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ADVANCES IN ROADM TECHNOLOGIES AND SUBSYSTEMS

ABSTRACT

Until recently, reconfigurable optical add/drop multiplexer (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 devices (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.

Keywords: reconfigurable optical add/drop multiplexer, wavelength blocker, wavelength selective switch, optical cross-connect, MEMS, liquid crystal, planar lightwave circuit, silica, polymer, Telcordia qualification

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.

ROADMs allow avoiding 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.

A ROADM network element typically includes:

- Transponders
- ROADM Subsystem
- Optical Service Channel
- Optical Power Monitoring
- Amplifiers (Pre-Amp & Post-Amp)
- Dispersion Compensation Module

We focus in this manuscript on ROADM subsystems, describing the various technologies used to build them, and the different subsystem architecture enabled by each technology.

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2. ROADM SUBSYSTEM TECHNOLOGIES

Reconfigurable optical networks have needs for various types of ROADM. Figure 1 shows some of the dynamic functions needed at nodes in ring and mesh networks.

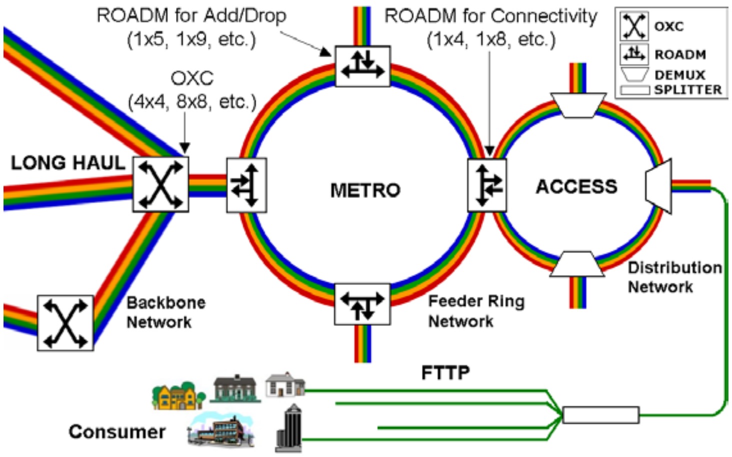


Fig. 1. Types of ROADM needed at optical network nodes.

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 1. Definition of ROADM types.

ROADM Type	Node Degree	Subsystems per Node	Add/Drop Channels	Colorless	Multiple λ's per Port
Type I ROADM	2	2 Subsystems per Degree 2 Node	N *	No	No
Type II ROADM	2	2 Subsystems per Degree 2 Node	M **	Yes	No
Wavelength Selective Switch (WSS)	N	N Subsystems per Degree N Node***	M-1 (1×M WSS) ****	Yes	Yes
Optical Cross-Connect (OXC)	N	1 Subsystem per Degree N Node	N/A (Mesh Connectivity only)	Yes	Yes

* N: number of channels
** M ≤ N
*** e.g., 4 1×4 WSS subsystems are needed for the interconnection of 2 fiber-pair rings
**** e.g., 1×5 WSS provides 1 express port and 4 Add/Drop ports

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

ROADM Type	Justification	Compatibility	Optical Components (Technology)
Type I ROADM Fixed ports	Stranded capacity reduction	Dual-use as DGE, DCE	• Wavelength Blocker (LCD or MEMS) + Fixed Filters (TFF) • Demux + Small Switch Array + 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	• Wavelength Blocker (LCD or MEMS) + Tunable Filters/Lasers • Demux + Small Switch Array + Mux + M×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	• 1×N Wavelength Selective Switch (LCD or LCoS or MEMS)
Optical Cross-Connect (OXC) Any multiple λ's from any port to any port	Mesh interconnect, mesh protection	Select locations only	• N×N Matrix Switch (PLC) • N×N Wavelength Selective Switch (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	Main Deployment Waves
Type I ROADM based on LCD WB	Up to 80 channels	Yes	Wave 1
Type I ROADM based on MEMS WB	Up to 80 channels	No	
Type I ROADM based on PLC WB	Up to 40 channels	Yes	
Type I ROADM based on PLC SSA	Up to 40 channels	Yes	Wave 2
Type II ROADM based on LCD WB	Up to 80 channels	Yes	
Type II ROADM based on MEMS	Up to 80 channels	No	
Type II ROADM based on PLC SSA	In Development	No	
WSS based on MEMS 1×N WSS	Up to 1×9	No	Wave 3A (Add/Drop)
WSS based on LCD 1×N WSS	Up to 1×4	No	Wave 3B (Ring-to-Ring Interconnect)
WSS based on LCoS 1×N WSS	In Development	No	
OXC based on PLC Matrix Switch	Up to 8×8	Yes	Wave 4 -- Preparation Stage
OXC based on MEMS N×N WSS	Development Not Started	No	
OXC based on LCD N×N WSS	Development Not Started	No	
OXC based on LCoS N×N WSS	Development Not Started	No	

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

- Wavelength Blocker (WB) – used in deployment wave 1
- Small Switch Array (SSA) – 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 summarizes the pros and cons of each of these approaches. Table 5 lists ROADM use by market and approach, some component and system vendors, and some carriers who deployed the systems. OXCs are not deployed yet.

TABLE 4. Pros and cons of the main ROADM approaches being deployed by carriers.

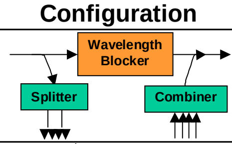
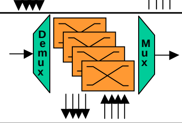
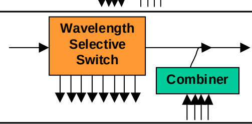
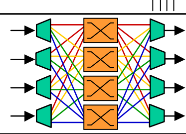
ROADM	Configuration	Pros	Cons
WB		First to be ready # A/D ports = N (all λ's)	Large size Expensive Fixed λ/port Not degree upgradeable
SSA		Low cost Small size Simple software & hardware # A/D ports = N (all λ's)	Fixed λ/port Not degree upgradeable
WSS		Any multiple λ's to any port Degree upgradeable	Expensive, extra $ for 'Add' Complex software & hardware # A/D ports M < N, not λ upgradeable Large size
OXC		Any multiple λ's from any port to any port Degree upgradeable, λ upgradeable Simple software & hardware Small size	Next generation for some carriers

TABLE 5. ROADM use by market and approach, some component and system vendors, and some carriers who deployed the systems.

Market (Approach)	Component Vendors	System Vendors	Carriers (System Suppliers)
Long-Haul (WB)	JDSU, Avanex, DuPont, CoAdna	Lucent, Ciena, Huawei, Marconi, Siemens	Qwest (Lucent), Verizon (Lucent), GigBE project (Ciena), MCI (Ciena), BT (Marconi), MCI (Siemens), AT&T (Siemens)
Metro (WB)	JDSU, Avanex, DuPont, CoAdna, LightConnect, Polychromix, Xtellus	Alcatel/Tropic, Mahi, Lucent/Movaz	Verizon, MCI, SBC (Alcatel/Tropic), BellSouth (Tellabs), NTT, Comcast (Lucent/Movaz, Cisco, Fujitsu, Nortel), Cox (Fujitsu), Bright House (Fujitsu), Shaw (Fujitsu)
Metro (SSA)	JDSU, DuPont, OpTun, Chromux, Neophotonics, NEL	Cisco, Tellabs, Hitachi	
Metro (WSS)	JDSU, DuPont, CoAdna, Engana, Metconnex, Capella	Fujitsu, Meriton, Nortel	

3. ROADM SUBSYSTEMS

3.1 Type I ROADM

A Type I ROADM is the simplest type of ROADM. It has fixed (colored) ports, and it is offered at the lowest price of any ROADM subsystem.

3.1.1 Type I ROADM – Generation 1

One type of subsystem implemented in DuPont's PLC platform is an SSA-based Type I ROADM that performs channel demultiplexing/multiplexing, add/drop switching, and optical power monitoring/load balancing (shared by the Express and Add signals). The subsystem configuration is shown in Fig. 2.

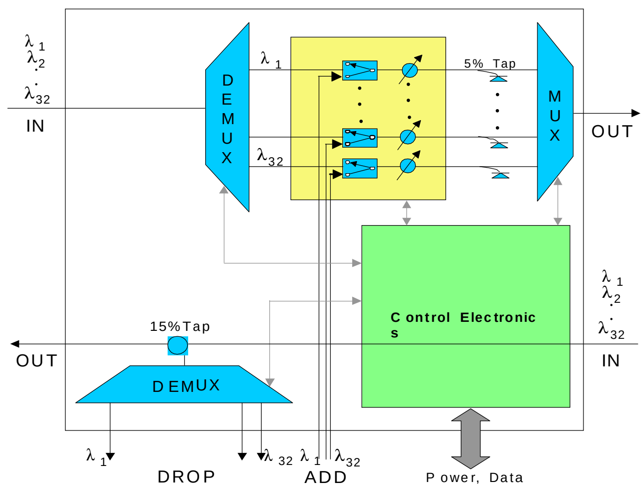


Fig. 2. Configuration of an SSA-based Gen 1 Type I ROADM subsystem implemented in DuPont's PLC platform.

In this subsystem, individually packaged chips are spliced together, namely silica-on-silicon arrayed waveguide grating (AWG) chips and polymer-on-silicon chips that include switches and VOAs.[1-3] The total number of channels N is 32. The subsystem included 5 packages: 3 32-channel AWGs and 2 16-channel switch/VOA arrays. The packages are mounted on both sides of a PCB that contains the control electronics. The entire assembly with optimized fiber management was enclosed in a case as shown schematically in Fig. 3. The case was mounted on a line card with electrical connectors, as shown in Fig. 4.

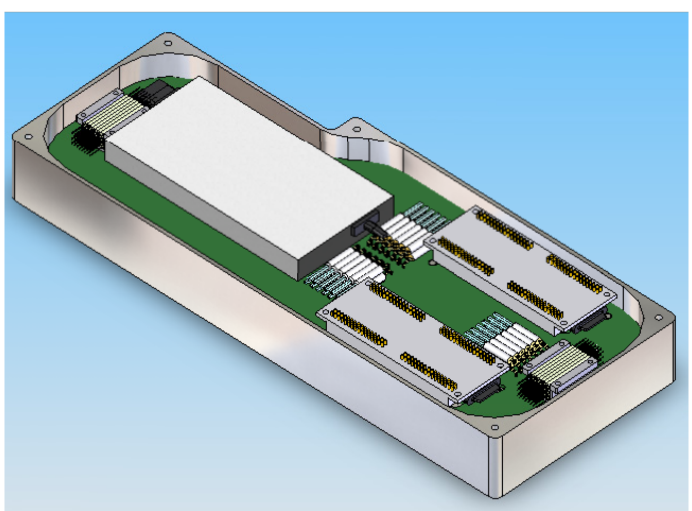


Fig. 3. Schematic of an SSA-based Gen 1 Type I ROADM subsystem.

Fig. 4. SSA-based Gen 1 Type I ROADM subsystem with optical connectors on a line card with electrical connectors.

These 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 0.5 dB at maximum attenuation, and the polarization mode dispersion (PMD) is 0.01 ps. The channel-to-channel crosstalk is 50 dB, the switch isolation (extinction) is 50 dB, and the return loss is 50 dB.

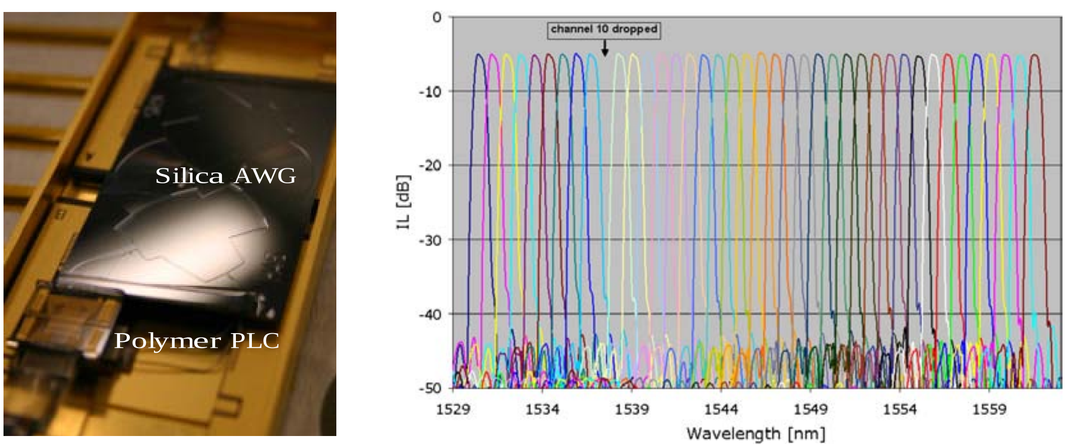
3.1.2 Type I ROADM – Generation 2

A second generation of the SSA-based Type I ROADM of Fig. 2 is also being developed at DuPont. The Gen 2 implementation involves further integration through chip-to-chip attachment.

The advantages of chip-to-chip integration include:

- Elimination of fiber arrays between chips, resulting in cost reduction
- Elimination of space needed for fiber ribbons and splices
- Elimination of excess loss by replacing two fiber array pigtails 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 AWG chips and polymer-on-silicon switch/VOA array chips. Figure 5a shows a sub-assembly of this hybrid ROADM. In this implementation, the total number of channels N was 40.[4] Figure 5b shows the output when channel 10 is dropped. The chip-to-chip alignment and attachment is performed in a manner similar to that of pigtailing a chip with a fiber array. Next-generation AWGs will be made in high-index-contrast silicon oxynitride and will be more compact.



(a) (b)

Fig. 5. (a) Subassembly of a 40-channel planar SSA-based Gen 1 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.

3.2 Type II ROADM

A Type II ROADM offers colorless Add/Drop ports. Three generations of such subsystems are described below, based on the WB and SSA approaches.

3.2.1 Type II ROADM – Generation 1

Figure 6 shows (a) a Gen 1 WB and (b) a Gen 1 SSA Type II ROADMs. The WB-based subsystem has a 'Broadcast and Select' architecture and is based on free-space optics, which can use MEMS or LCD actuation. It is mostly used in long-haul networks, and typically has 80 channels with a channel spacing of 50 GHz. The ports are made colorless through the use of tunable filters at the Drop ports and tunable lasers at the Add ports, without having an impact on the through path. This subsystem occupies 4 slots. The SSA-based PLC solution is smaller and more cost-effective. It has M colorless Add/Drop ports (M can be up to N, the total number of channels), which is achieved through the use of M×N switches. Today, N is typically 8, 16, 32, or 40 channels, and M is typically 4 or 8 ports. This subsystem occupies 1 slot. This solution is typically used in metro networks, and has a channel spacing of 100 GHz.

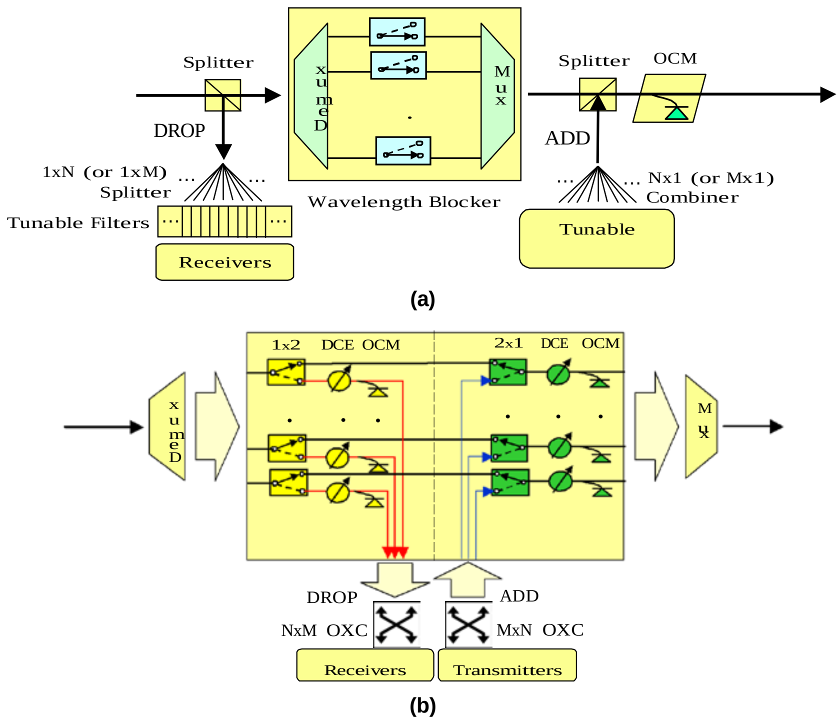
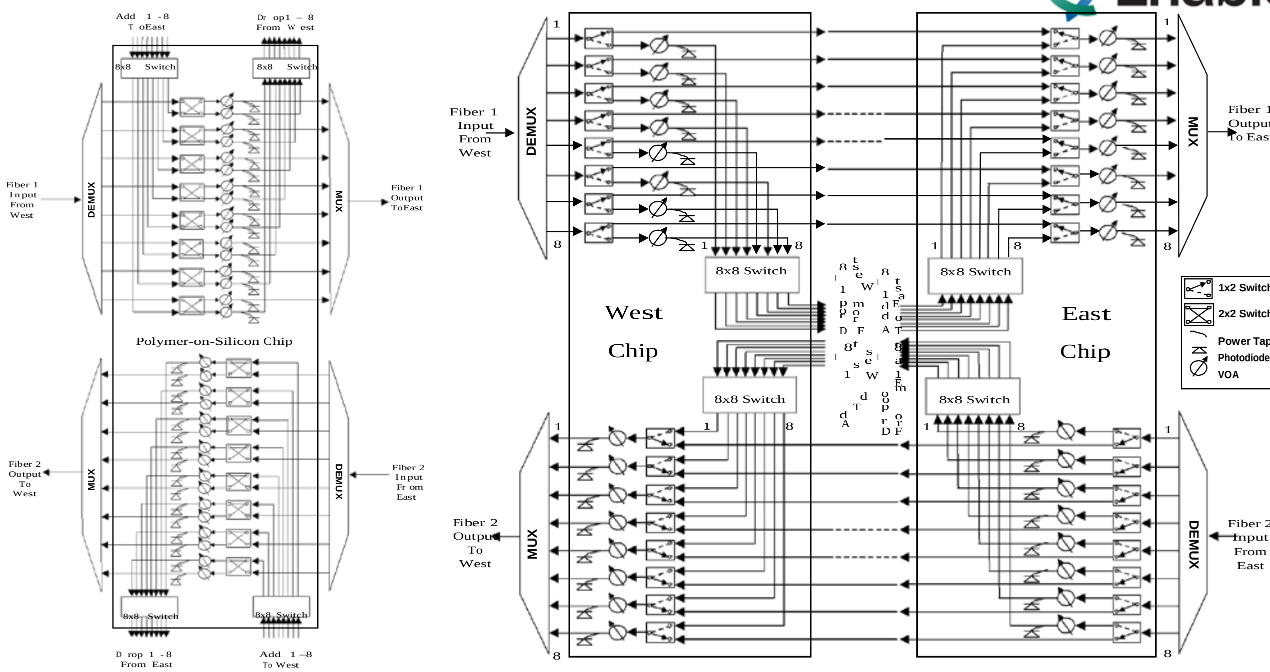


Fig. 6. (a) Architectures of Gen 1 Type II ROADM subsystems based on the (a) WB and (b) SSA approaches.

3.2.2 Type II ROADM – Generation 2

DuPont developed a Gen 2 SSA-based Type II ROADM using a polymer-on-silicon single-chip integrated channel switching/monitoring/equalizing/shuffling photonic circuit for an East/West fiber pair.[5] When this module is placed between two silica-on-silicon AWG demux/mux pairs, a self-balanced wavelength-agile ROADM functionality is achieved. Fig. 7a shows such a module for 8 channels per fiber. This subsystem includes 2×2 cross-bar switches for adding/dropping individual channels, optical power taps and integrated photodiodes for power monitoring, and VOAs for channel power equalization. Strictly non-blocking 8×8 matrix switches make the Add and the Drop ports colorless.

A two-chip solution was also developed for networks that require East/West separation, with each chip being combined with a demux/mux pair to constitute an East or a West ROADM subsystem. These two subsystems include an array of 1×2 switches for adding or dropping individual channels, optical power taps and integrated photodiodes for power monitoring, and VOAs for channel power equalization, all in a polymer-on-silicon chip, and AWGs in silica-on-silicon chips. In this configuration as well, strictly non-blocking 8×8 cross-bar switches are used at the Add and Drop ports to render them colorless.



(a) **(b)**

Fig. 7. Self-balanced 8-channel Gen 2 Type II ROADM for a WDM fiber pair in network architectures that (a) do not require East/West separation and (b) require East/West separation.

3.2.3 Type II ROADM – Generation 3

DuPont is developing a Gen 3 SSA-based Type III ROADM using a polymer-on-silicon integrated 32-channel switching/monitoring/equalizing chip, four 32×8 polymer-on-silicon matrix switches, and 4 silica-on-silicon AWG chips, for an East/West fiber pair, as shown in Fig. 8.

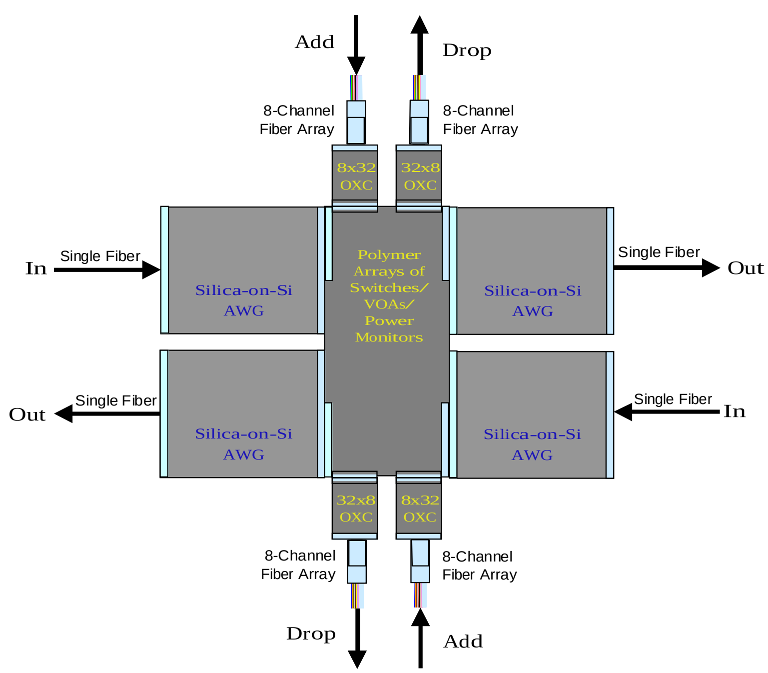


Fig. 8. Self-balanced 32-channel Gen 3 Type II ROADM with 8 colorless Add/Drop ports.

3.3 Wavelength Selective Switch

A 1×N WSS can be used either for degree-N connectivity as in a ring-to-ring interconnect, or for adding/dropping channels as a ROADM with 1 Express port and N-1 Drop ports. A WSS allows any number of channels to exit any port. When used as a ROADM, the Add functionality is implemented separately, typically through the use of a Mux and a tap. For a 1×N WSS with n channels, n 1×N switches are needed. A connectivity node where two fiber-pair rings interconnect is a degree-4 node, requiring one 1×4 WSS per fiber, and a total of 4 1×4 WSSs for the node. A fiber-pair ring Add/Drop node needing N Drop ports requires one 1×N+1 WSS per fiber, so two 1×N+1 WSSs for the node. Fig. 9 shows schematically a 1×9 WSS with 8 Drop ports.

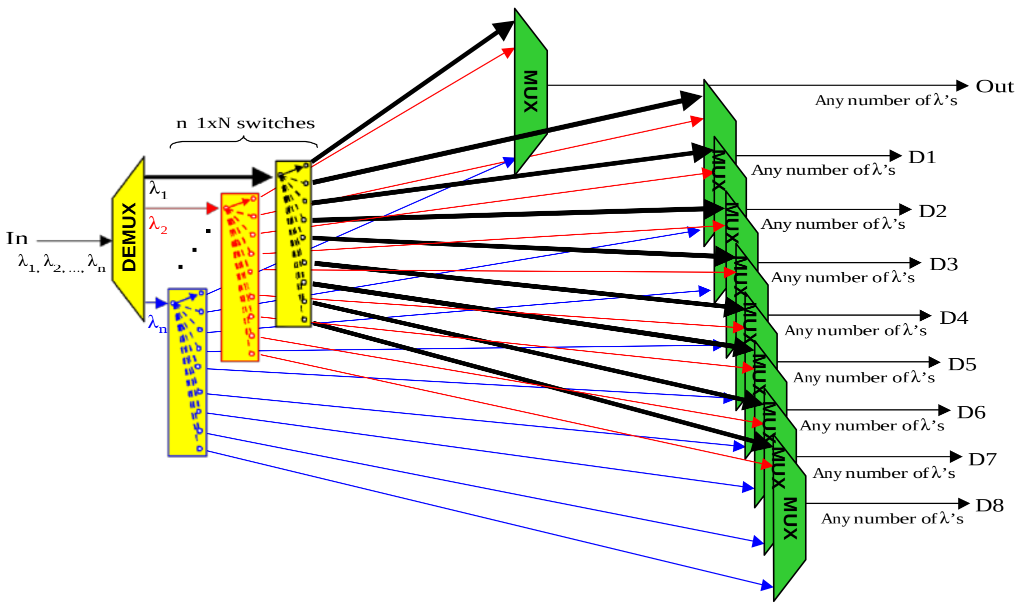


Fig. 9. Functional diagram of an n-channel 1×9 WSS used at an Add/Drop node, providing one Express port and 8 Drop ports.

The number of elements shown in the functional diagram of Fig. 9 is the actual number that would be needed if a WSS is implemented in a guided-wave platform. However, most WSS implementations use free-space optics, where typically a single bulk diffraction grating is shared for all the demultiplexing and multiplexing, as shown schematically in Fig. 10.[6] The generic WSS of Figure 10 represents the basic design used with all free-space actuation mechanisms, including MEMS, LCD, and LCoS.

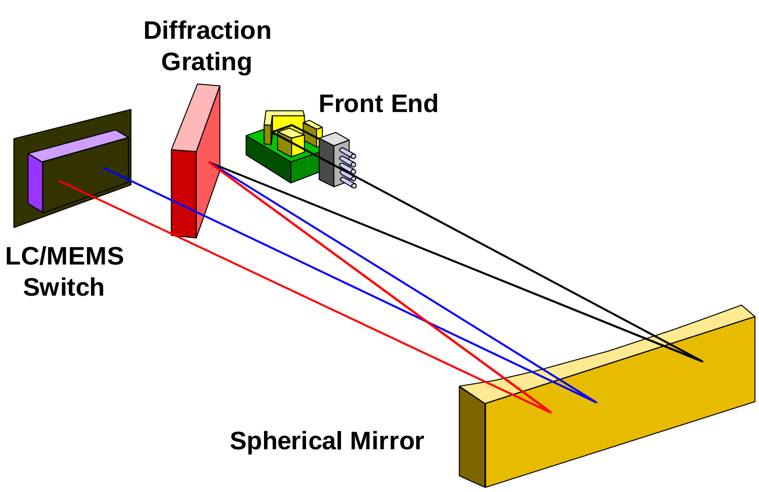


Fig. 10. Schematic diagram of a free-space WSS.

3.4 Optical Cross-Connect

OXCs used for wavelength cross-connect switching are particularly important in mesh networks. The mesh topology offers increased network capacity, efficiency, and reliability through an increased number of connections and a higher level of redundancy. This topology is highly desirable from an operational point of view, however its chief drawback is capex, because of the volume of hardware required. Although the opex savings increase the return on investment and quickly outweigh the capex spent, the upfront capex investment has been a significant barrier to the deployment of mesh networks. PLC-based solutions address the capex concern because they take advantage of integration, which inherently delivers high cost reduction for complex optical circuitry. Figure 11 shows a reconfigurable mesh network made up of interconnected islands of transparency. As depicted in that figure, an OXC is used at each node in the transparent sub-networks.

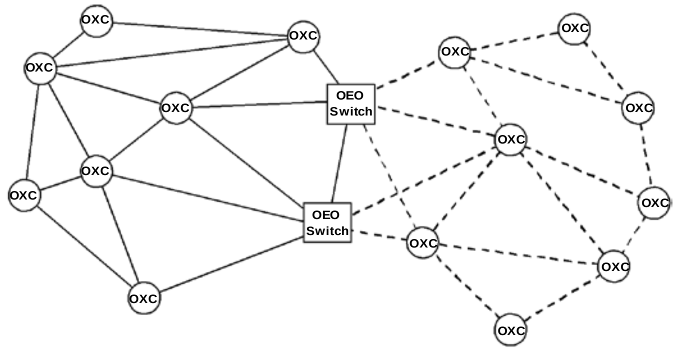


Fig. 11. A reconfigurable mesh network comprising two interconnected islands of transparency (solid and dashed). An OXC is used at each node in the transparent sub-networks.

An OXC solution that is available today is based on a polymer-on-silicon PLC platform that delivers low cost, small size, high optical performance, low electrical power consumption, high yield, high throughput, short cycle time, and fast time to market.[2]

Some of the most important criteria in an OXC are:

- Non-blocking reconfigurable node
- Reliable configuration (several medium size switch matrices)
- Optical properties (IL, XT, etc.)
- No regeneration, no wavelength conversion

For a degree N node (N fibers) and M wavelengths per fiber, N demuxes, M N×N switches, and N muxes are needed. Figure 12 shows a degree 4 node in a mesh network. A degree 4 node requires 4×4 switches, and assuming 4 channels per fiber for illustrative purposes, 4 switches are used.

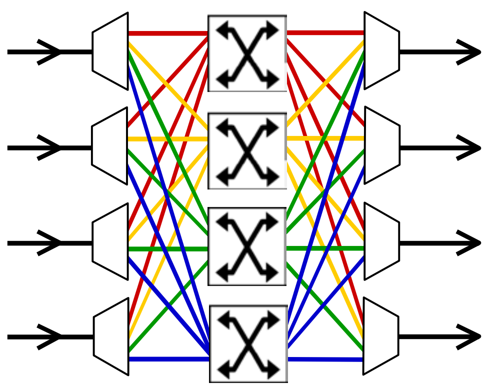


Fig. 12. A degree 4 mesh node with 4 channels per fiber.

Future-proof mesh systems are being built with degree 8 node capability, therefore requiring 8×8 matrix switches. DuPont produced an 8-channel intelligent matrix switch that performs 8×8 switching with power monitoring and power balancing on a single polymer-on-silicon PLC. This chip (Fig. 13) includes 112 1×2 switches that make up a strictly non-blocking 8×8 switch matrix, 8 optical power taps and 8 integrated photodiodes for per-channel power monitoring, and 8 VOAs for power level control. The photocurrents generated by the photodiodes are used by a feedback electronic circuit to control the VOAs, thereby achieving closed-loop automatic power balancing on all the channels. A pigtailed and packaged chip (before lid sealing) is shown in Fig. 14.

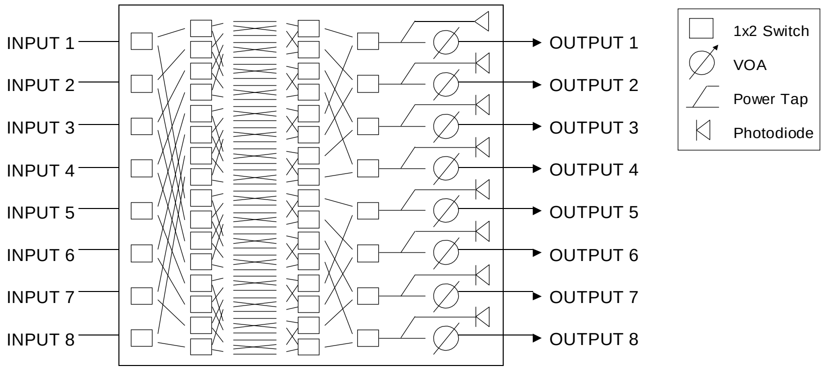


Fig. 13. Chip architecture of an 8×8 matrix switch with power monitoring and automatic power balancing.

Fig. 14. 8×8 matrix switch with power monitoring and automatic power balancing.

The fiber-to-fiber insertion loss of the component shown in Fig. 14, between 1528 and 1610 nm wavelength, is 4 dB (including 5% tapped power). The VOAs have a dynamic range of 20 dB. The PDL is 0.2 dB at minimum insertion loss and 0.5 dB at maximum attenuation. The PMD is 0.01 ps, and the CD is 0.1 ps/nm. The switch isolation (extinction) is 50 dB, the crosstalk from any port to any port is 50 dB, and the return loss is 50 dB.[7]

4. SUMMARY

We reviewed the different optical component technologies developed for use in ROADM subsystems, and described their principles of operation, designs, advantages, and challenges. The technology platforms that we covered include MEMS, LCD, LCoS, and PLC. For each technology, we described the corresponding ROADM subsystem architectures in terms of functionality, features, size, cost, and maturity. We described in detail the approaches used in the four main ROADM deployment waves: WB, SSA, WSS, and OXC.

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