first step is to realize that the WSS contain demultiplexers and there is generally a point, after the 1×2 switching in them, at which the demultipexed light could be coupled out. This leads to the elimination of the separate multiplexer and demultiplexer as illustrated in Figure 5b. This brings advantage in reducing the number of components required and reduces the loss in the drop path. However it removes the capability to make an incrementally scalable demultiplexer or to use a common amplifier to overcome the loss of all the dropped channels. Another alternative, as shown in Figure 5c, is to replace the 1×2 drop switch with a power splitter and utilize a 1×1 WSS, which is often called a wavelength blocker, since light either comes out of its single output port or is internally blocked. The dropped signal in this case actually contains a copy of all the channels in the system including the through channels. Only ports of the demultiplexer that have receivers represent dropped data channels and the 1×1 WSS is configured to block those channels from the through path. There is also the option, by not blocking a dropped channel, of being able to provide a multicast, also called "optical drop and continue" function, useful in applications like video distribution. The add function can be achieved using a multiplexer and a power combiner to bring together the through channels and the add channels. This provides the same equivalent network function as two 1×2 WSS while requiring only a single 1×1 WSS. This is attractive since the 1×1 switch is often considerably easier to build than the 1×2 WSS, as it is has only two fiber connections and is engineered to have only one low loss state. One disadvantage is that only one device, the 1×1 WSS, provides isolation, which necessitates higher extinction characteristics. There are of course other variants than those shown in Figure 5 for using 1×2 WSS for drop and power combiners for add, or power splitters for drop and 2×1 WSS for blocking and add.

One of the major limitations of these approaches is that the ports of the demultiplexer, which are attached to the receivers, have a fixed wavelength assignment and are colored ports. This significantly reduces the flexibility and ability to remotely reconfigure and manage the bandwidth in the network, as dropped channels can be received only if a receiver is physically connected to the specific channel. This implies that for flexibility in remote management, many more receivers need to be deployed than would be used at any given time. The ability to drop any wavelength to any receiver would eliminate this inefficiency. While this could be achieved by placing an optical cross-connect at the output of the demultiplexer, which would create colorless ports, there is an alternative approach using higher port-count WSSs.

If instead of using 1×2 WSS for dropping channels a $1 \times K$ WSS is used, as shown in Figure 5d, then $K - 1$ drop ports can be supported (with one port reserved for through traffic). These K ports are multicolored and can have any or all wavelengths dropped to them. In the case of a ROADM, we would generally consider dropping only a single optical channel for ports that are subsequently attached to a receiver, as receivers are typically wavelength insensitive. With this configuration there is no preset assignment of wavelength channels, providing much more flexibility around which channels to drop. The add path can use a similar switch or may use power combiners. There is an additional requirement on the transmitters that they have tunable lasers to take full advantage of the flexibility offered. Initially, a concern with this approach might be that building a WSS with as many ports as the number of channels in the system would be impractical ($K = N$). This architecture assumption originates from ROADMs with colored ports, where the need to be able to drop any channel equates to the requirement to drop all channels and a number of ports equal to N. However, once the flexibility to drop any channel at any port is available, it is no longer necessary to have a WSS with K = N: if we envision dropping all the traffic at an add-drop, then it would probably make more sense to terminate the line system at the node. It is reasonable to assume that the realistic drop fraction is <50% and probably much lower. This approach can also be made scalable by attaching additional WSSs to the ports of the first WSS to act as reconfigurable demultiplexers, or by adding the fixed demultiplexer of the conventional ROADM scheme to one of the ports so that both fixed and flexible ports are available.

The flexibility to put any wavelength on any port adds an additional constraint that the switching function may need to be hitless. By this we mean that in the process of reconfiguring the switch state of a particular channel, that signal must not appear on another intermediate port, which could be carrying live traffic. The importance of hitless switching and methods of implementing it will be discussed further in the sections on WSXC and WSS technology.

Wavelength Selective Cross Connects WSXC

A wavelength selective cross-connect (WSXC) can be thought of as an extension of the functionality of a ROADM in an optical mesh network. Whereas with the ROADM, channels are added and dropped from a single line system for OEO conversion, in the WSXC channels are routed in a transparent fashion from one or more line systems and added to one or more line systems. The term "degree," is often used, the degree being the number of outgoing (or ingoing) paths connected to the node. A ROADM is a degree 2 node, and a WSXC node is a degree D node, where D > 2. Typically a WSXC node would also be expected to provide the same local add-drop functionality as a ROADM, although strictly this is a hybrid WSXC and ROADM function. We will first consider the case of cross-connect and then the local add-drop function.

The most obvious way of constructing this functionality with D = K + 1 line systems converging on a network node that we wish to cross-connect, is to use a 1 × K WSS in each line system to distribute the incoming traffic to K output ports corresponding to the K destination line systems. A K × 1 WSS can then be used in each outbound line system to accept traffic from the one port of each of the K dropping WSS as illustrated in **Figure 6**.

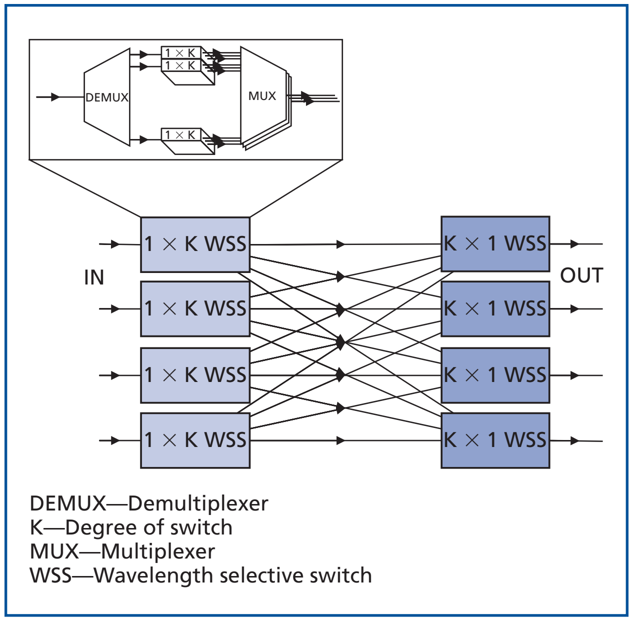


Figure 6.
Wavelength selective crossconnect.

As with the ROADM, there are several alternate ways of implementing this. One method analogous to the blocker arrangement of the ROADM is to use a 1:K power splitter to distribute the light to an array of 1 × 1 WSSs or blockers, and then use K:1 power combiners to add the traffic to the outgoing paths. While in the ROADM case the use of blockers reduced the number of active components, in the case of the WSXC it tends to increase them. The blocker approach for WSXC requires K^2 devices versus the 2K devices of the 1 × K WSS approach. An additional concern is the accumulated loss from the 1:K power splitters and combiners as the number of ports increases. An alternative is to replace either the K × 1 or the 1 × K WSS with a power combiner/splitter to reduce the complexity. Introducing a power combiner requires that the switch be hitless to avoid adding interfering data channels to other paths during switching. If the distribution 1 × K WSS is replaced with a 1:K splitter then the K × 1 WSS may not need to be hitless as it cannot create an interfering data channel present in the line system. However, if a hitless technology is not used, the desired path may still experience transient hits related to the channel being switched during the switching cycle.

The functionality of a ROADM can be added to the WSXC by increasing the number of ports on the WSS or power splitters. Adding one extra port permits a single multicolored local add or drop port, which could be connected to a fixed demultiplexer or another WSS to act as a reconfigurable demultiplexer with multicolored ports. If multiple ports are added, then multicolored port ROADM functionality can be provided directly.

WSS Technologies

As is illustrated in Figure 2 and Figure 3, a wavelength selective switch (WSS) performs demultiplexing, switching and multiplexing. In this section we will describe some of the technology approaches which are attractive for building WSSs. Typically, since we wish to manage a large number of channels simultaneously, the demultiplexer is implemented using a grating: This can either be a planar waveguide grating like an arrayed waveguide grating (AWG) (also called a waveguide grating router (WGR) or phased-array (PHASAR)) [13, 60, 67] or a free space system with a ruled or holographic diffraction grating. Both of these approaches will be discussed further in subsequent sections. While there are many switching technologies that can produce wavelength blockers (1×1 WSS) and even 1×2 WSSs, we are primarily interested in being able to make large arrays of switches with $1 \times K$ functionality and this requires an approach which can be highly integrated. Integration can be achieved using either high-dimensional switching for each switch element as with a MEMS tilt mirror or the cascading of multiple 1×2 switches as with silica PLC waveguide approaches.

The spectral characteristics, such as the passband and stopband, are of fundamental importance for capacity and transmission performance in optical networks. The optical passband of a device is defined as the frequency range within which the transmissivity changes less than a specified ratio. The passband defines the bandwidth available for data transmission on that channel and is critical to achieving the desired performance in an optical line system. If a certain type of device, such as a wavelength add-drop multiplexer, has to be traversed multiple times during signal transmission, then maximizing the flatness of the top of the passband becomes more important. The phase component of the transfer function is also important since it can induce dispersion in the data signal. The passband is typically a function of the spectral resolution of the demultiplexer but it may also be limited by the switching element and interactions between spectrally adjacent switching elements. Devices with higher spectral resolution can typically achieve wider flatter amplitude passbands but are physically larger and more susceptible to imperfections such as mirror curvature [46] or phase errors that induce loss and dispersion.

Free Space WSS Systems

In this section, we focus on WSSs that have multiplexers and demultiplexers that are integrated in the free space section of the switch. The multiplexing is achieved by a diffraction grating, and we present the typical configuration of a free space grating-based demultiplexer and its properties.

An example configuration [44] for grating-based wavelength selective switches is shown in **Figure 7**. The free space $1 \times K$ WSS design is based on two major subassemblies. The first subassembly is used to spatially overlap the beams from the individual input and output fibers to allow for switching between multiple ports; the second is used to spectrally resolve the channels and introduce the wavelength selectivity. The role of the first subassembly is to image the input and K output optical fiber end faces onto an angular multiplexed common magnified spot. This subassembly converts the distinct spatial locations of the fibers to unique angular propagation directions. The second subassembly introduces the desired wavelength-selectivity property with the use of a diffraction grating. It spatially disperses the input-magnified common spot, consisting of the N WDM channels, onto a liquid crystal or MEMS micromirror array such that each channel is imaged upon a separate pixel or mirror (or set of) in the

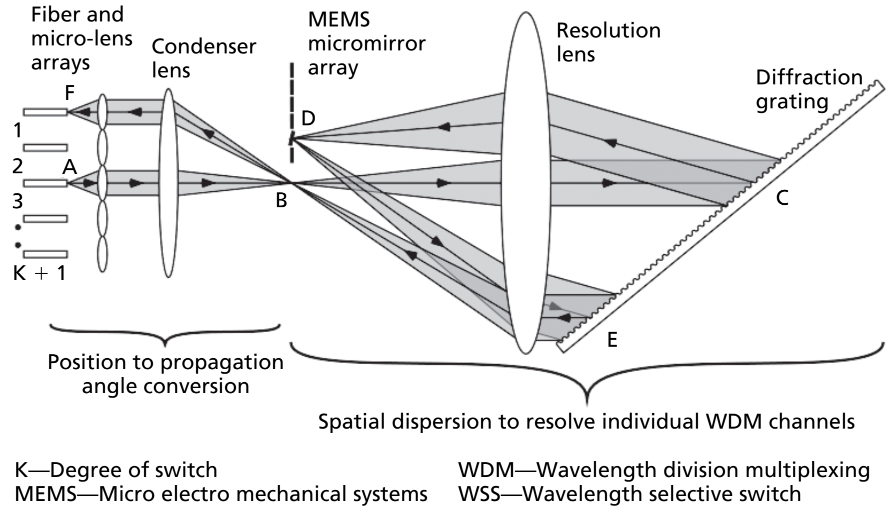


Figure 7.
WSS optical system configuration.

array for independent addressing using the imaging optics represented by the resolution lens. For the case of one micromirror per channel each micromirror in the array is tilted to a desired angle, which subsequently determines the output fiber to which the reflected light will couple upon imaging back to the fiber array, on a per channel basis. The first subassembly determines the optical beam magnification ratio, the fiber array layout, and the required mirror tilts to reach each output fiber. The second subassembly determines the amount of spatial dispersion for separating the WDM channels and obtaining the necessary passband width.

The optical subassembly responsible for imaging the optical fiber end faces onto a common magnified spot is comprised of a fiber array, a matching microlens array, and a condenser lens whose aperture subtends all the beam apertures from the fibers. The fiber array consists of K + 1 fibers, where one fiber is assigned to carry the input signal and the remaining K fibers are the output fibers. The microlens array and fibers are coaxially aligned and result in collimated beams arranged in a one-dimensional array to accommodate mirrors with a single tilt axis. Gaps are introduced between some of the lens apertures to allow for the variable attenuation feature without giving rise to crosstalk [44]. The condenser lens focuses the K + 1 collimated beams at its back focal plane, where the beams are superimposed and differentiated only in propagation direction. The optical arrangement of the first subassembly implements a telescopic imaging system of the fiber modes via the lenses from the microlens array and the condenser lens. The imaging operation magnifies the optical beam emerging from the single mode fiber by the ratio of the condenser lens to the microlens focal lengths. For the 1×1 WSS there is the possibility of using only one fiber with an optical circulator. If the unity magnification of the fiber mode size is acceptable then no additional optics are required for this stage [51].

The second optical subassembly spatially disperses the magnified mode that was generated by the first subassembly and images it on the micromirror array. Its design is similar to a spectrometer with a Littrow mounted diffraction grating. A single lens collimates the light that is then incident on the grating. The diffracted light, which is propagating back towards the lens and is angularly dispersed, is imaged by the same lens onto the micromirror array. As is well known from classical spectrography, the spectral resolution of the instrument increases with increasing focal length and grating frequency, and with decreasing input slit size. In our switch, the magnified mode size is equivalent to a spectrograph slit size. Our analysis shows that the spectral performance of the free space WSS is directly related to the dimensionless ratio ξ, which is defined as the ratio of MEMS micromirror size to the magnified spot mode size. All of the optical system parameters of the WSS contribute to this dimensionless ratio: The focal lengths of the lenses, the grating frequency and the fiber mode. The ratio measures how well the Gaussian mode is confined within the micromirror, and will be shown to determine the passband performance. The channel passband performance of the WSS is derived by solving the frequency-dependent, power-coupling efficiency integral. Using some simplifying assumptions, which are satisfied in most cases of interest for example micromirror size nearly equal to channel spacing (mirror array with 100% fill-factor); the coupling efficiency is defined by

$$\eta(\nu) = \frac{1}{4}\left\{\operatorname{erf}\left[\sqrt{2}\xi\left(1 - \frac{2\nu}{\nu_{ch}}\right)\right] + \operatorname{erf}\left[\sqrt{2}\xi\left(1 + \frac{2\nu}{\nu_{ch}}\right)\right]\right\}^2 \qquad (1)$$

where ν is the temporal frequency variable, ν_{ch} is the DWDM channel separation, and erf is the error function. The frequency-dependent coupling efficiency can be plotted for various values of the ratio ξ. **Figure 8** displays calculated passbands showing

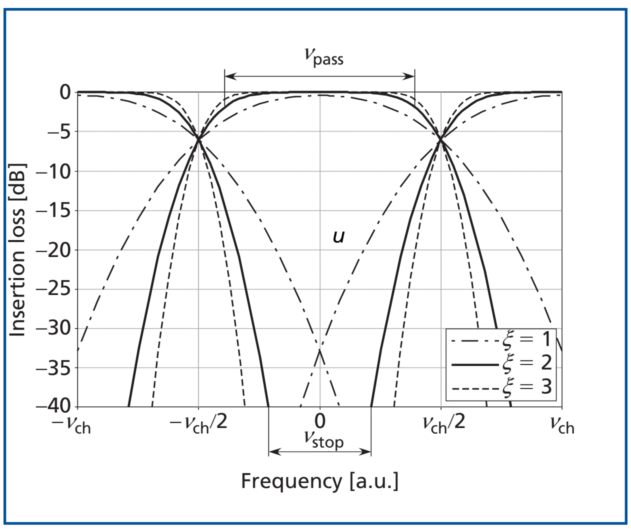


Figure 8.
Calculated passbands for a wavelength selective switch.

insertion loss as a function of the confinement parameter ξ which is the ratio of mirror size to beam size and ν_{ch} is the channel-to-channel frequency spacing. We assume a 100% fill-factor micromirror array, and the effect of the neighboring mirror is neglected. Thus, passband requirements can be accommodated in the design of the WSS by varying the ratio of the mirror size to the magnified Gaussian mode size, which sets ξ, in fulfillment of the optical transport requirements.

While free space systems can be combined with a variety of switching technologies including liquid crystal for 1 × 1 WSS [2] or 1 × 2 WSS [2, 57, 58], or even higher degree using beam steering, to date MEMS tilting micro mirrors have shown the greatest ability to scale to greater switching degrees (K > 2).

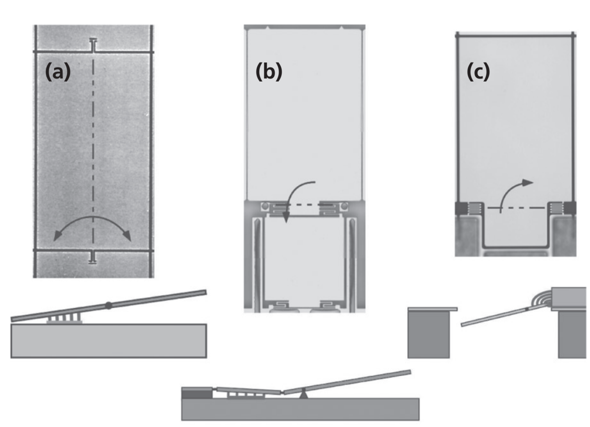
Micro Electro Mechanical Systems

Free space-based WSSs require a linear micromirror array, where each mirror in the array can be independently tilted for the reflected light to couple to the different output ports. Since the mirror has to address multiple states, its control tends to be analog in nature. The micromirror fill-ratio has to be very high, with minimal gaps between mirrors, to maximize the passband widths. This high fill-ratio requirement represents a challenge in the design of the MEMS device. The mirrors need to be supported by a flexure mounting without resulting in mechanical crosstalk. The actuation mechanism, typically electrostatic, must be well shielded to prevent electrical crosstalk. The mirrors must be sufficiently flat to prevent beam and wavefront distortions upon reflection. The reliability of the MEMS device has to be very high, as a mirror failure would render a WDM channel inoperable. Fortunately, research and development in the field of MEMS has matured in the last decade and multiple foundries around the globe can produce micromirror arrays in a variety of materials (typically silicon is chosen), meeting the required specifications for a telecom product.

Each micromirror in the MEMS linear array needs to tilt about one axis when the fiber ports are aligned as a linear array. It would be most desirable, from an optical performance point of view, to have the rotation axis be at the center of the mirror surface and parallel to the dispersion direction. However, due to the high fill-ratio requirement, such a solution is unfeasible. Three different solutions have been pursued to circumvent this difficulty: placement of the rotation axis beneath the mirror surface [72, 75], shifting of the rotation axis to the edge of the mirrors [29, 38, 39], or turning the rotation axis to be orthogonal to the dispersion direction [55]. The first solution requires multilevel processing and hence is more complex to fabricate, in the second solution the rotation will be accompanied by displacement into the plane, and the third solution is more sensitive to both mirror curvature and diffraction off the mirror edge [46, 47]. Having the tilt axis parallel to the dispersion direction is most desirable since it not only provides fewer features in the passband [47], and lower sensitivity to mirror curvature [46], but it also decouples the spot size setting the spectral resolution from the spot size determining the angle required to tilt between ports. This allows for the use of anamorphic optics [44, 48] to increase the number of ports without sacrificing spectral resolution.

To illustrate the second and third types of mirrors, we will discuss micromirrors developed at Bell Laboratories [29, 38, 39, 55] for WSS and shown in **Figure 9**. A mirror utilizing the scheme of changing the axis of rotation to be orthogonal to the dispersion is shown in Figure 9a. This arrangement results in simple torsion spring structures and a balanced mirror, with electrostatic actuation provided by electrodes embedded below the mirror surface. As noted, there are advantages to mirrors with a rotation axis parallel to dispersion direction. This has lead to the development of parallel mirrors of the cantilever support type, with a mirror supported from the edge. An embedded parallel-plate approach electrode beneath the actuator was used with the design is shown in Figure 9b, along with an angle magnification mechanism [38]. This was achieved by separating the actuator plate from the mirror plate, and unequal arm lengths for transferring the motion from the actuator to the mirror. An alternative option to the cantilever design is a novel fringe field actuator [29], shown in Figure 9c. It is created by deposition of a 10-micrometer thick layer of polysilicon in close proximity to the mirror. By charging the polysilicon electrode, the silicon plate moves out of plane due to electrostatic attraction. The fringe field actuation is advantageous in that there is no "pull-in" effect, a known unstable regime in parallel plate actuation.

The MEMS mirror array performance can be characterized in several ways. Of primary importance is the ability of the mirrors to reach the required tilt range at a certain voltage. Mirror A utilizes two electrodes, each disposed at an opposite side of the rotation axis. By applying a voltage to one electrode or the other, the mirror will tilt in one direction or another. Since the mirror utilizes a parallel plate actuation, the tilt angle becomes unstable as the pull-in voltage is reached. The designed operating range for the mirror in Figure 9a was ± 6 degrees. The mirror in Figure 9b also utilizes a single electrode with parallel plate actuation, and the mirror exhibits the pull-in effect, which occurs after the design tilt angle of 6.5 degrees. Mirror C, with fringe field actuation, exhibits saturation in the angle versus voltage curve. Such behavior increases the mirror stability at larger tilt ranges and can achieve 9 degrees of tilt. All mirrors exhibited resonance frequencies higher than 2 kHz, meeting current Telcordia requirements [69].



MEMS—Micro electro mechanical systems

Figure 9.
Electrostatically actuated MEMS mirrors for wavelength selective switches.

Two axis-tilt mirrors have also been developed using placement of the rotation axes beneath the mirror surface [71] and by using a structure similar to Figure 9b with an actuator plate but allowing torsion rotation using two activating electrodes [34]. These allow greater port count as well as the possibility of achieving hitless switching.

Planar Lightwave Circuits

While the term planar lightwave circuit, or PLC, may be applied to a variety of integrated optic material systems, the most prevalent in terms of commercial availability and deployment is that based on silica-on-silicon with waveguides formed in silica patterned on standard silicon wafers. This technology has been widely used, initially for WDM filters, but increasingly for more complex functions including recent commercial deployments of ROADM devices. The main advantages of silica-on-silicon PLCs are the very low propagation loss, the ease of coupling to fiber (no AR coating or complex spot size converter required), the lack of a need for hermetic packaging, and the ability to be mass-produced.

The key attraction of integrated optics has always been reducing component costs. Using wafer-scale processing of many devices simultaneously, the tedious, precision alignment of different optical elements required in bulk optics is unnecessary, replaced by the alignment of only one or two fiber arrays to the waveguides of a chip and the electrical, mechanical and thermal packaging of that chip.

Arrayed Waveguide Grating Filters. The first commercial success of the PLC technology was in providing multiplexing and demultiplexing filters for WDM transmission systems. The basic building block is a so-called arrayed waveguide grating (AWG), shown in **Figure 10**, which is an integrated optic equivalent of a bulk Echelle grating with imaging lenses.

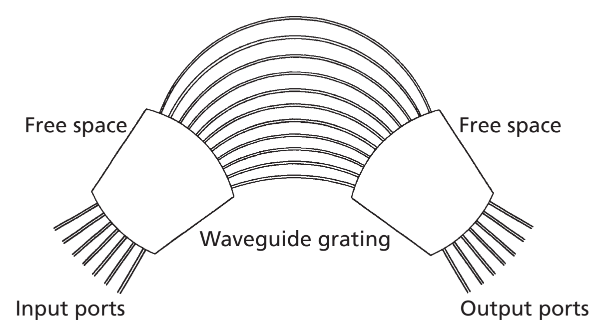


Figure 10.
Arrayed waveguide grating.

The AWG is made from a parallel array of waveguides of monotonically increasing path length. Light is imaged onto the waveguide array from the input waveguides by an input star coupler. Similarly, a second star coupler is used to capture the output of the waveguide array into output waveguides. The path length difference in the array causes the wavefront to tilt in wavelength and so the input beam, after dispersion in the grating array and interference in the output star coupler, is spread across the output waveguides as a function of wavelength.

A typical AWG has a single input waveguide with light of many wavelengths, corresponding to WDM channels. The AWG separates the light at the output plane where the discrete WDM channels are transmitted into individual channelized output waveguides. Thus this basic device provides a WDM demultiplexing function. The device may be operated in reverse to multiplex individual wavelength channels to a single WDM stream. Advances in AWG design have enabled low-loss, flat-top filter designs to be made commercially at low per-channel cost. Currently AWGs are the technology of choice for DWDM filter applications with more than approximately eight channels.

Thermo-Optic Control of Light. The second key building block of PLC technology is an element which can dynamically route light on the circuit. We may wish to switch light between different paths, divide light into a multitude of different paths in different amounts, attenuate a light beam by a certain amount or completely extinguish a light path. These are all functions, which may be performed by thermo-optic Mach-Zehnder interferometer elements [65]. The basic element comprises a Y branch power splitter, a phase shifter in the Mach-Zehnder and a balanced 2×2 coupler. An example design [11] is shown in **Figure 11** where the marked angles represent the

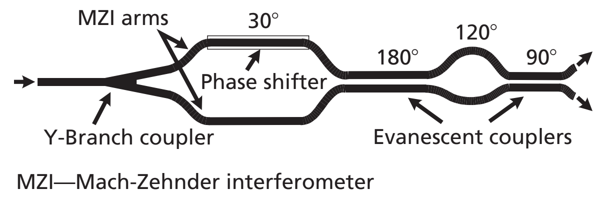


Figure 11.
1 × 2 switch using a thermo-optic Mach-Zehnder interferometer.

accumulated phase difference between the local eigenmodes of a particular section.

The power splitters and combiners may be three- or four-port elements combined in different ways to make attenuator, 1 × 2 switch, 2 × 1 switches or 2 × 2 switch functionalities. As an example, consider a device with four ports: with no power applied and assuming the two Mach-Zehnder arm lengths are equal, light input to the upper input arm will exit from the lower output arm. Once a π phase shift is applied the light will exit from the upper output arm. In a two-port device, the light is coupled to or from the output port to unguided modes as the phase is changed. This device then operates as an attenuator rather than a switch.

While thermo-optic switches are relatively slow, with response times on the order of a millisecond, and need high powers of approximately 300–500 mW [36, 64] to switch each element, they have significant advantages such as very low losses of under 0.25 dB, high isolation of >20 dB and, importantly, the advantage of solid-state reliability. High levels of integration have been demonstrated with 256 switches on a single PLC chip [26]. If greater isolation or extinction is required, then dilated switch architectures can be used.

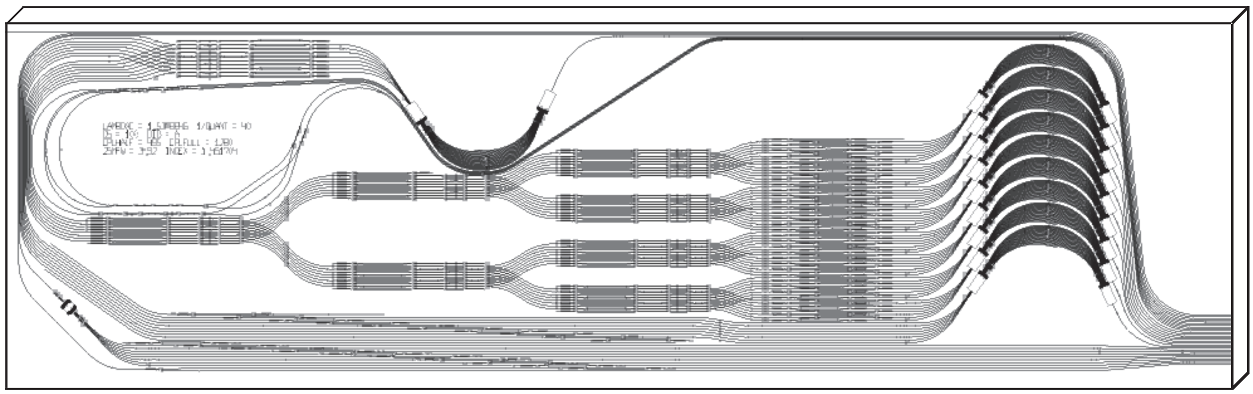
As mentioned earlier, the ability to provide hitless switching is necessary for certain applications in ROADM and WSXC and this can be achieved in PLCs by adding an extra switching stage, which acts as a shutter.

Demonstrated Functionality

A large number of devices and functionalities have been demonstrated on PLCs from basic blockers (1 × 1 WSS) and 2 × 2 WSS [10, 52, 53] to higher port count WSS [11, 16, 66] as well as structures incorporating features of both [4, 17, 19, 20, 26, 53, 62]. A review of a range of devices has been given in [18] and [54]. The first examples of wavelength routing PLC structures were simple 2 × 2 WSS devices demonstrated by Okamoto [52, 53] based on two AWGs and an array of thermo-optic switches similar to the approach illustrated in Figure 5b. It is normally necessary to use two stages of switch elements in series to achieve the necessary isolation performance [28]. Low insertion losses of under 8 dB with high isolation levels better than 40 dB have been shown [18]. These devices reported in the literature are not east-west separated although it is possible to make then separable by splitting the functionality across two separate 1 × 2 WSS and 2 × 1 WSS chips.

Limited mesh connectivity may be added by integrating two further AWGs to the basic structure [53]. However, for more practical mesh networks the degree of connectivity is higher and typical WSS structures are more appropriate. These are constructed from AWG demultiplexers and multiplexers and "trees" of thermo-optic switch arrays to direct the light. The first example was an 8-channel 1 × 9 WSS [11], which has full flexibility to direct wavelengths to operate as a multicolored WSS for use in a fully flexible ROADM. Another example is a 20-channel 1 × 3 WSS targeted at a WSXC node [16]. These two examples illustrate the inherent tradeoffs of the integrated approach in that the available die size and relatively high power consumption of the switches limits the functionality that may be integrated. Of course, advances in reducing power consumption [36, 64] and higher index contrasts [31] continually increase the range of functionality that may be monolithically integrated.

Recent advances have included the addition of some colorless or multicolored add-drop capability to ROADMs with large numbers of channels. The approach of allowing K = N as demonstrated for 8 multicolored ports illustrated in **Figure 12** [11] does not easily scale to larger channel counts. An alternative is to use a cross-bar switch architecture to create colorless ports. This has been shown with the capability to



PLC—Planar light wave circuits
WSS—Wavelength selective switch

Figure 12.
Silica-on-silicon PLC 1 × 9, eight-wavelength WSS.

drop 4 out of 32 channels [4], which is a very limiting number of drop ports. A different structure using two stages of switching to construct an asymmetric cross-connect achieved a 33% drop fraction (8 channels out of 24) [19]. Although the performance of these newer device designs is not yet adequate for practical systems, these are still promising avenues for further research.

Free space optics and MEMS have also been used to demonstrate a large number of devices and functionalities. 2 × 2 WSS [22], blockers (or 1 × 1 WSS) [37, 51], and higher port count WSS [14, 33, 34, 42, 43, 44] have been shown. The first examples of wavelength routing using free space and MEMS were simple 2 × 2 WSS devices demonstrated by Ford [22]. The switch uses free space optical wavelength multiplexing and a column of micromechanical tilt-mirrors to switch 16 channels at 200 GHz spacing. The electrostatically actuated tilt mirrors had a 20 μs switching response. The total fiber-to-fiber insertion loss for the packaged switch is 5 dB for the passed signals and 8 dB for added and dropped signals, with switching contrast of more than 30 dB for all 16 channels and all input and output states.

Wavelength blockers (1 × 1 WSS) were of interest because of the simpler design requirements with only one state with low insertion loss being required. A 64 channel equalization and blocking filter utilizing a free space lens and grating multiplexer with micromechanical tilt mirrors providing variable attenuation was demonstrated in [51]. It achieved a 5 dB insertion loss with a 3 dB passband of 87 GHz for 100 GHz spaced channels. Attenuation range achieved is in excess of 35 dB. Devices [37] with diffractive MEMS [25, 61] have also been demonstrated.

A blocker device with a channel spacing of 13 GHz, is used to demonstrate seamless support of data rates from 2.5 Gb/s to 160 Gb/s by using one to 32 wavelength channels [59]. It showed typically a 1 dB dip between wavelength channels, which generated a negligible penalty. Using MEMS micromirrors for channel bundling offers some unique advantages, particularly if micromirrors with two tilt axes and out-of-plane movement are used. With such an array, in fact it would be possible not only to control the passband shape, but also to control the in band group delay curve, thus opening a realm of new transmission mitigation capability for higher order linear impairments [70].

WSS with 1 × K switching functionality implemented in free space arrangements have been demonstrated with various configurations. The ability of a single WSS to route a record number of WDM channels has been confirmed in a 128-channel count switch, with 4 output ports, operating on 50 GHz channel separation with bandwidth sufficient to support 10 Gb/s data rates [43, 44]. The switch exhibited wide and flat passband widths, in support of core optical networking specifications for cascading switches. Further WSS efforts emphasized 100 GHz channel separation (64-channel counts) with bandwidth support suitable for 40 Gb/s data rates [42, 43]. A 1×2 switch configuration as well as a 4×1 WSS configuration were demonstrated [43] using an identical packaging solution, based on a tubular housing with sufficient degrees of freedom for simple alignment [21, 23, 51, 68]. The increased port count was achieved by the introduction of anamorphic optics [48]. The WSS development effort yielded switches with losses of less than 4 dB with low polarization dependencies, as well as 10 dB dynamic spectral equalization range and blocking capability (loss $>$40 dB). WSS 1×4 switches using reflective optics arrangements have also been demonstrated [14, 33] and qualified for deployment [34]. 1×2 WSS scalable to 1×14 [71] and 1×9 hitless [34] devices, which use two-axis MEMS tilt mirrors to avoid beams crossing output ports during switching and increase port count, have been shown.

Utilizing four 1×4 WSS modules [43, 44], a complete wavelength selective cross-connect has been demonstrated [45] following the architecture of Figure 6 with passive splitters instead of 1×4 WSS. This 4×4 WSXC is capable of handling 64 channels on each of its input ports (total channel count of 256) as well as 40 Gb/s data rates, for a total throughput exceeding 10 Tb/s. Such a modular WSXC architecture is attractive as it can be deployed incrementally, as links are added to the network, and is more robust against failures, as a single WSS module failure does not render the WSXC inoperable for the remaining links.

Systems that incorporate both waveguides and micromechanical devices to provide WSS functionality have been demonstrated [15, 24, 40, 41]. The MEMS mirrors have been used as phase shifters to allow the construction of a 1×2 switch [24]. Alternatively the PLC has been used to replace the conventional grating and fiber coupling optics in free space systems [15, 40, 41]. This combination of PLC and MEMS results in a WSS that is smaller and easier to package than a pure free space WSS. Importantly, it saves one from having to hermetically package a large bulk grating.

Future of Wavelength Selective Switching Devices

The benefits afforded by WSS in the operation and economics of optical networks encourages the development of alternative switching technologies. For these technologies to succeed they must provide either a new functionality or significant improvements in cost, size, performance, or power consumption. We provide a brief survey of alternative technologies for WSS implementation that show promise in these directions.

Silicon Photonic Devices

As previously discussed, silica-on-silicon-based PLC technology offers a robust, guided-wave optics platform for implementation of both active and passive photonic devices. Active switching components implemented using the thermo-optic effect are relatively slow: They require $\approx$1 ms settling time, are high power consuming, and require a minimum spacing between dynamic elements to avoid thermal crosstalk. This, in turn, limits the achievable density of integration. Alternatively MEMS-based micromirror devices can have negligible power consumption and switching times of 20 μs [22], but are typically fabricated in silicon. As recently demonstrated, it is possible to implement a completely integrated, silicon-based $1 \times K$ WSS, where the single silicon substrate is used for both guiding the light and for forming tilting MEMS mirrors [5], but the use of MEMS micromirrors still necessitates high voltage drive electronics, which consumes power and increases cost.

The motivations for using silicon for photonic devices fabrication include the opportunity to co-integrate control electronics, and if they are compatible with a CMOS process, fabricate them in a high volume electronics fabrication facility. The latter brings the process expertise and control from the field of microelectronics and the cost reduction benefits of the high volume such facilities support. Silicon's high index of refraction also supports very small bending radii, allowing for the formation of compact passive photonic devices. Active components can still be based on slow, high power consuming thermo-optic modulation in silicon although electro-optic switching based of field or carrier injection effects can provide faster modulation.

Lithium Niobate Photonic Devices

Lithium niobate ($LiNbO_3$) crystals offer many physical effects that can be used for photonic devices, such as a strong electro-optic effect, piezo-electric effect, and optical nonlinearities. They have been commercially very successful as data modulators using the electro-optic effect, and were instrumental in ushering in 10 Gb/s data rate transmission systems in the 1990s. While the commercial modulators widely used today contain essentially one switch each, larger arrays of switches have also been demonstrated [49]. Since $LiNbO_3$ waveguides are usually made by diffusion, the waveguide bend radii are consequently relatively large, making it difficult to realize the high density AWGs that are required for the demultiplexing function of the WSS devices. One possible solution is hybrid integration of $LiNbO_3$ switches with silica PLCs AWGs, which could represent a path to realizing WSS, which would support packet-switching rates. The coupling for a hybridized silica $LiNbO_3$ PLC device could be easier than a fiber array coupling commonly used for $LiNbO_3$ switch arrays since the waveguide pitch could be reduced and the silica waveguide can provide mode-size conversion functions to make mode matching easier.

Acousto-optic ROADMs have been demonstrated on $LiNbO_3$ [50] by generating an acoustic wave on the surface of $LiNbO_3$ with the use of the piezo-electric effect. The acoustic wave acts like a grating, diffracting the wavelengths in different directions. Acousto-optic switching is relatively fast at $\approx 1\ \mu s$, with relatively low switching power. However, acousto-optic switching frequency-shifts the diffracted light, and the acoustic wave non-linearity threshold is very low (limiting the number of acoustic frequencies that can be added together).

Polymer Photonic Devices

Polymer-based devices provide a wide range of material attributes that can be chemically synthesized and engineered. Furthermore, polymers are easy to process; they can be spin-coated, low-temperature cured, plasma etched, and molded. Demultiplexing and switching functionalities have been demonstrated in thermo optic polymer-based devices [1, 32, 56] and recently commercialized, but long-term reliability remains a concern. Very high bandwidth electro-optic modulation has been demonstrated in polymer devices [3], but they have not matured enough to support the complexity required in fabricating a WSS, even though polymer electro-optics have been worked on for several years now.

III-V Semiconductor Photonic Devices

Devices grown from III-V semiconductor materials on GaAs and InP are widely utilized for photonics devices. Due to their direct bandgap, they can be used for optical amplification and integration with laser sources and detectors. They provide the strong electro-optic effects necessary for compact, efficient modulators and switches. The GaAs material system is generally less expensive than InP but materials grown on it cannot currently provide optical gain at the telecom band around 1550 nm like those grown on InP can. Both ROADMs and WSSs have been demonstrated in InP [6, 7, 8, 30, 35, 49, 74]. The first demonstrated ROADM in InP had 4-channels, consisting of AWGs and switches [49]. The first demonstrated WSS in InP was a 6-channel 2×2 WSS, which was based on two interleave-chirped AWGs connected by a waveguide lens [8]. A 4-channel 2×2 WSS using AWGs and switches [30] has been demonstrated and a 16-channel ROADM was also demonstrated. [7] Blockers and channel selectors have been demonstrated by connecting two AWGs by an array of SOAs [35]. A spatial 9×9 OXC was demonstrated using beam steerers [6]. This concept can be extended to make a WSS by replacing some of the waveguide lenses with waveguide gratings. Fast electro-optic switching in these materials can support a packet-switching WSS, as opposed to the previously described circuit switching WSS. Furthermore, since detectors and amplification can be integrated, losses can be compensated and monitoring schemes can be added onto the WSS.

A serious obstacle for realizing a practical InP WSS is overcoming two-photon absorption (TPA). TPA becomes a problem when significant optical power is launched into an InP waveguide. TPA means two photons are absorbed simultaneously, even though the photon energy is below the crystal bandgap energy. This generates high-energy electrons. These high-energy electrons make the InP more metallic, causing it to absorb even more photons. It usually takes several nanoseconds for the carriers to recombine. TPA can cause inter-channel crosstalk when multiple wavelength channels that are multiplexed together are in an InP device [73]. It is possible to fabricate waveguides on GaAs with bandgaps greater than twice the photon energy, which would reduce the TPA effects significantly, though the lack of a suitable gain material on GaAs for 1550 nm wavelength remains a problem.

Conclusions

Managing bandwidth in the optical layer has been driven by the rapid growth in bandwidth required by the network and made available by the use of DWDM systems, and the fact that electronic-based switching systems have been unable to deliver equivalent switching capacity at reasonable cost and power consumption. ROADMs are currently being deployed in many systems both for ultra long haul and metro applications. WSXCs are nearing deployment as ultra long haul systems are connected to form transparent networks. Various architectural implementations can be utilized to provide the ROADM and WSXC functionality, each leading to specific switching functionality. Subsystem implementations with PLC utilizing thermo-optic modulation, or with free space optics using MEMS micromirrors, and in some hybrid PLC and MEMS configurations have been presented, and emerging technologies reviewed.

As $1 \times K$ WSS gain acceptance and proliferate in the telecom market place, we expect the emphasis will be directed towards three significant aspects of wavelength selective switching technology that we have discussed and that will allow for greater development of optical bandwidth management:

- Increased use of colorless or multicolored ports,
- Increased switching speed to allow packet or fast circuit switching in the optical layer,
- Variable bandwidth channels.

The use of colorless or multicolored ports has not yet been fully exploited in networks. With the increasing deployment of tunable lasers in the network, the flexibility to recolor a port will give significant advantages for reducing operating cost and giving greater reconfigurability to the network. Such reconfigurability on the add and drop paths can resolve network blocking by providing alternate routing paths and support wavelength assignment without the need to resort to wavelength conversion using either OEO conversion or optical regeneration schemes.

The higher switching rate of ROADMs will enable each wavelength channel to carry packetized traffic or for channels to be subdivided in the optical layer into several TDM circuits at lower rates than the channel rate. This overcomes the limitation on current ROADMs and WSXC, which currently can manage traffic only at a wavelength channel granularity, and essentially perform only circuit switching.

Using wavelength-switching elements with variable bandwidth channels allows networks to evolve with new transmission formats and data rates without having to replace in-line hardware. It allows for efficient use of the optical bandwidth while allowing both low and high data rate channels to be managed efficiently in the optical domain.

References

[1] A. Borreman, T. Hoekstra, M. Diemeer, H. Hoekstra, and P. Lambeck, "Polymeric 8 × 8 Digital Optical Switch Matrix," Proc. European Conf. on Optical Communication (ECOC '96), (Oslo, Norway, 1996), vol. 5, paper ThD.3.2, pp. 59–62.

[2] O. Bouevitch, D. Touahri, J. P. Morgan, S. Panteleev, and C. Reimer, "Channel-Power Equalizer and Dynamic Gain Equalizer Based on the Optical Bench Platform," All-Optical Networking: Existing and Emerging Architecture and Applications/Dynamic Enablers of Next-Generation Optical

Communications Systems/Fast Optical Processing in Optical Transmission/VCSEL and Microcavity Lasers, Digest of IEEE/LEOS Summer Topical Meetings, (Quebec, Can., 2002), pp. MD1-4–MD1-5.

[3] D. Chen, H. R. Fetterman, A. Chen, W. H. Steier, L. R. Dalton, W. Wang, and Y. Shi, "Demonstration of 110 GHz Electro-Optic Polymer Modulators," Applied Physics Lett., 70:25 (1997), 3335–3337.

[4] W. Chen, Z. Zhu, Y. J. (R.) Chen, J. Sun, B. Grek, and K. Schmidt, "Monolithically Integrated 32 x Four-Channel Client Reconfigurable Optical Add/Drop Multiplexer on Planar Lightwave Circuit," IEEE Photonics Technol. Lett., 15:10 (2003), 1413–1415.

[5] C.-H. Chi, J.-C. Tsai, M.-C. M. Lee, D. Hah, and M. C. Wu, "Integrated 1 × 4 Wavelength-Selective Switch with On-Chip MEMS Micromirrors," Proc. Quantum Electronics and Laser Science Conf. (QELS '05), (Baltimore, MD, 2005), vol. 3, paper JThE58, pp. 1732–1734.

[6] C. R. Doerr, "Planar Lightwave Devices for WDM," Optical Fiber Telecommunications, Vol. IVA, (I. P. Kaminow and T. Li, eds.), Academic Press, San Diego, CA, 2002, pp. 405–476.

[7] C. R. Doerr, C. H. Joyner, and L. W. Stulz, "Programmable 16-Channel Add/Drop Using an Interleave-Chirped Waveguide Grating Router," Proc. Integrated Photonics Research Conf., (Victoria, BC, Can, 1998), paper PD1.

[8] C. R. Doerr, C. H. Joyner, L. W. Stulz, and R. Monnard, "Wavelength-Division Multiplexing Cross Connect in InP," IEEE Photonics Technol. Lett., 10:1 (1998), 117–119.

[9] C. R. Doerr, L. W. Stulz, M. Cappuzzo, L. Gomez, A. Paunescu, E. Laskowski, S. Chandrasekhar, and L. Buhl, "2 × 2 Wavelength-Selective Cross Connect Capable of Switching 128 Channels in Sets of Eight," IEEE Photonics Technol. Lett., 14:3 (2002), 387–389.

[10] C. R. Doerr, L. W. Stulz, M. Cappuzzo, E. Laskowski, A. Paunescu, L. Gomez, J. V. Gates, S. Shunk, and A. E. White, "40-Wavelength Add–Drop Filter," IEEE Photonics Technol. Lett., 11:11 (1999), 1437–1439.

[11] C. R. Doerr, L. W. Stulz, D. S. Levy, L. Gomez, M. Cappuzzo, J. Bailey, R. Long, A. Wong-Foy, E. Laskowski, E. Chen, S. Patel and T. Murphy, "Eight-Wavelength Add-Drop Filter with True Reconfigurability," IEEE Photonics Technol. Lett., 15:1 (2003), 138–140.

[12] W. E. Donath, "Wire Length Distribution for Placements of Computer Logic," IBM J. Res. Dev., 25:2/3 (1981), 152–155.

[13] C. Dragone, "An N × N Optical Multiplexer Using a Planar Arrangement of Two Star Couplers," IEEE Photonics Technol. Lett., 3:9 (1991), 812–815.

[14] T. Ducellier, J. Bismuth, S. F. Roux, A. Gillet, C. Merchant, M. Miller, M. Mala, Y. Ma, L. Tay, J. Sibille, M. Alavanja, A. Deren, M. Cugalj, D. Ivancevic, V. Dhuler, E. Hill, A. Cowen, B. Shen, and R. Wood, "The MWS 1 × 4: A High Performance Wavelength Switching Building Block," Proc. European Conf. on Optical Communication (ECOC '02), (Copenhagen, Denmark, 2002).

[15] T. Ducellier, A. Hnatiw, M. Mala, S. Shaw, A. Mank, D. Touahri, D. McMullin, T. Zami, B. Lavigne, P. Peloso, O. Leclerc, "Novel High Performance Hybrid Waveguide-MEMS 1 × 9 Wavelength Selective Switch in a 32 Cascade Loop Experiment," Proc. European Conf. on Optical Communication (ECOC '04), (Stockholm, Sweden, 2004), post deadline paper Th4.2.2.

[16] M. P. Earnshaw, M. Cappuzzo, E. Chen, L. Gomez, A. Griffin, E. Laskowski, and A. Wong-Foy, "Highly-Integrated Planar Lightwave Circuit Wavelength Selective Switch," Electronics Lett., 39:19 (2003), 1397–1398.

[17] M. P. Earnshaw, M. Cappuzzo, E. Chen, L. Gomez, A. Griffin, E. Laskowski, and A. Wong-Foy, "Reconfigurable Optical Add–Drop Multiplexer (ROADM) with Full Add and Drop Path Cross Connect," Proc. Integrated Photonics Research Conf. (IPR '04), (San Francisco, CA, 2004).

[18] M. P. Earnshaw, M. Cappuzzo, E. Chen, L. Gomez, A. Griffin, E. Laskowski, A. Wong-Foy, and J. Soole, "Planar Lightwave Circuit Based Reconfigurable Optical Add–Drop Multiplexer Architectures and Reusable Subsystem Module," IEEE J. Select. Topics Quantum Electronics, 11:2 (2005), 313–322.

[19] M. P. Earnshaw, A. Griffin, C. Bolle, and J. B. D. Soole, "Reconfigurable Optical Add-Drop Multiplexer (ROADM) with Integrated Sub-Band Optical Cross-Connect," Proc. Optical Fiber Communication Conf. (OFC/NFOEC '05), (Anaheim, CA, 2005), vol. 2, paper OTuD2.

[20] M. P. Earnshaw and J. B. D. Soole, "Integrated Reconfigurable Optical Wavelength Add–Drop Multiplexer," Electronics Lett., 38:22 (2002), 1351–1352.
[21] J. E. Ford, "Optomechanical Platform," U.S. Patent 6,307,657 (2001).
[22] J. E. Ford, V. A. Aksyuk, D. J. Bishop, and J. A. Walker, "Wavelength Add-Drop Switching Using Tilting Micromirrors," J. Lightwave Technol., 17:5 (1999), 904–911.
[23] J. E. Ford, K. W. Goossen, J. A. Walker, D. T. Neilson, D. M. Tennant, S. Y. Park, and J. W. Sulhoff, "Interference-Based Micromechanical Spectral Equalizers," IEEE J. Select. Topics Quantum Electronics, 10:3 (2004), 579–587.
[24] D. T. Fuchs, C. R. Doerr, V. A. Aksyuk, M. E. Simon, L. W. Stulz, S. Chandrasekhar, L. L. Buhl, M. Cappuzzo, L. Gomez, A. Wong-Foy, E. Laskowski, E. Chen, and R. Pafchek, "A Hybrid MEMS-Waveguide Wavelength Selective Cross Connect," IEEE Photonics Technol. Lett., 16:1 (2004), 99–101.
[25] A. Godil, "Diffractive MEMS Technology Offers a New Platform for Optical Networks," Laser Focus World, 38:5 (2002), 181+.
[26] T. Goh, M. Yasu, K. Hattori, A. Himeno, M. Okuno, and Y. Ohmori, "Low-Loss and High-Extinction-Ratio Silica-Based Strictly Nonblocking 16x16 Thermooptic Matrix Switch," IEEE Photonics Technol. Lett., 10:6 (1998), 810–812.
[27] E. L. Goldstein and L. Eskildsen, "Scaling Limitations in Transparent Optical Networks Due to Low-Level Crosstalk," IEEE Photonics Technol. Lett., 7:1 (1995), 93–94.
[28] E. L. Goldstein, L. Eskildsen, and A. F. Elrefaie, "Performance Implications of Component Crosstalk in Transparent Lightwave Networks," IEEE Photonics Technol. Lett., 6:5 (1994), 657–660.
[29] D. S. Greywall, C.-S. Pai, S. H. Oh, C.-P. Chang, D. M. Marom, P. A. Busch, R. A. Cirelli, J. A. Taylor, F. P. Klemens, T. W. Sorsch, J. E. Bower, W. Y.-C. Lai, and H. T. Soh, "Monolithic Fringe-Field-Activated Crystalline Silicon Tilting-Mirror Devices," J. Microelectromechanical Syst., 12:5 (2003), 702–707.
[30] C. G. P. Herben, Compact Integrated Cross Connects for Wavelength-Division Multiplexing Networks, Ph.D. Thesis, Delft University of Technology, 2000.
[31] C. G. P. Herben, C. G. M. Vreeburg, D. H. P. Maat, X. J. M. Leijtens, Y. S. Oei, F. H. Groen, J. W. Pedersen, P. Demeester, and M. K. Smit, "A Compact Integrated InP-Based Single-Phasar Optical Crossconnect," IEEE Photonics Technol. Lett., 10:5 (1998), 678–680.
[32] N. Keil, H. H. Yao, C. Zawadzki, F. Beyer, O. Radmer, M. Bauer, and C. Dreyer, "Super Compact Optical Add-Drop Multiplexer for FTTH Applications Based on Low-Loss Polymer Waveguide Materials," Electronics Lett., 41:4 (2005), 186–188.
[33] B. P. Keyworth, "ROADM Subsystems & Technologies," Proc. Optical Fiber Communication Conf. (OFC/NFOEC '05), (Anaheim, CA, 2005), vol. 3, paper OWB5, pp. 35–38.
[34] B. P. Keyworth, JDS Uniphase, "Wavelength Selective Switch (WSS) Technology and Applications," Crawford Hill Open Seminar, Bell Labs, Holmdel, NJ, Sept. 14, 2005.
[35] N. Kikuchi, Y. Shibata, H. Okamoto, Y. Kawaguchi, S. Oku, Y. Kondo, and Y. Tohmori, "Monolithically Integrated 100-Channel WDM Channel Selector Employing Low-Crosstalk AWG," IEEE Photonics Technol. Lett., 16:11 (2004), 2481–2483.
[36] D. Krabe, G. Heise, M. Zavrsnik, J. Dieckroeger, Z. Gao, C. Schinke, M. Scheubeck, T. Kraeker, B. Krombholz, and I. Baumann, "Packaging of Highly Integrated PLC Components," Proc. Optical Fiber Communication Conf. (OFC '04), (Los Angeles, CA, 2004), vol. 2, paper ThL1.
[37] LightConnect, DCE50 Dynamic Channel Equalizer 50GHz, Product Data Sheet, http://www.lightconnect.com/pdf/dce50v8.pdf.
[38] D. López, M. E. Simon, F. Pardo, V. Aksyuk, F. Klemens, R. Cirelli, D. T. Neilson, H. Shea, T. Sorsch, E. Ferry, O. Nalamasu, and P. L. Gammel, "Monolithic MEMS Optical Switch with Amplified Out-of-Plane Angular Motion," Proc. IEEE/LEOS Internat. Conf. on Optical MEMS (MOEMS '02), (Lugano, Switzerland, 2002), paper ThB5, pp. 165–166.
[39] D. O. López, F. Pardo, V. A. Aksyuk, M. E. Simon, H. R. Shea, D. M. Marom, D. T. Neilson, R. A. Cirelli, F. P. Klemens, W. M. Mansfield, L. A. Fetter, E. Bower, J. F. Miner, and T. W. Sorsch, "MEMS Mirror Array for a Wavelength Selective 1xK Switch," Proc. SPIE First Internat. Symposium on Microtechnologies for the New Millennium 2003: Smart Sensors, Actuators and MEMS (SPIE '03), (Canary Islands, Spain, 2003), 5116-59, pp. 445–455.

[40] D. M. Marom, C. R. Doerr, N. R. Basavanhally, M. Cappuzzo, L. Gomez, E. Chen, A. Wong-Foy, and E. Laskowski, "Wavelength-Selective 1 × 2 Switch Utilizing a Planar Lightwave Circuit Stack and a MEMS Micromirror Array," Proc. Optical MEMS 2004, Inter. Conf. on Optical MEMS and Their Applications, (Takamatsu, Japan, 2004), paper C-1.
[41] D. M. Marom, C. R. Doerr, M. Cappuzzo, E. Chen, A. Wong-Foy, and L. Gomez, "Hybrid Free-Space and Planar Lightwave Circuit Wavelength-Selective 1 × 3 Switch with Integrated Drop-Side Demultiplexer," Proc. European Conf. on Optical Communication (ECOC '05), (Glasgow, Scotland, 2005), vol. 4, paper Th3.6.4, pp. 993–994.
[42] D. M. Marom, D. T. Neilson, D. S. Greywall, V. Aksyuk, M. E. Simon, N. R. Basavanhally, P. R. Kolodner, Y. L. Low, F. Pardo, C. A. Bolle, C. S. Pai, D. López, J. A. Taylor, J. E. Bower, J. Leuthold, M. Gibbons, and C. R. Giles, "Wavelength Selective 4 × 1 Switch with High Spectral Efficiency, 10 dB Dynamic Equalization Range and Internal Blocking Capability," Proc. European Conf. on Optical Communication (ECOC '03), (Rimini, Italy, 2003), paper Mo3.5.3.
[43] D. M. Marom, D. T. Neilson, D. S. Greywall, N. R. Basavanhally, P. R. Kolodner, Y. L. Low, F. Pardo, C. A. Bolle, S. Chandrasekhar, L. Buhl, C. R. Giles, S.-H. Oh, C. S. Pai, K. Werder, H. T. Soh, G. R. Bogart, E. Ferry, F. P. Klemens, K. Teffeau, J. F. Miner, S. Rogers, J. E. Bower, R. C. Keller, and W. Mansfield, "Wavelength Selective 1 × 4 Switch for 128 WDM Channels at 50 GHz Spacing," Proc. Optical Fiber Communication Conf. (OFC '02), (Anaheim, CA, 2002), paper FB7-1, pp. 857–859.
[44] D. M. Marom, D. T. Neilson, D. S. Greywall, C-S. Pai, N. R. Basavanhally, V. A. Aksyuk, D. O. Lopez, F. Pardo, M. E. Simon, Y. Low, P. Kolodner, and C. A. Bolle, "Wavelength-Selective 1 × K Switches Using Free-Space Optics and MEMS Micromirrors: Theory, Design, and Implementation," J. Lightwave Technol., 23:4 (2005), 1620–1630.
[45] D. M. Marom, D. T. Neilson, J. Leuthold, M. Gibbons, and C. R. Giles, "64 Channel 4 × 4 Wavelength-Selective Cross-Connect for 40 Gb/s Channel Rates with 10 Tb/s Throughput Capacity," Proc. European Conf. on Optical Communication (ECOC '03), (Rimini, Italy, 2003), paper We4.P.130.
[46] D. M. Marom, D. T. Neilson, R. Ryf, and H. R. Shea, "Effect of Mirror Curvature in MEMS Micro-Mirror Based Wavelength-Selective Switches," Proc. 16th Annual Meeting IEEE Lasers and Electro-Optics Society (LEOS '03), (Tucson, AZ, 2003), vol. 1, paper TuO4, pp. 305–306.
[47] D. M. Marom and S.-H. Oh, "Filter-Shape Dependence on Attenuation Mechanism in Channelized Dynamic Spectral Equalizers," Proc. 15th Annual Meeting IEEE Lasers and Electro-Optics Society (LEOS '02), (Glasgow, Scot., 2002), vol. 2, pp. 416–417.
[48] M. Meyers, S. T. Stanton, and D. T. Neilson, "Optical Demultiplexer/Multiplexer Architecture," U.S. Patent 6,859,324 (2005).
[49] E. J. Murphy, T. O. Murphy, A. F. Ambrose, R. W. Irvin, B. H. Lee, P. Peng, G. W. Richards, and A. Yorinks, "16x16 Strictly Nonblocking Guided-Wave Optical Switching System," J. Lightwave Technol., 14:3 (1996), 352–358.
[50] T. Nakazawa, S. Taniguchi, and M. Seino, "Ti: $LiNbO_3$ Acousto-Optic Tunable Filter (AOTF)," Fujitsu Scientific and Tech. J., 35:1 (1998), 107–112.
[51] D. T. Neilson, H. Tang, D. S. Greywall, N. R. Basavanhally, L. Ko, D. A. Ramsey, J. D. Weld, Y. L. Low, F. Pardo, D. O. Lopez, P. Busch, J. Prybyla, M. Haueis, C. S. Pai, R. Scotti, and R. Ryf, "Channel Equalization and Blocking Filter Utilizing Microelectromechanical Mirrors," IEEE J. Select. Topics Quantum Electronics, 10:3 (2004), 563–569.
[52] K. Okamoto, M. Okuno, A. Himeno, and Y. Ohmori, "16-Channel Optical Add/Drop Multiplexer Consisting of Arrayed-Waveguide Gratings and Double-Gate Switches," Electronics Lett., 32:16 (1996), 1471–1472.
[53] K. Okamoto, T. Takiguchi, and Y. Ohmori, "16-Channel Optical Add/Drop Multiplexer Using Silica-Based Arrayed-Waveguide Gratings," Electronics Lett., 31:9 (1995), 723–724.
[54] M. Okuno, "Highly Integrated PLC-Type Optical Switches for OADM and OXC Systems," Proc. Optical Fiber Communication Conf. (OFC '03), (Atlanta, GA, 2003), vol. 1, paper TuE1, pp. 169–170.
[55] F. Pardo, V. A. Aksyuk, S. Arney, H. Bair, N. R. Basavanhally, D. J. Bishop, G. R. Bogart, C. A. Bolle, J. E. Bower, D. Carr, H. B. Chan, R. A. Cirelli, E. Ferry, R. E. Frahm, A. Gasparyan,

J. V. Gates, C. R. Giles, L. Gomez, S. Goyal, D. S. Greywall, M. Haueis, R. C. Keller, J. Kim, F. P. Klemens, P. R. Kolodner, A. Kornblit, T. Kroupenkine, W. Y. Lai, V. Lifton, J. Liu, Y. L. Low, W. M. Mansfield, D. Marom, J. F. Miner, D. T. Neilson, M. A. Paczkowski, C.-S. Pai, A. G. Ramirez, D. A. Ramsey, S. Rogers, R. Ryf, R. E. Scotti, H. R. Shea, M. E. Simon, H. T. Soh, H. Tang, J. A. Taylor, K. Teffeau, J. Vuillemin, and J. Weld, "Optical MEMS Devices for Telecom Systems," Proc. SPIE First Internat. Symposium on Microtechnologies for the New Millennium 2003: Smart Sensors, Actuators and MEMS (SPIE '03), (Canary Islands, Spain, 2003), 5116-59, pp. 435–444.

[56] A. M. Radojevic, J. Fujita, R. Gerhardt, T. Izuhara, and L. A. Eldada, "Hybrid-Integrated ROADM for Reconfigurable Optical Networks," Proc. European Conf. on Optical Communication (ECOC '04), (Stockholm, Sweden, 2004), paper Tu1.4.5.

[57] A. R. Ranalli, B. A. Scott, and J. P. Kondis, "Liquid Crystal-Based Wavelength Selectable Cross-Connect," Proc. European Conf. on Optical Communication (ECOC '99), (Nice, Fr., 1999), pp. 68–69.

[58] J.-K. Rhee, F. Garcia, A. Ellis, B. Hallock, T. Kennedy, T. Lackey, R. G. Lindquist, J. P. Kondis, B. A. Scott, J. M. Harris, D. Wolf, and M. Dugan, "Variable Passband Optical Add-Drop Multiplexer Using Wavelength Selective Switch," Proc. European Conf. on Optical Communication (ECOC '01), (Amsterdam, Neth., 2001), vol. 4, paper Th.L.1.7, pp. 550–551.

[59] R. Ryf, Y. Su, L. Möller, S. Chandrasekhar, X. Liu, D. T. Neilson, and C. R. Giles, "Wavelength Blocking Filter with Flexible Data Rates and Channel Spacing," J. Lightwave Technol., 23:1 (2005), 54–61.

[60] M. K. Smit, "New Focusing and Dispersive Planar Component Based on an Optical Phased Array," Electronics Lett., 24:7 (1988), 385–386.

[61] O. Solgaard, F. S. A. Sandejas, and D. M. Bloom, "Deformable Grating Optical Modulator," Optics Lett., 17:9 (1992), 688–690.

[62] R. Spanke, "Architectures for Large Nonblocking Optical Space Switches," IEEE J. Quantum Electronics, 22:6 (1986), 964–967.

[63] J. Spencer, D. Johnson, A. Hastie, and L. Sacks, "Emergent Properties of the BT SDH Network," BT Tech. J., 21:2 (2003), 28–36.

[64] T. Spott, A. Schumacher, J. Dieckroeger, D. Krabe, W. Schenk, H. Schneider, S. Ramminger, and I. Baumann, "Macroscopic and Microscopic Thermal Management of a Planar Integrated Optical Device," Proc. Optical Fiber Communication Conf. (OFC '03), (Atlanta, GA, 2003), vol. 1, paper TuE6, pp. 175–176.

[65] A. Sugita, K. Jinguji, N. Takato, K. Katoh, and M. Kawachi, "Bridge-Suspended Silica-Waveguide Thermo-Optic Phase Shifter and Its Application to Mach-Zehnder Type Optical Switch," Trans. Institute of Electronics, Information and Communication Engineers (IEICE), Special Issue on Internat. Conf. on Integrated Optics and Optic Fiber Communication, E73-E:No.1 (1990), 105–108.

[66] K. Suzuki, T. Mizuno, M. Oguma, T. Shibata, H. Takahashi, Y. Hibeno, and A. Himeno, "Low Loss Fully Reconfigurable Wavelength-Selective Optical $1 \times N$ Switch Based on Transversal Filter Configuration Using Silica-Based Planar Lightwave Circuit," IEEE Photonics Technol. Lett., 16:6 (2004), 1480–1482.

[67] H. Takahashi, S. Suzuki, K. Kato, and I. Nishi, "Arrayed-Waveguide Grating for Wavelength Division Multi/Demultiplexer with Nanometer Resolution," Electronics Lett., 26:2 (1990), 87–88.

[68] H. Tang, N. R. Basavanhally, L. Ko, and D. T. Neilson, "Optical Modeling of Channelized MEMS Equalization Filter/Blocker," Proc. Photonic Devices & Systems Packaging Symposium (PhoPack '03), (San Francisco, CA, 2003).

[69] Telcordia, "Generic Requirements for Singlemode Fiber Optic Switches," GR-1073-CORE, Jan. 2001.

[70] W. J. Tomlinson, "Dynamic Gain Equalization for Next-Generation DWDM Transport Systems," Advanced Semiconductor Lasers and Applications/Ultraviolet and Blue Lasers and Their Applications/Ultralong Haul DWDM Transmission and Networking/WDM Components, Digest of IEEE/LEOS Summer Topical Meetings, (Copper Mountain, CO, 2001), pp. 35–36.

[71] J.-C Tsai and M. C. Wu, "$1 \times N2$ Wavelength-Selective Switches with High Fill-Factor Two-Axis Analog Micromirror Arrays," Proc. Optical Fiber Communication Conf. (OFC '04), (Los Angeles, CA, 2004), vol. 1, paper MF42, pp. 23–27.

[72] J.-C. Tsai and M. C. Wu, "Gimbal-Less MEMS Two-Axis Optical Scanner Array With High Fill-Factor," J. Microelectromechanical Syst., 14:6 (2005), 1323–1328.
[73] D. Van Thourhout, C. R. Doerr, C. H. Joyner, and J. L. Pleumeekers, "Observation of WDM Crosstalk in Passive Semiconductor Waveguides," IEEE Photonics Technol. Lett., 13:5 (2001), 457–459.
[74] C. G. M. Vreeburg, T. Uitterdijk, Y. S. Oei, M. K. Smit, F. H. Groen, E. G. Metaal, P. Demeester, and H. J. Frankena, "First InP-Based Reconfigurable Integrated Add-Drop Multiplexer," IEEE Photonics Technol. Lett., 9:2 (1997), 188–190.
[75] M. C. Wu, J.-C. Tsai, S. Huang, and H. Dooyoung, "MEMS WDM Routers Using Analog Micromirror Arrays," Proc. 15th Annual Meeting IEEE Lasers and Electro-Optics Society (LEOS '02), (Glasgow, Scot., 2002), vol. 2, pp. 582–583.

(Manuscript Approved February 2006)

DAVID T. NEILSON is a technical manager with Bell Labs' Research and is based at the Crawford Hill Laboratory in Holmdel, New Jersey. He is currently leading a team conducting research on highly integrated InP-based optoelectronic components and subsystems and has responsibility for optoelectronic device growth and fabrication facility. He received the B.Sc. (Hons) degree in physics and the Ph.D. degree in physics from Heriot-Watt University in Edinburgh, Scotland. His thesis work was done on optical nonlinearities in InGaAs Quantum well devices. Prior to joining Bell Labs, he was a Postdoctoral Researcher at Heriot-Watt University, working on systems and devices for free space optical interconnects and switching. He later served as a Visiting Scientist at NEC Research Institute, Princeton, NJ, researching optical interconnects for high-performance computing. During his tenure at Bell Labs, Dr. Neilson has worked on MEMS-based crossconnects, wavelength selective switches, equalizers, and dispersion compensators. His research interests also include the role of optical interconnects and switching for high capacity optical switches and routers. He has over 100 publications and 17 issued patents in the field of optical interconnects, switching and optoelectronic devices. He is a Senior Member of LEOS and a Member of the Optical Society of America (OSA).

CHRISTOPHER R. DOERR is a distinguished member of technical staff at Bell Labs' Crawford Hill Laboratory in Holmdel, New Jersey. He earned a B.S. in aeronautical/astronautical engineering and a B.S., M.S., and Ph.D. in electrical engineering, all from the Massachusetts Institute of Technology (MIT) in Cambridge. He attended MIT on an Air Force ROTC scholarship and earned his pilot wings at Williams AFB, Arizona, in 1991. His Ph.D. thesis, on constructing a fiber-optic gyroscope with noise below the quantum limit, was supervised by Prof. Hermann Haus. Dr. Doerr's research at Bell Labs has focused on integrated devices for optical communication. He is Editor-in-Chief for IEEE Photonics Technology Letters, is an elected member of the LEOS Board of Governors, and was a subcommittee chair for OFC 2005. He received the OSA Engineering Excellence Award in 2002, and has authored/co-authored over 100 journal and conference papers and three book chapters and holds 58 issued U.S. patents.

DAN M. MAROM is a member of technical staff at the Advanced Photonics Research Department of Bell Labs in Holmdel, New Jersey. His research activity has focused on novel photonic devices utilizing MEMS, PLC and free space technologies for optical communications. He received a B.Sc. degree in mechanical engineering, and a M.Sc. degree in electrical engineering, both from Tel-Aviv University, Tel-Aviv, Israel, and a Ph.D. in electrical engineering from the University of California at San Diego. In his doctoral dissertation he investigated femtosecond-rate optical signal processing with applications in ultrafast communications. From 1996 through 2000, he was a Fannie and John Hertz Foundation Graduate Fellow at UCSD. In 2005 he joined the faculty of the School of Computer Science and Engineering, Hebrew University, in Jerusalem, Israel.

ROLAND RYF is a member of technical staff in the Photonic Subsystems and the Advanced Photonics Research Departments at Bell Labs in Holmdel, New Jersey. His current research includes optical design and prototyping of optical microelectromechanical systems (MEMs)-based devices, in particular large port count crossconnect switches, programmable spectral filters, dispersion compensators, and beam steering applications for free space optics communication. He received the B.S.-equivalent degree in electrical engineering from *the Interstate University of Applied Sciences of Technology Buchs, Switzerland, and a diploma and Ph.D. degree in physics from the Swiss Federal Institute of Technology (ETH) Zürich, Switzerland, working on photorefractive self-focusing and spatial solitons, parallel optical processing based on holographic storage, and fast optical correlation. Dr. Ryf has over 40 publications and five patents in the field of optical switching.*

MARK P. EARNSHAW is a member of technical staff in the Department of Integrated Photonics at Bell Labs in Murray Hill, New Jersey. He holds M. Eng. and D. Phil. degrees from the University of York in England. From 1994 to 1995, Dr. Earnshaw worked at British Telecom Research Labs on fibre amplifiers and lasers. In 1999 he joined Bell Labs where he has since worked on silica waveguide devices including optical cross-connects and a variety of wavelength switches. ◆