

40-CHANNEL ULTRA- LOW-POWER COMPACT PLC-BASED ROADM SUBSYSTEM

Abstract: We review the main ROADM subsystem technologies, and propose a 40-channel PLC-based ROADM subsystem that exhibits ultra-low power consumption and compact size, while meeting the requirements for high optical performance, high reliability, and low cost.

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OCIS codes: (060.1810) Couplers, switches, and multiplexers; (060.2360) Fiber optics links and subsystems; (130.3120) Integrated optics devices; (130.6750) Systems; (160.5470) Polymers; (160.6030) Silica; (160.6840) Thermo-optical materials

1. Introduction

Large amounts of information traveling on multiple wavelengths around an optical network need to be switched at the network nodes. Information arriving at a node is forwarded to its final destination via the best possible path, which is determined by such factors as distance, cost, and the reliability of specific routes. The conventional way to switch the information is to convert the input fiber optical signal to an electrical signal, perform the switching in the electrical domain, then convert the electrical signal back to an optical signal that goes down the desired output fiber. This optical-electrical-optical (O-E-O) conversion uses systems that are expensive, bulky, and are bit-rate/protocol dependent.

Reconfigurable optical add/drop multiplexers (ROADMs) allow circumventing the unnecessary O-E-O conversion, enabling O-O-O systems that use optical switching, which has significant advantages for carriers and service providers. Optical switching involves lower capital expenditures (capex), as there is no need for a large amount of expensive high-speed electronics. Furthermore, operational expenditures (opex) are decreased and reliability is increased because fewer network elements such as back-to-back terminals are required. Reducing the complexity also makes for physically smaller switches. Additionally, optical switches are relatively future-proof. An electrical switch has electronics designed to detect incoming optical signals of specific bit rates and formats. When the bit rate increases or when the format changes, the electronics need to be upgraded. ROADMs route the optical signals directly, and are bit-rate/protocol transparent, so future upgrades of bit-rate or protocol can be accommodated without the need to upgrade the switch.

We start by reviewing the main optical component technologies developed for ROADM subsystems, and we propose a 40-channel PLC-based ROADM subsystem that exhibits ultra-low power consumption and compact size, while meeting the requirements for high optical performance, high reliability, and low cost.

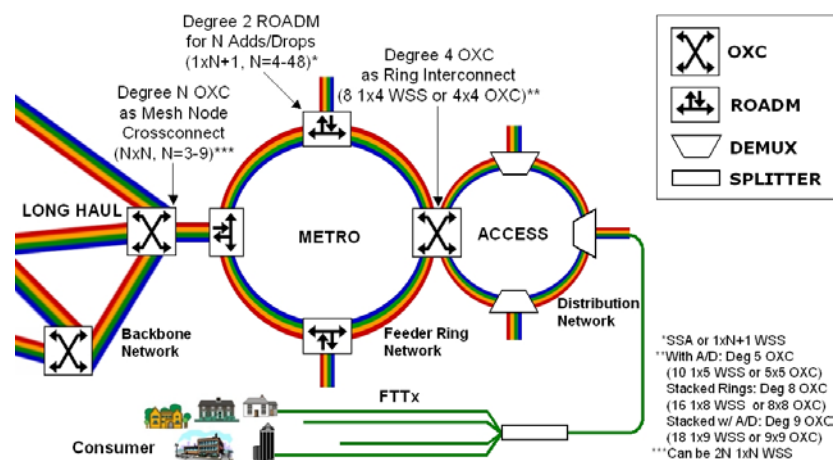


Fig. 1. Types of ROADM needed at optical network nodes.

2. ROADM Subsystem Technologies

Until recently, ROADM systems did not exist, their components were unselected, and their market was unclear. Today, every major system vendor has a ROADM offering, and a large number of component vendors have announced ROADM products based on a variety of technologies, some more mature than others.

We review the different optical component technologies that have been developed for use in ROADM subsystems, and describe their principles of operation, designs, advantages, and challenges. The technology platforms that we cover include MEMS, liquid crystals (liquid crystal device (LCD) and liquid crystal on silicon (LCoS) technologies), and monolithic and hybrid planar lightwave circuits (PLC) based on silica on silicon and polymer on silicon platforms. For each technology, we describe the corresponding ROADM subsystem architectures in terms of functionality, features, size, cost, and maturity.

Reconfigurable optical networks have needs for various types of ROADM [1,2]. Figure 1 shows some of the connectivity functions needed at nodes in ring and mesh networks. Table 1 defines the four main types of ROADM, where ROADM is used in the broadest sense to include Type I/II ROADM, Wavelength Selective Switches (WSS), and Optical Cross-Connects (OXC). Table 2 lists, for the four main ROADM types, the key justifications for their deployment, their compatibility with prior generations, the optical components used for each type, and the technologies used for the components. Table 3 lists the different ROADM subsystems developed, their implementation status, whether they are Telcordia qualified, and whether they were/will be part of a main deployment wave by carriers.

TABLE 1. Definition of ROADM types.

Network Function	Node Degree	Subsystems per Node	Add/Drop Ports	Add/Drop Channels	Colorless	Multiple λ 's per Port
Type I ROADM	2	Number: 2 Size: $1 \times (N+1)$	Up to N^*	Up to N	No	No
Type II ROADM	2	Number: 2 Size: $1 \times (N+1)$	Up to N	Up to N	Yes	No
Wavelength Selective Switch (WSS)	2 D	Number: 2 Size: $1 \times M^{**}$ Number: $2(D+1)$ Size: $1 \times (D+1)^{****}$	Up to $M-1^{***}$ 1	Up to N	Yes	Yes
Optical Crossconnect (OXC)	D	Number: 1 Size: $(D+1) \times (D+1)$	1	Up to N	Yes	Yes

* N : number of channels
 ** M : number of Add or Drop ports -- $M \leq N$ (typically $M=4,8$ for $N=32,40$)
 *** e.g., 1×5 WSS provides 1 express port and 4 Add/Drop ports
 **** e.g., 10×5 WSS provide degree 4 crossconnect and 1 Add/Drop port

TABLE 2. ROADM types, the main justifications for their deployment, their compatibility with prior generations, and the optical components used in each ROADM type.

Network Function	Justification	Compatibility	Approach (& Technology Used)
Type I ROADM Fixed ports	Stranded capacity reduction	Dual-use as DGE, DCE	<ul style="list-style-type: none"> Wavelength Blocker (LCD, LCOS, or MEMS) + Fixed Filters (TFF) Small Switch Array (PLC) + Demux/Mux (PLC)
Type II ROADM Any λ to any port	No manual intervention, monitor & control	Retain blocker, add tunable filters and tunable lasers, no impact to thru path; or all PLC solution, more cost-effective	<ul style="list-style-type: none"> Wavelength Blocker (LCD, LCOS, or MEMS) + Tunable Filters/Lasers Small Switch Array (PLC) + Demux/Mux (PLC) + $M \times N$ Switches (PLC)
Wavelength Selective Switch (WSS) Any multiple λ 's to any port	Ring interconnect without OEO	Select locations only; interoperability with other nodes, same lasers	<ul style="list-style-type: none"> $1 \times N$ Free-Space WSS (LCD or LCoS or MEMS)
Optical Crossconnect (OXC) Any multiple λ 's from any port to any port	Mesh crossconnect, mesh protection	Select locations only	<ul style="list-style-type: none"> Demux + $N \times N$ Matrix Switch Array + Mux (PLC) $1 \times N$ Free-Space WSS (LCD or LCoS or MEMS)

TABLE 3. Specific ROADM subsystems, status of their implementation and Telcordia qualification, and identification of the subsystems used in the main deployment waves.

ROADM Subsystem	Implementation Status	Telcordia Qualified	Deployment Waves
Type I ROADM based on LCD WB	Up to 80 50-GHz channels	Yes	Wave 1
Type I ROADM based on MEMS WB	Up to 90 50-GHz channels	No	
Type I ROADM based on PLC WB	Up to 40 100-GHz channels	Yes	
Type I ROADM based on PLC SSA	Up to 40 100-GHz channels	Yes	Wave 2
Type II ROADM based on LCD WB	Up to 80 50-GHz channels	Yes	
Type II ROADM based on MEMS WB	Up to 90 50-GHz channels	No	
Type II ROADM based on PLC SSA	In Dvpt, 8 colorless A/D, 40 ch	No	
WSS based on MEMS 1xN WSS	Up to 1x9, 90 50-GHz channels	No	Wave 3A (Trials)
WSS based on LCD 1xN WSS	Up to 1x4, 80 50-GHz channels	No	Wave 3B (Trials)
WSS based on LCoS 1xN WSS	In Dvpt, 100 50-GHz channels	No	
OXC based on PLC Matrix Switch	Up to 16x16	Yes	Wave 4 (Dvpt)
OXC based on MEMS NxN WSS	Development Not Started	No	
OXC based on LCD NxN WSS	Development Not Started	No	
OXC based on LCoS NxN WSS	Development Not Started	No	

From Tables 2 and 3, the main approaches in ROADM subsystems deployed by carriers can be summarized as:

- Wavelength Blocker (WB) in Broadcast and Select configuration – used in deployment wave 1
- Small Switch Array (SSA) ROADM, including demux/mux – used in deployment wave 2
- Wavelength Selective Switch (WSS) – used in deployment wave 3
- Optical Cross-Connect (OXC) – to be used in deployment wave 4

Table 4 defines the functionality obtained with each of the ROADM subsystem approaches, and Table 5 summarizes the pros and cons of each of these approaches.

TABLE 4. Functionality of the main ROADM subsystem approaches. DWDM port: multi-channel port, λ port: single-channel port.

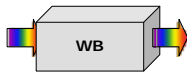

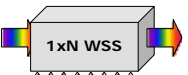
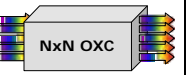
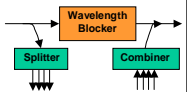

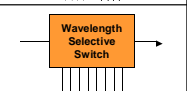

Wavelength Blocker (WB)	Small Switch Array (SSA)	Wavelength Selective Switch (WSS)	Optical Crossconnect (OXC)
			
<ul style="list-style-type: none"> • 2 DWDM ports (1 In, 1 Out) • Dynamic Channel Equalizer (DCE) with blocking capability • Blocks or attenuates λ's • No built-in Add/Drop 	<ul style="list-style-type: none"> • 2 DWDM ports (1 In, 1 Out) + 2N single-λ ports (N Add, N Drop) • One 2x2 or two 1x2 switches per λ • Switches single λ's from (In or Add) to (Out or Drop) 	<ul style="list-style-type: none"> • N+1 DWDM ports (1 In, 1 Out, N-1 Service) • Service: Add or Drop or in-service expansion • 1xN: switches λ's from In to (Out or Drop) • Nx1: switches λ's from In or (Add to Out) 	<ul style="list-style-type: none"> • 2N DWDM ports (N-1 In, N-1 Out, 1 Add, 1 Drop) • Built with 1xN WSS's or Demuxes / NxN Matrix Switches / Muxes • Switches λ's from (In or Add) to (Out or Drop)

TABLE 5. Pros and cons of the main approaches used in ROADMs being deployed by carriers.

ROADM	Configuration	Pros	Cons
WB		<ul style="list-style-type: none"> First to be ready # A/D ports = N (all λ's) 	<ul style="list-style-type: none"> Large size, Expensive Taps + splitters + filters for Drop Combiner + Tap for Add Fixed λ/port, Not degree upgradeable
SSA		<ul style="list-style-type: none"> Low cost Small size Simple software & hardware # A/D ports = N (all λ's) 	<ul style="list-style-type: none"> Fixed λ/port Not degree upgradeable
WSS		<ul style="list-style-type: none"> Any multiple λ's to any port Degree upgradeable 	<ul style="list-style-type: none"> Expensive, 2 subsystems for A/D Complex software & hardware # A/D ports M < N, Not λ upgradeable Large size
OXC		<ul style="list-style-type: none"> Any multiple λ's from any port to any port Degree upgradeable, λ upgradeable Simple software & hardware Small size 	<ul style="list-style-type: none"> Next generation for some carriers Cost if non-PLC

3. ROADM Subsystem

3.1 ROADM Subsystem Architecture and Key Properties

We propose a 40-channel ultra-low-power compact PLC-based degree-2 Type I ROADM subsystem using the SSA configuration shown in Figure 2. The subsystem includes an Add module and a Drop module.

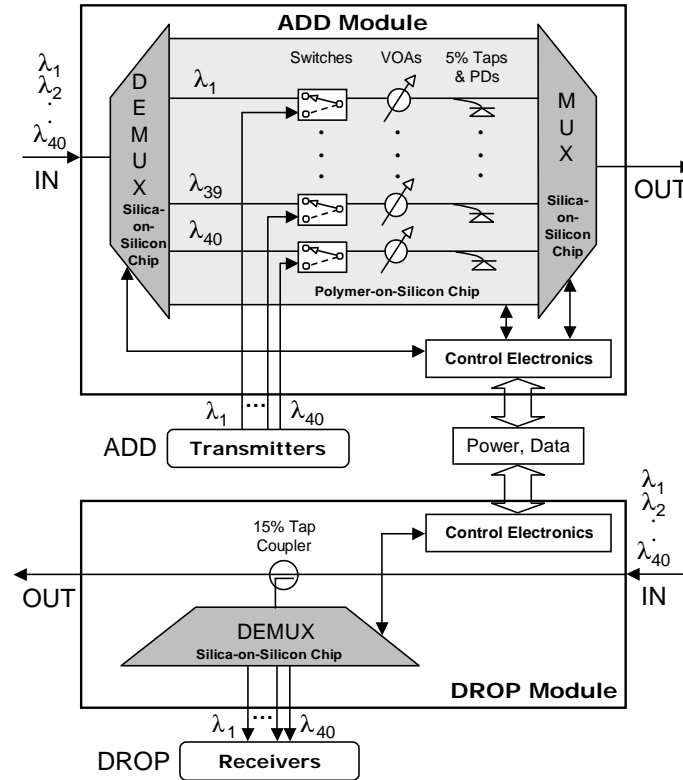


Figure 2. Architecture of the proposed 40-channel ultra-low-power compact PLC-based ROADM subsystem.

The ultra-low power consumption is achieved mainly through the use of polymers with a large thermo-optic effect for the dynamic functions, and athermal AWGs (arrayed waveguide gratings) for the multiplexers/demultiplexers (mux/demux). The compact size is achieved by using polymeric chips with compact devices that are densely packed, integrated photodiodes that are flip-chip mounted on the polymer chips, and chip-to-chip attachment of the dynamic polymer chips and the static silica chips.

3.2 ROADM Subsystem: Technologies for Low Power Consumption

The first technology used to achieve ultra-low power consumption in the ROADM is that of polymeric thermo-optic dynamic components [3]. The unique combination of large thermo-optic coefficient and low thermal conductivity in custom nano-engineered optical polymers makes these materials ideal for the dynamic devices needed in the ROADM, including the switches and the VOAs [4]. The thermo-optic effect is the change of refractive index, n , with temperature, T , and is commonly referred to as dn/dT . For an amorphous polymer, the refractive index change is predominantly due to its density change. Therefore, in order to increase the thermo-optic effect, we designed our polymers with a high coefficient of thermal expansion (CTE). In addition, these polymers have a glass transition temperature (T_g) that is well below the lower limit of telecom temperature specification (-40°C), and a large free volume. Figure 3 illustrates the refractive index change of these polymers with temperature. The measurement was performed with a thin polymer film using an Abbe refractometer. This polymer has a thermo-optic coefficient of about $-3.2 \times 10^{-4}/^\circ\text{C}$. This dn/dT is 32 times larger than that of silica, and 3-5 times larger than that of common optical polymers such as polymethylmethacrylate (PMMA) and polycarbonate (PC). A proportionate decrease in power consumption is obtained in thermo-optic devices.

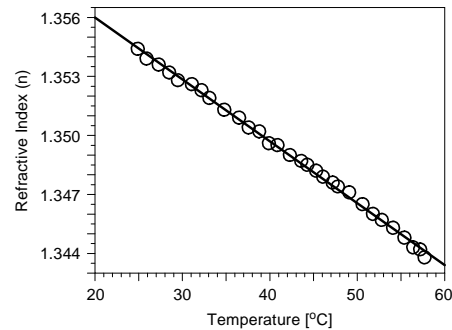


Fig. 3. Refractive index change with temperature for a DuPont optical polymer. The large thermo-optic coefficient enables ultra-low power consumption.

Thermo-optic $M \times N$ switches can be interferometric switches based on directional couplers or Mach-Zehnder interferometers (MZIs), or they can be digital optical switches (DOS's) based on X junctions or Y junctions [3]. The most widely used switch design is the Y-junction-based DOS (Y-DOS), because of its simplicity, and its insensitivity to applied electrical power, wavelength, polarization, ambient temperature, and dimensional variation. The insensitivity to applied electrical power is what enables the digital behavior. The building-block Y-branches can be connected with bends and crossings to form $M \times N$ switching matrices. Each 1×2 switch relies on adiabatic evolution of the mode profile in its two waveguides into the mode of the ON guide (the guide with the higher effective refractive index) when the OFF guide is heated to reduce its index, as shown in the computer simulation of Fig. 4a. The device is considered to have switched once it reaches the desired isolation value, which occurs at some level of electrical power dissipation in the electrodes, beyond which power level the device maintains the isolation, resulting in its well-known “digital” behavior (Fig. 4b). A typical maximum time for restoration and restructuring of multiple circuit connections for SONET is 50 ms. The measured response time for these thermo-optic switches is approximately 3 ms, a value that is adequate for system restoration.

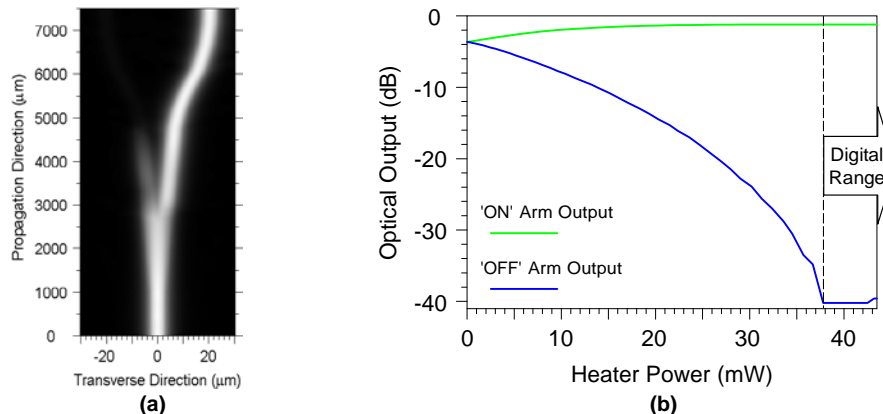


Fig. 4. (a) Computer simulation of a Y-branch digital optical switch where the left arm is heated, switching the light to the right arm, and (b) operational characteristics of the switch showing the digital behavior.

VOAs can be based on any switching principle including interferometry, modal transition, or mode confinement. Interferometric VOAs typically use an MZI where heat can be applied to at least one of the arms to induce a phase shift between the two arms before they recombine, thereby controlling the level of optical power exiting the output guide. Fig. 5a shows a simulation of this device when power is applied to thermally induce a π phase difference between the optical signals in the two arms, causing the signals at recombination to form an asymmetric mode that radiates into the cladding, since it is not supported by the single-mode output waveguide, resulting in full attenuation. Fig. 5b shows the operational characteristics of an MZI VOA exhibiting very low power consumption of about 1.4 mW for 30 dB attenuation. One performance specification that is typically difficult to achieve in VOAs is low PDL at high attenuation. The PDL achieved in our polymeric VOAs is under 0.2 dB across the entire attenuation range, a value that is lower than that achieved in any other material system.

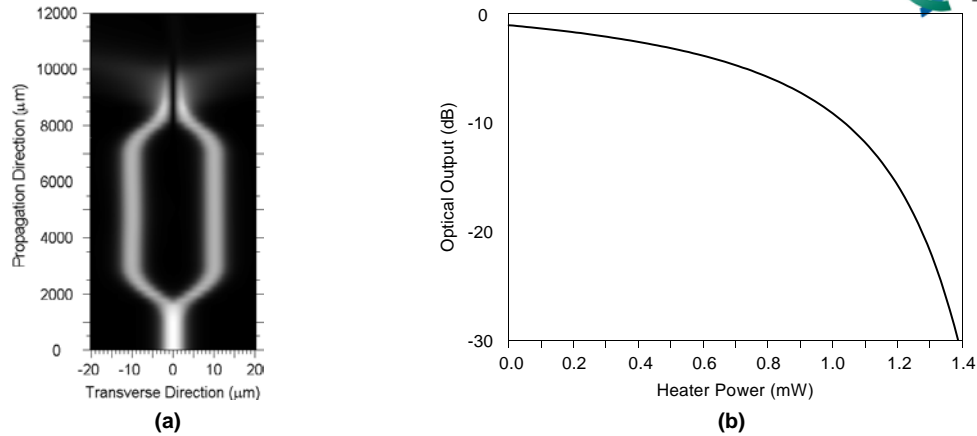


Fig. 5. (a) Computer simulation of a MZI VOA where heat is used to induce a π phase difference between the interferometer arms for full attenuation, and (b) attenuation curve of such a VOA.

The second technology used to achieve the ultra-low power consumption is athermal AWGs. The AWGs are passively compensated to achieve virtually athermal behavior for operation between -30 and $+70^\circ\text{C}$, and meet the uncontrolled environment requirements of WDM-PON, which are significantly more stringent than the central office requirements (-5 to $+70^\circ\text{C}$) of the ROADM. The power consumption is exactly zero, and the turn-on time delay is also exactly zero. The mux and demux in the proposed ROADM are 40-channel athermal AWGs with flat-top filter spectral shapes. Figure 6a shows for the athermal AWG a wavelength temperature stability that is better than $\pm 0.3 \text{ pm}/^\circ\text{C}$ from -30 to 70°C , compared to more than $10 \text{ pm}/^\circ\text{C}$ wavelength shift for a standard non-compensated AWG. The passive behavior of the athermal AWG meets the thermal stability requirements in our ROADM, where up to $1 \text{ pm}/^\circ\text{C}$ is acceptable. Figure 6b shows the athermal flat-top AWG's temperature stability in terms of both the wavelength and the filter spectral shape from -5 to 70°C . The 100-GHz channel spacing flat-top AWG has a 0.5-dB bandwidth of 0.32 nm, a 1-dB bandwidth of 0.48 nm, and a 3-dB bandwidth of 0.65 nm. Those bandwidths do not measurably change over the operating temperature range.

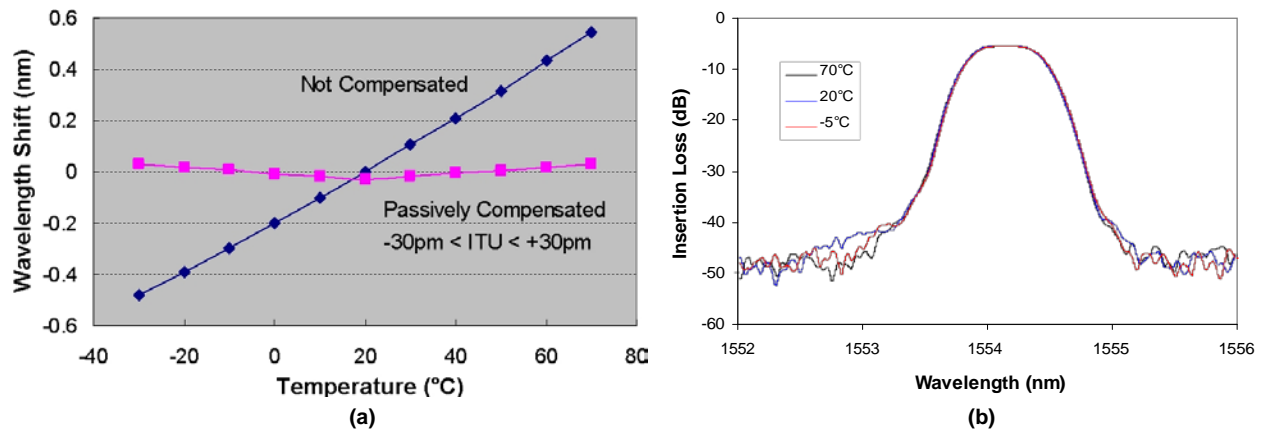


Figure 6. (a) Wavelength thermal stability of a passively compensated athermal AWG compared with a standard non-compensated AWG, over the temperature range of -30 to 70°C , and (b) thermal stability of the wavelength and spectral shape of a passively compensated flat-top athermal AWG over the central office temperature range of -5 to 70°C .

With all the above-described power consumption reduction technologies implemented, the worst-case total power consumption of this subsystem (for both the optical components and the electronic controls) over the operating temperature range is 5 W.

3.2 ROADM Subsystem: Technologies for Size Reduction

The compact size of the two modules of the ROADM subsystem is made possible by a number of technologies, the first of which being the small size of the polymeric chips. The polymer chips use compact device designs, with both switches and VOAs being only a few mm in length. Furthermore, these devices are densely packed on the chip without thermal dissipation issues or thermal crosstalk issues, because of the large thermo-optic coefficient and the low thermal conductivity of the polymer [5].

Another technology enabling small size is that of integrated photodiodes (IPD) for power monitoring [6]. We hybridly integrated photodiode arrays in our polymer platform, by flip-chip mounting array chips (Fig. 7a) on top of out-of-plane mirrors (Fig. 7b) at the ends of tap waveguides. We produce out-of-plane mirrors by ablating the polymer waveguide stack with an Excimer laser. The ablation is followed by surface treatment for planarization, then by metalization for high reflectivity. The mirror quality has been characterized by coupling light from a fiber into the input facet of a chip, and monitoring the tap-transmitted power by detection with the photodiodes. The measured excess loss and PDL were 0.3 dB and 0.1 dB, respectively, a performance level that meets the need in our ROADM. The IPDs allow significant space savings on the PCB compared with traditional external tap/PD.

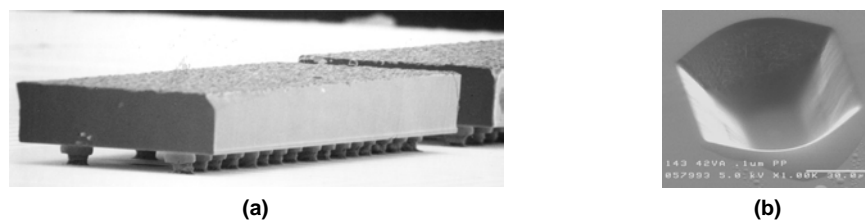


Fig. 7. Photodiode arrays (a) flip-chip mounted on top of out-of-plane mirrors (b) fabricated by Excimer laser ablation.

Further size reduction was achieved using chip-to-chip attachment of polymer-based switch/VOA/tap/IPD chips and silica AWG chips, minimizing the number of components and fiber splices in the subsystem.

The advantages of chip-to-chip integration include:

- Elimination of the fiber arrays between the chips, resulting in cost reduction
- Elimination of the space needed for fiber ribbons and splices
- Elimination of excess loss by replacing two fiber array pigtailed with a single chip-to-chip coupling
- Improvement in reliability due to the reduction in the number of interfaces

The two types of chips being attached are silica-on-silicon chips and polymer-on-silicon chips. Figure 8a shows a ROADM sub-assembly consisting of a silica AWG chip coupled to a polymer switch/VOA/tap/IPD array chip [7]. Figure 8b shows the output when channel 10 is dropped. The chip-to-chip alignment and attachment is performed in a manner similar to that of pigtailed a chip with a fiber array, and achieves a similar coupling loss of 0.1 dB.

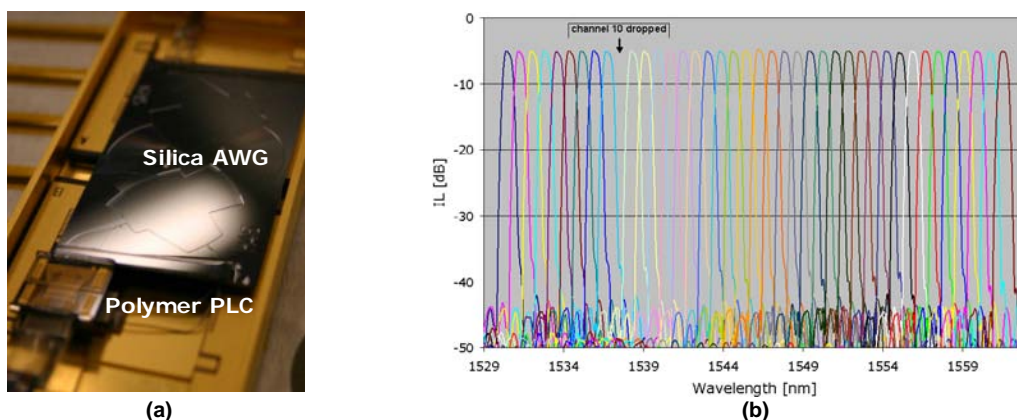


Fig. 8. (a) Subassembly of a 40-channel SSA-based Type I ROADM subsystem consisting of a pigtailed chip-to-chip assembly of a silica AWG chip and a polymer switch/VOA array chip, and (b) output of this assembly when channel 10 is dropped.

With all the above-described size reduction technologies implemented, the compact 40-channel ROADM subsystem fits within a single-slot line card.

3.3 ROADM Subsystem: Overall Performance

The ROADM subsystems are used in pairs, East and West, with the post-Drop fiber of one subsystem feeding into the pre-Add fiber of the other subsystem. The worst-case fiber-to-fiber insertion loss through a pair of such subsystems, between 1528 and 1565 nm wavelength, is 7 dB for Express signals, including the 15% tap/demux/switch/VOA/5% tap/mux. The VOAs have a dynamic range of 20 dB, the PDL is 0.2 dB at minimum insertion loss and 0.4 dB at maximum attenuation, the polarization mode dispersion (PMD) is 0.1 ps, and the chromatic dispersion (CD) is ± 10 ps/nm. The channel-to-channel crosstalk is 50 dB, the switch extinction is 50 dB, and the return loss is 50 dB.

Furthermore, our network-level simulations show that the athermal AWGs with flat-top low-ripple passbands enable cascadability of 16 ROADM nodes in a ring network. The simulation tool used was RSoft's OptSim software package. Experimentally measured spectral IL and CD of the AWGs were input into the software, and two optical amplifiers were used at each node. The simulated network is shown in Fig. 9.

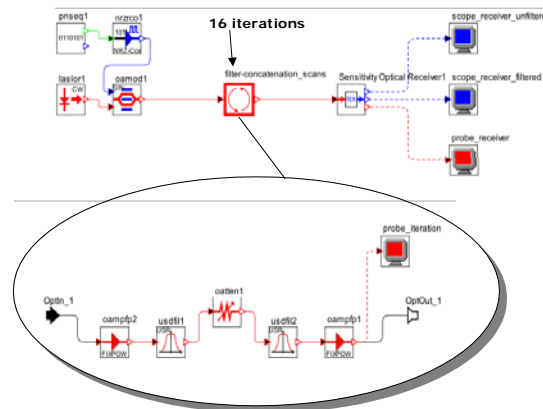


Fig. 9. Architecture of ring network simulated with 16 ROADM subsystems containing 32 flat-top AWGs.

Fig. 10 shows the eye diagrams obtained at 10 Gbps bit rate for 3 simulation runs where (1) the laser center frequency and the demux/mux filter centers are perfectly aligned, (2) the laser center frequency is misaligned by 11 GHz, and (3) the laser center frequency is misaligned by 11 GHz and the demux and mux filter centers are misaligned by -5 GHz and +5 GHz respectively. The results show that, for the types of flat-top AWGs used along with all other ROADM performance characteristics described above, in all 3 cases the eye diagram is wide open.

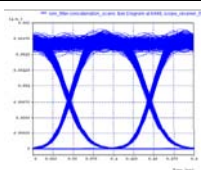
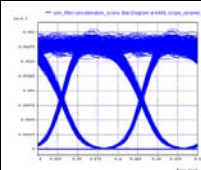
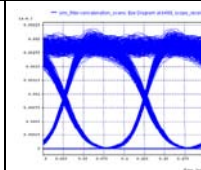
	Run 1	Run 2	Run 3
Laser Center Frequency (THz)	194.000	194.011	194.011
Demux Filter 3-dB Center (THz)	194.000	194.000	194.005
Mux Filter 3-dB Center (THz)	194.000	194.000	193.995
Eye Diagram			

Fig. 10. Eye diagrams obtained at the end of a 16-node ring network, with each node containing 2 flat-top AWGs.

The environmental stability of optical polymers is an important issue because most polymers do not have properties that are adequate for operation in communication environments. Our optical components based on custom nano-engineered thermo-optic polymers have passed Telcordia GR-1209-CORE/GR-1221-CORE qualification tests with a large margin (Fig. 11), as well as life tests at high temperature (5000 hours at 225°C) and high optical power (6000 hours at 1.5 W of 1550-nm light).

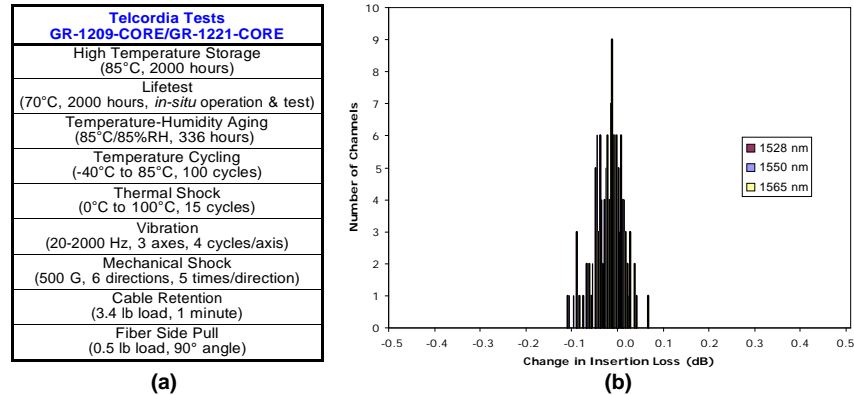


Fig. 11. (a) Telcordia GR-1209-CORE/GR-1221-CORE tests, and (b) results obtained from 11 4-channel polymer VOA parts that were subjected to these tests. The variation in insertion loss is within about ± 0.1 dB, with the Telcordia-defined pass criterion being ± 0.5 dB.

Future developments include building an SSA-based Type II ROADM. It uses a polymer-on-silicon integrated 40-channel switching/monitoring/equalizing chip, four 40×8 polymer-on-silicon matrix switches, and 4 silica-on-silicon AWG chips, for an East/West fiber pair, as shown in Fig. 12.

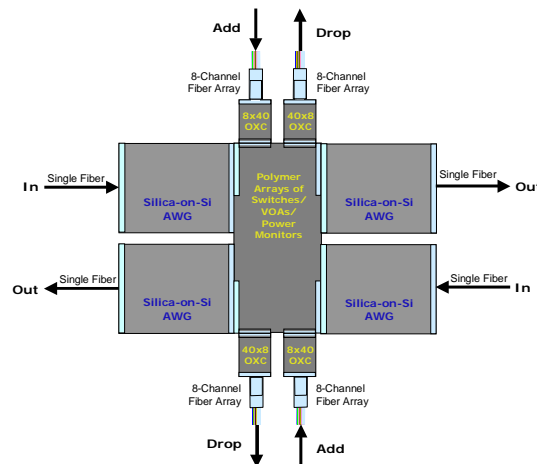


Fig. 12. A 40-channel SSA-based Type II ROADM with 8 colorless Add/Drop ports.

4. Conclusion

We reviewed the main optical component technologies used in ROADM subsystems, and described their principles of operation, designs, advantages, and challenges. We proposed a 40-channel PLC-based degree-2 Type I ROADM subsystem that exhibits ultra-low power consumption and compact size, while meeting the requirements for high optical performance, high reliability, and low cost.

Degree-2 Type I (colored) and Type II (colorless) SSA-based ROADM subsystems have broad applicability in network nodes where their functionality meets the needs of carriers and their low cost enables deployment. Systems using these types of subsystems are being deployed today in volume, and will continue to be deployed for years to come in cost-sensitive networks.

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