A Review of DWDM
The Heart of Optical Networks

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Introduction

It is needless to mention that the 21st century activities will be drastically hindered without the advent of modern communication system. Off all, the most advanced communication system has been culminated in the form of "Internet," allowing all computers on the planet and in the orbit to be connected to each other – simultaneously! While telecommunication remains as a major medium and has its own demand for higher bandwidth, the demand for even higher bandwidth is skyrocketed by exponential growth of the Internet traffic. The cumulative demand for bandwidth poses a serious limitation for the existing carrier technologies. However, this extraordinary growing demand, coupled with the advent of dense wavelength division multiplexing (DWDM) fiberoptic systems to meet those demands, have sparked a revolution in the optical component and networking industry.

DWDM has been proven to be one of the most capable technologies for communication systems. Although usually applied to optical networks (ONs), wavelength division multiplexing (WDM), in general, can manyfold the capacity of existing networks by transmitting many channels simultaneously on a single fiberoptic line. In the few short years of deployment, DWDM performance has been improved dramatically. Channel count has grown from 4 to 128 and channel spacing has shrunk from 500 GHz to 50 GHz. This boost has been built upon, and has been driven by, advancements in fiber optic components, photonic integrated circuits (PICs) and advanced packaging technology. For a general introduction on the topic, see refs. 1-2.

Although “all-optical” technologies are replacing most transmission lines, the nodes of the networks, such as switching and cross-connect nodes, still depend on relatively slow electronic technologies. This poses a problem, because, nodes in the networks will limit the throughput due to the limitations of the electronic circuitry. Only solution to this problem is to make the nodes all-optical as well. Migration from electronic and/or electro-optic nodes to all-optical nodes requires multiplexing, demultiplexing and cross-connection via optical technologies.

Presently time division multiplexing (TDM) systems are widely used in optical communication networks. TDMs are inherently dependent on electronic technology for multiplexing and demultiplexing (MUX/DMUX). The nodes in TDMs use optical-to-electronic conversion, MUX and DMUX in the electronic domain, and electronic-to-optical conversion. Thus, the throughput is limited by the processing speed in the electronic domain. Wavelength Division Multiplexing (WDM) technologies, on the other hand, are based on all-optical MUX/DMUX; thereby enabling construction of WDM networks where node functionality is supported by all-optical technologies without back and forth optical and electronic conversions.

In this article the basics of WDM technology is reviewed. A brief review of different topologies and technologies used in WDMs is presented. Finally, important parameters to characterize the MUX/DMUX components have been outlined.

WDM Communication Basics

One of the important enabling technologies for optical networking is wavelength division multiplexing (WDM) and demultiplexing (WDDM). The basic concept of a WDM is illustrated in Fig. 1. At the heart of the WDM system is the optical multiplexing and demultiplexing devices. Optical signals are generated by laser diodes (LDs) at a series of monochromatic wavelengths λ_1, λ_2, … λ_N, (in the appropriate wave length range) and sent through N fibers to a WDM.

The WDM combines these input signals into a polychromatic output signal, a process known as multiplexing. Multiplexing allows to access very large bandwidth available in an optical fiber. This multiplexed, polychromatic signal is

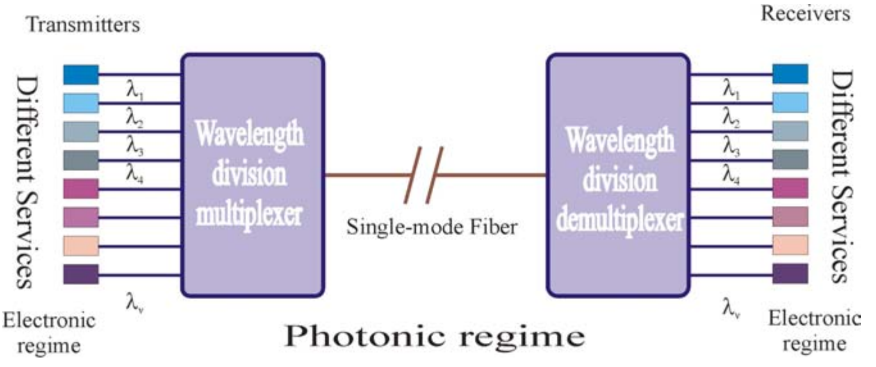

Fig. 1. Bsic concept of WDM and WDDM in fiberoptic communications.

launched into a single optical fiber for transportation. At the destination, a WDDM separates the polychromatic signal into constituent wavelengths, identified as a series of narrow band channels; this process is called demultiplexing.

The WDDM must be designed such that the channels have center wavelengths that are the same as the original wavelengths. The WDDM channels must also have spectral widths, $\Delta\lambda_N$, (i.e., passbands) that are large enough to accommodate system tolerances, but small enough to avoid overlapping of the channels. Ordinarily, the WDM and the WDDM are spectrogram devices that are not tunable; therefore, their performance depends on the perfection of design and fabrication.

Depending on application needs, different types of WDM systems are deployed; the list includes point-to-point long distance transmission, local access network, reconfigurable network, etc. Each of these systems needs different WDM components. Fig. 2 shows the basic configuration of a point-to-point transmission system. At the transmitter end a laser array is used as the signal source. The lasers in the array are set to predetermined wavelengths with fixed channel parameters set by the international telecommunication union (ITU) standard. Other key components of WDM networks are optical add/drop multiplexers

(OADM), optical cross connect switches (OCX), and optical amplifiers such as erbium doped fiber amplifiers (EDFAs).

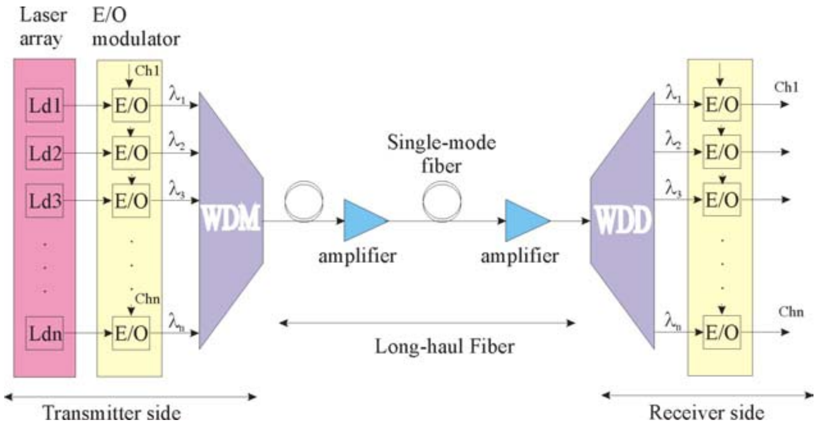

Figure 2. Basic structure of a point-to-point optical transmission system.

The ITU has adapted a standard for optical communication that specifies that certain standard frequencies be used to identify and specify WDM channels. ITU channels begin at 190.00 THz (channel 0, 1577.86 nm) and increments by 0.10 THz for each subsequent channels. It usually spans over the C-band (1520-1570 nm). The wavelength, λ, and frequency, ν, of a wave traveling in a medium are related by,

$$n\lambda\nu = c\,, \tag{1}$$

where, n is the refractive index of the medium and c is the speed of light in vacuum. WDMs must be designed such that the center wavelength of each channel coincides with an ITU channel. For instance, a 40-channel AWG with 100GHz spacing may be used for DWDM application such that its center wavelength would coincide with the ITU channel 30 (193.00 THz, 1553.33 nm). The channel wavelengths and corresponding ITU frequencies can be calculated from Eq. 1. In terms of frequencies, the ITU channels are given by,

$$\nu_N = 190.000 + 0.1N \text{ (THz)}, N = 0, 1, 2, \ldots\,. \tag{2}$$

Thus, ITU channels are spaced at a frequency of 100 GHz; the operating frequencies are called ITU grid frequencies (or wavelengths). The corresponding wavlength spacing is given by,

$$\Delta\lambda = \frac{1}{c}(\Delta\nu\lambda^2) \tag{3}$$

where c = 299792.458 THz.nm, and $\Delta\nu$ = 0.1 THz. (4)

From Eq. (4) one can see that $\Delta\lambda \sim 0.8$ nm, however, it increases slightly with λ ($\propto \lambda^2$). WDMs can be designed to operate at ITU grid frequencies as well as their multiples (e.g., 200 GHz, 500 GHz, etc.) and sub-multiples (e.g., 50 GHz). As indicated in Fig. 2, the laser outputs are modulated by individual electronic signals, either by direct or external electro-optic (EO) method.

WDM Topologies

Applying DWDM technology to long-haul and metropolitan transport systems involves different sets of requirements. This imposes separate design strategies

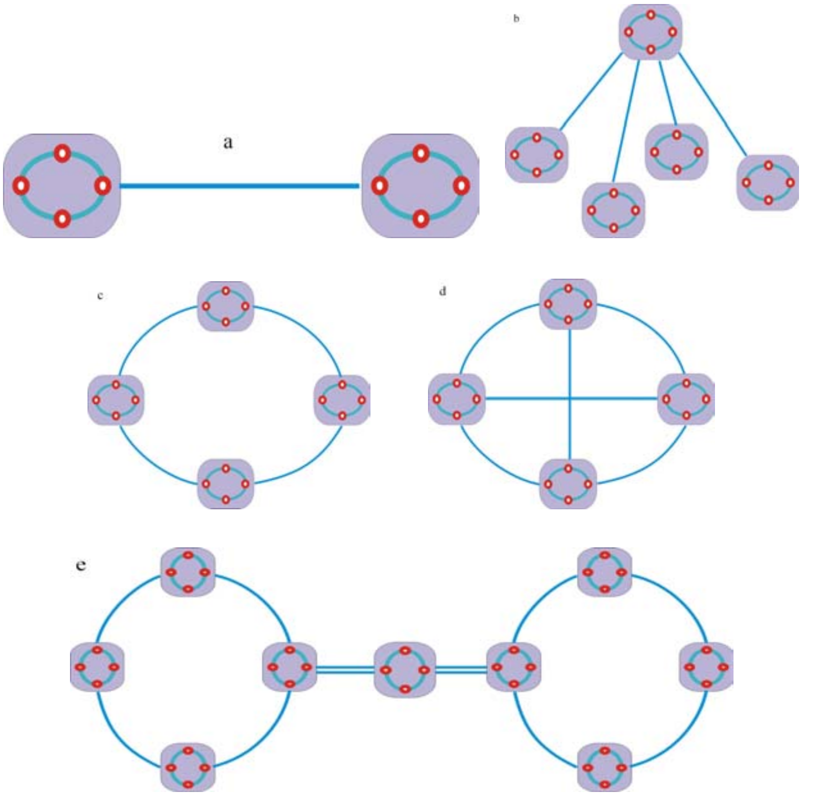

Fig. 3. Different WDM topologies. a) Point-to-point, b) Star, c) Ring, d) Mesh, e) Cross-connect.

for metropolitan and long-haul transmissions. For instance, long-haul transmission spans over hundreds to thousands of kilometers while for metro systems it is typically up to 100 km. Both fiber and traffic topologies are linear (point-to-point) in long-haul, while a ring, mesh or cross-connect topology is used in metro. Metropolitan solutions must also have multiple features suitable for a diversity of services. Fig. 3 shows the main WDM topologies that an engineer can choose from to suit a given design need.

In long-haul, optical amplification becomes necessary because of fiber attenuation losses associated with much longer distance. Addition of optical amplifiers, however, significantly increases the overall network cost, complicates network design, and can reduce available channels. While for long-haul transport these additional complicacies and cost factors are justified, for metro networks that is not the case. Moreover, in a metro optical network, it is likely that a traffic channel will transmit through many add/drop sites before reaching its destination. Therefore, equipment related attenuations become very important, demanding a fine balance between fiber and component losses in the metro design. With efficient design, integrated WDM components such as arrayed waveguide gratings (AWGs), use of optical amplifiers can be avoided in metro design.

WDM Technologies

WDM systems use different wavelengths for different channels. Each channel may transport homogeneous or heterogeneous traffic, such as SONET/SDH (synchronous optical network/synchronous digital hierarchy) over one wavelength, ATM (asynchronous transfer mode) over another, and yet another may be used for TDM voice, video or IP (internet protocol). WDMs also make it possible to transfer data at different bit rates. Thus, it offers the advent that one channel may carry traffic at OC-3, OC-12, OC-48, OC-192 or up to OC-768 rate and another channel may carry a different rate transmission; all on the same fiber. These functions are accomplished by a MUX at the transmitter end and a DMUX at the receiver end (see Fig. 2).

There are mainly three kinds of MUX/DMUXes commercially available for WDM applications. These are thin-film interference filters, fiber bragg gratings (FBGs) and arrayed waveguide gratings (AWGs). The first two categories are discrete component devices, i.e., multiple discrete components are assembled together to perform MUX/DMUX functions. The AWGs are Photonic Integrated Circuits (PICs) formed on silicon substrate. This emerging technology is very important and requires a complete discussion to appreciate its capabilities and usefulness. Other technologies such as free space diffraction gratings also promise lower channel cost and higher channel count with better performance. Here a brief description of the three competing technologies is provided.

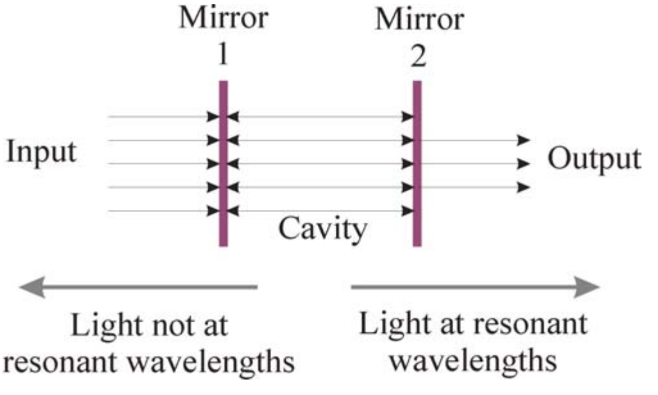

Fig. 4. Basic structure of a Fabry-Perot Etalon filter.

Filter based WDM

The structure of a thin-film interference filter is based on that of a Fabry-Perot etalon (Fig. 4). Composed of stacked mirrors separated by cavities (usually 4 or 5 cavities), these act as a bandpass filter. The passband wavelength is determined primarily by the cavity length. Because the mirrors are partially silvered, some of the incident light enters the cavity while most light is reflected back. Multiple mirror and cavity combinations help to select a very narrow band to exit from the etalon; the cavity length can be adjusted to choose a particular wavelength. This way, etalons can be designed for any given ITU channel.

While conceptually simpler, filter based WDMs are complicated to manufacture. Precision fiber alignment and bonding is necessary to stabilize the passband for each ITU channel. Also, for every channel, a different filter corresponding to its passband is necessary (Fig. 5). Therefore, the center wavelength of each passband can differ from the ITU frequency at random.

For multiple channels, the filters are cascaded; and since the losses are cumulative, this yields highest loss for the last channel in a module. To adjust the insertion loss uniformity within tolerable range, attenuation is added to low loss channels to bring them closer to the highest loss channel. Since many filters are involved, packaging is tedious and prone to various kind of failure. The overall yield of filter based WDM is only about 40%, making this technology not the best choice for WDM applications. Nevertheless, other technologies are still not matured enough to claim major market share, therefore, filter based WDM enjoy a sizable market share.

Fiber Bragg Grating

A fiber Bragg grating (FBG) is a “corrugated” waveguide formed in the fiber core by a periodic perturbation of refractive index along its length. For near infrared (~ 1.55 μm) operation, the FBG periodicity corresponds to somewhere between 1 to 10 μm. A FBG placed at the output of a circulator reflects back only the wavelength it is designed for, thus acting as a bandpass filter.

The main WDM parameters such as center wavelength, bandwidth, and reflectance peak are controlled by manipulating the grating parameters. Primary design parameters for a FBG are the grating period, the grating length, and the modulation depth (determined by the degree of variation in refractive index within the grating area). Uniform periodicity of refractive index (RI) in the grating produces unwanted sidelobes in the transmission spectra of a FBG. Therefore, practical WDMs are made from a chirped FBG, where either the grating period or the average RI is varied over the length of the grating. A major problem with FBGs is that they are reflective device rather than transmissive; as a result they need circulators or filters to work as a WDM (Fig. 6).

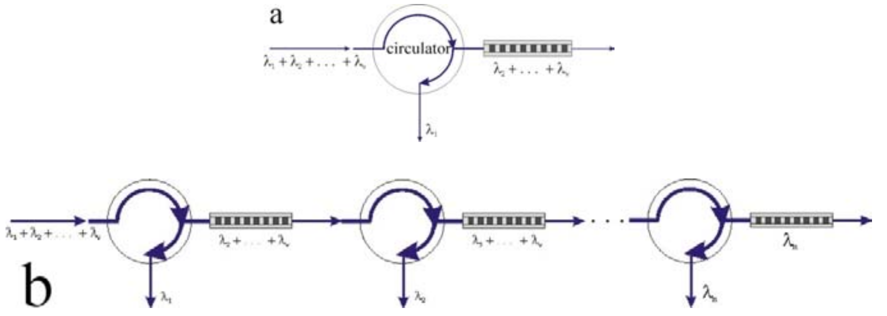

Fig. 6. a) Filtering a single wavelength from a multiplexed signal with an in-fiber Bragg grating. b) Basic structure of a DMUX by cascaded FBGs and circulators.

Arrayed Waveguide Grating

While the silicon technology is saturated in the micoelectronics arena, engineers have found a new and exciting use of this matured technology. These are optical waveguides on a silicon wafer that can be designed to perform many important optical signal processing. These chips, designed for optical multiplexing and demultiplexing, are commonly known as photonic integrated circuits (PIC) or Planar Lightwave Circuit (PLC). The most popular application of PICs is the arrayed waveguide grating (AWG) that has revolutionized the optical communication industry. AWGs are used for multiplexing (MUX) and demultiplexing (DMUX) of optical signals in optical communication systems. While there are a handful of technologies currently deployed to manufacture optical MUX/DEMUXes, and each one has its own strength and weaknesses, the search for better performing, cost reducing and more reliable technology is ongoing. A comprehensive discussion of various properties of several contemporary technologies can be found in ref 11.

Arrayed waveguide gratings offer an attractive alternative to produce integrated and concise DWDM. AWGs are key devices in the rapidly expanding all-optical DWDM networks, because, they integrate multiple optical functions on a single substrate leading to a single package, volume manufacturable on a fab that is well developed in the semiconductor industry [7]. Moreover, this technology allows integration of actives and passives on a single substrate leading to further size reduction, efficiency and reliability. An AWG optical chip is composed of input waveguides, an input slab, array of waveguides, output slab, and output waveguides. All of these are fabricated on a single substrate forming an optical integrated circuit. Fig. 7 shows a photomicrograph of the slab–array waveguide interface area. The spectral response from an AWG is shown in Fig. 8.

WDM Specifications

The key parameters that define the WDMs are listed below. Conventional single-mode fibers transmit wavelengths in the 1300 nm and 1550 nm ranges and absorb wavelengths in the 1340-1440 nm ranges.

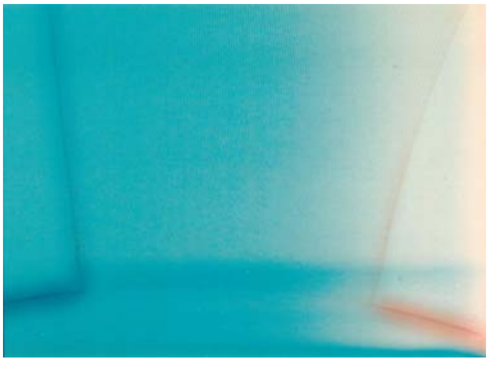

Fig. 7. Photomicrograph of the interface between the slab and array waveguides of an AWG chip (arbitrary magnification).

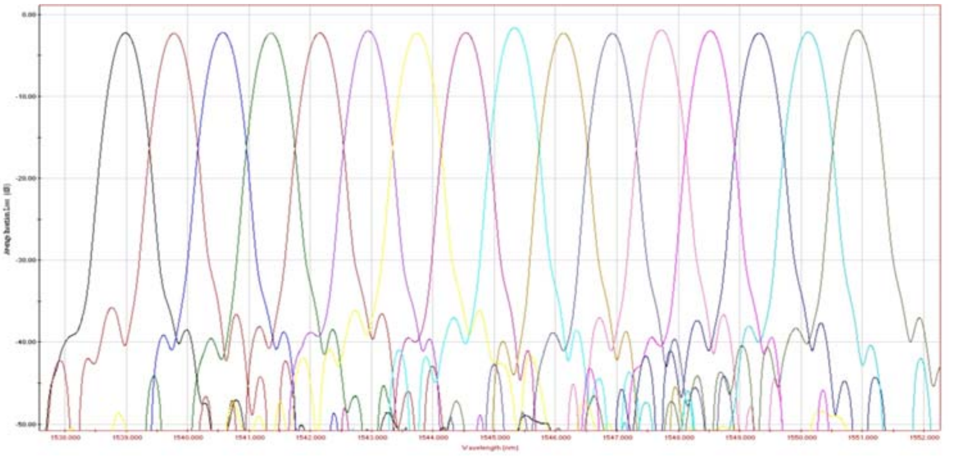

Fig. 8. Spectral response of a 40 channel arrayed waveguide grating (mid 16 channels shown here).

WDM systems, therefore, use wavelengths in the two regions of 1310 and 1550 nm. For a WDM system, independence of MUX/DMUX function to data rate and format is also important. A design engineer cares for the following critical parameters of the MUX and DMUX components.

- Insertion loss and its uniformity over all channels.
- Channel passband width (or bandwidth), passband accuracy, stability and uniformity (or ripple).
- Center wavelength stability and accuracy i.e., offset from ITU grid.
- Crosstalk between adjacent and non-adjacent channels.
- Polarization dependent loss (PDL).
- Return loss or back reflection (for DMUX).
- Directivity or forward reflection (for MUX).
- Chromatic dispersion and group delay.

These parameters are defined in Telcordia documents [4] as well as reviewed by manufacturers [5,6]. Figs. 8 & 9 depicts graphical definitions of some of the key parameters; their typical values are given in Table 1. However, there are significant variations from technology to technology, as well as on perfection of a particular technology. Table 1 represents a reasonable set of WDM parameters; most vendors are able to meet these values with existing technologies.

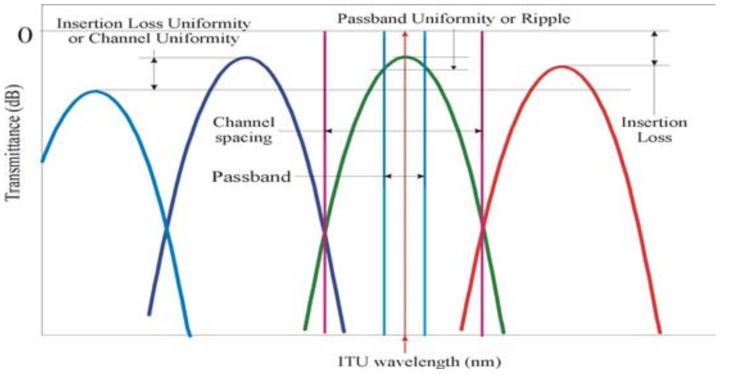

Fig. 8. Graphical representation of insertion loss, insertion loss uniformity, and passband uniformity.

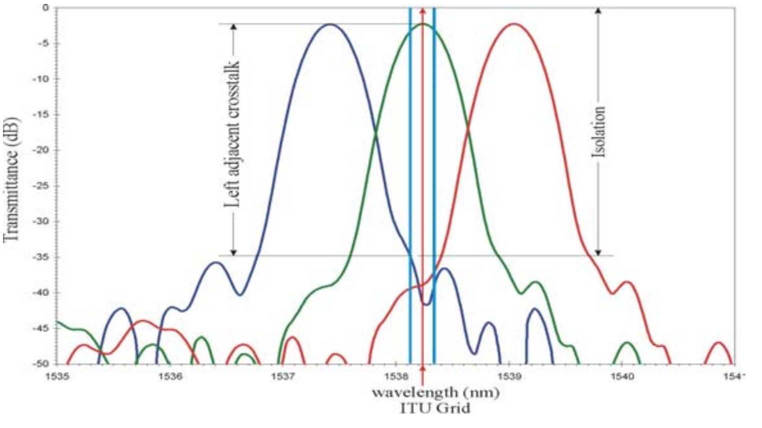

Fig. 9. Graphical representation of channel isolation and adjacent crosstalk.

Table 1. Typical values for MUX/DMUX Parameters		
Parameter	**(Unit)**	**Value**
Passband width	(GHz) or (nm)	25 or 0.8
Passband uniformity	(dB)	1.5
Insertion loss and uniformity	(dB)	5 and 1.5
PDL	(dB)	0.5
Adjacent and non-adjacent crosstalk	(dB)	25 and 30
Integrated average crosstalk	(dB)	20
Return loss	(dB)	45
Directivity	(dB)	50
Chromatic dispersion	(ps/nm)	10
Differential group delay	(ps)	0.5

Summary

Deployment of fiber-optic solutions to the space based satellite constellations, in the short-haul, and in the next generation internet, will require inventions of smarter, more reliable, and more cost-effective photonic devices. The driving force for lower cost and higher performance in the semiconductor industry has always been and continues to be more functionality per square centimeter. This can only be achieved by integrated approach such as arrayed waveguide grating (AWG) or the photonic integrated circuits (PICs) in general.

As the technology ages and with the current debt load that the Telecom companies carry, the market driving force for the telecom industry is lower cost and higher performance. The PIC technology offers many advantages by integrating several tiers on a single substrate. For instance, one can integrate a gain medium which will substantially overcome the loss issues. The integration of higher functionality will allow PIC based products to attract a better market share compared to the discrete counterparts currently available.

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