MOSAIC: A Multiwavelength Optical Subcarrier Multiplexed Controlled Network

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Abstract— **The experimental demonstration of MOSAIC, a reconfigurable WDM add/drop network with subcarrier multiplexed control, is presented. The MOSAIC network implements the optical layer protocol to support bit-rate transparent multichannel lightpaths. Two types of add/drop multiplexers are implemented and combined in a three-node experiment. Multihop lightpaths are established giving an end-to-end bit error rate of better than 10^{-9} at 1.2 Gbps. The reconfigurable add/drop multiplexer is based on a novel dilated 2×2 acoustooptic filter switch crossconnect and an analog optoelectronic crossconnect that drives a ten-wavelength laser array transmitter up to 2.5 Gbps per wavelength. The fixed wavelength add/drop multiplexer utilizes a fast digitally tunable laser transmitter. Both add/drop multiplexers support bit-rate transparent 2R optoelectronic regeneration as well as wavelength translation. Subcarrier multiplexing on each wavelength is used to support channel state monitoring and channel equalization as well as transmission of digital network control information. Systems experiments demonstrate cascaded 2R optoelectronic regeneration with wavelength translation and cascaded multichannel optical switching with up to seven hops. It is shown that combining cascaded 2R optoelectronic regeneration with cascaded multichannnel optical switching can be used to balance jitter accumulation and amplified spontaneous emission generated amplitude noise to yield high signal-to-noise ratio for lightpaths.**

Index Terms—**Optical add/drop multiplexers, optical networks, optical subcarrier multiplexing, optical transport networks, reconfigurable add/drop multiplexers, transparent optical networks, wavelength division multiplexing.**

I. INTRODUCTION

RECONFIGURABLE wavelength division multiplexed (WDM) add/drop fiber transport networks have the potential to satisfy the demands of future broadband communications applications [1]. Reconfigurability in the add/drop multiplexers will result in increased network configuration flexibility, remote provisioning, and protection switching capabilities.

Second-generation WDM optical transport networks must set up and maintain lightpaths that support the optical network layer in the network hierarchy [2], [3]. At the physical layer, these lightpaths may incorporate optical and electronic switching, signal regeneration, channel equalization, and wavelength conversion to ensure network scalability and add/drop node cascadability. Over the last several years, multiple WDM transport network testbed demonstrations have been reported [4]–[7].

In this paper we describe the design, implementation, and demonstration of the MOSAIC-network reconfigurable add/drop WDM testbed. This testbed was designed to study the issues of scalability, cascadability, bit-rate transparency, the tradeoffs between optical and electronic switching, and optoelectronic wavelength translation. The MOSAIC testbed was also designed to investigate network element functionality and the support systems needed to integrate enabling technologies into a network environment. In Section II we describe the relationship between MOSAIC and the optical layer protocol stack. In the same section we also describe the add/drop multiplexer (ADM) node design. In Section III, we describe the ADM node subsystems in further detail and report several experimental results including input channel monitoring, multichannel bit error rate (BER) measurement of a dilated acoustooptic tunable filter (AOTF) switch, optical channel equalization, and bit-rate transparent operation of a optoelectronic-optical crossconnect. Section IV describes results of network level demonstrations including cascaded, bit-rate independent, multihop optical bypass and cascaded, bit-rate independent, optoelectronic-optic (OEO) bypass with wavelength translation. Finally, we demonstrate lightpath establishment in a three-node ring network that traverses 150 km fiber and multiple ADM's with optical and optoelectronic drop-and-continue operations, optical bypasses and optoelectronic-optic wavelength translation with 2R regeneration.

II. MOSAIC ARCHITECTURE

MOSAIC supports the optical layer of second generation optical networks [2], [8]. The optical layer provides *lightpaths*, or end-to-end connections, across the network [3], [9], [10] with dedicated use of an entire wavelength per link in a path between source and destination. For each lightpath, the full bandwidth of a wavelength per link is provided to the higher layer.

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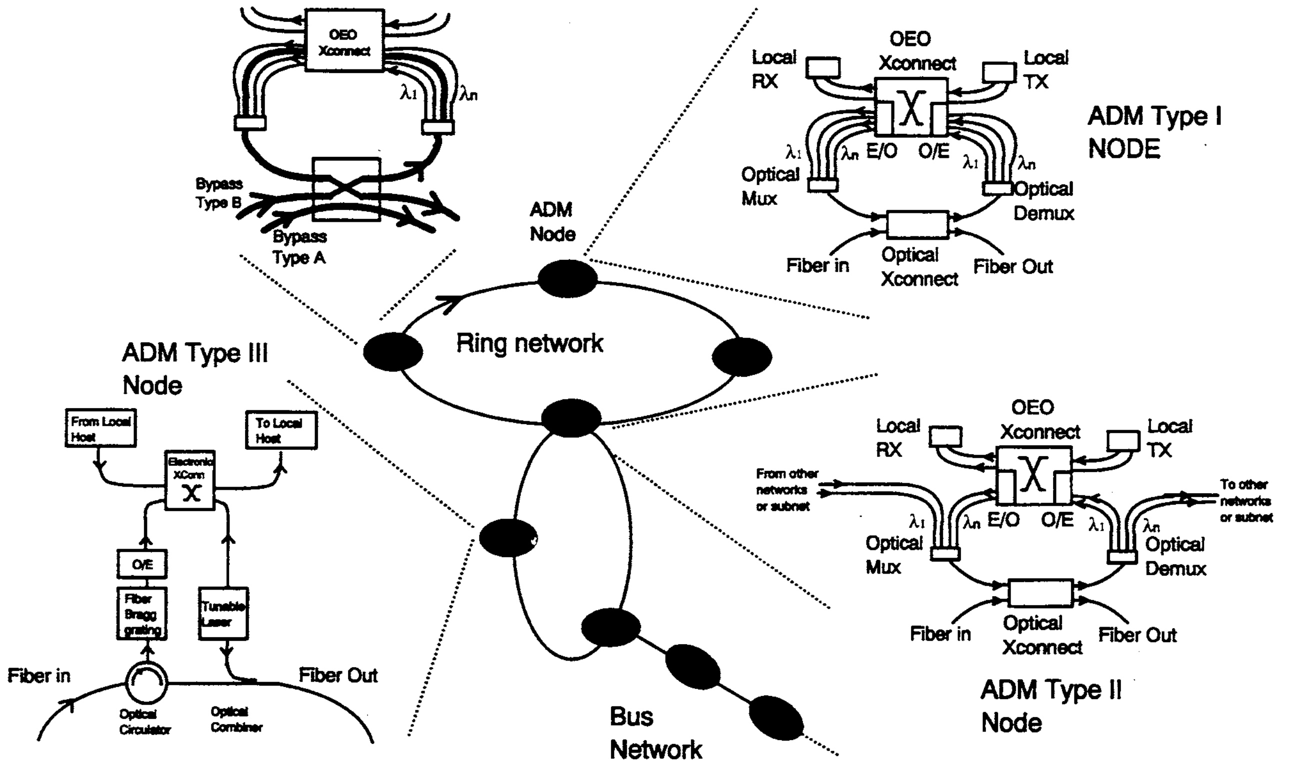


Fig. 1. MOSAIC WDM add/drop transparent network architecture illustrating three types of ADM nodes. Optical and OEO bypass with wavelength translation are also illustrated.

MOSAIC is an add/drop multiwavelength network that may be connected in a ring or bus fashion as shown in Fig. 1. Three types of ADM's have been designed and implemented and are shown in Fig. 1. Type I and II ADM's support multiwavelength add/drop, level regeneration, and wavelength-translation. The Type I ADM can pass a lightpath from the input fiber to the output fiber or add/drop data between the network and a local host. The Type II ADM, in addition to performing the basic functions of a Type I ADM, can route a lightpath to another optical network or subnet. The Type III ADM drops a single fixed wavelength and can add or wavelength translate to one of any network supported wavelengths.

The Type I ADM incorporates an OEO crossconnect based on arrayed detectors and a multiwavelength source fully connected to the mux/demux and the local host. The Type II ADM maintains a subset of the mux/demux channels in optical format for routing to other networks. The Type III ADM utilizes a fixed wavelength drop port and wavelength tunable transmitter. Two bypass modes, A and B, are supported and are shown in Fig. 1. Bypass mode A is used to optically route a wavelength without wavelength translation. Bypass mode B mode, also referred to as *drop-and-continue*, is used to route a wavelength through the bit-rate transparent OEOXC with level restoration and the option to perform wavelength translation. The Type B bypass mode also supports digital broadcasting [7].

The MOSAIC network elements (e.g., ADM's) contain hardware components that are applicable to a broader class of optical networking architecture and specific hardware components that are designed for MOSAIC. The four basic components within a MOSAIC ADM are a WDM optical crossconnect (WDM-OXC), an optoelectronic-optical crossconnect (OEOXC), a wavelength mux/demux, and a node control processor (NCP). The WDM-OXC performs the following general functions: rearrangable optically transparent crossconnections on a per wavelength basis, monitoring which wavelengths are present at the ADM input, extraction of control data on the incoming wavelengths, and equalization of the per wavelength power at the ADM output. Hardware that is specific to MOSAIC involves detection and decoding of subcarrier signals using multichannel RF/digital receivers at the ADM input and multichannel RF receivers for channel equalization at the ADM output. The OEOXC performs the general functions of a rearrangable analog electronic crossconnect with optoelectronic conversion and thresholding. The OEOXC outputs are wavelength division multiplexed, and therefore, wavelength conversion can be performed. Functions in the OEOXC specific to MOSAIC involve reinsertion of subcarrier multiplexed control signals with the retransmitted data channels. The wavelength mux/demux and NCP are generic functions applicable to most optical network architectures.

A. Subcarrier Signaling and Channel Monitoring

Several techniques to communicate control information in a WDM optical network have been studied and implemented including in-band signaling [4], out-of-band signaling on a separate control wavelength [11] and optical subcarrier multiplexing (OSCM) [12], [13].

Out-of-band signaling by OSCM is used in MOSAIC to achieve multiple functions simultaneously including wavelength identification, wavelength power monitoring and digital control signaling. In comparison with transmitting control on a separate wavelength, the subcarrier per wavelength approach supports distributed network control with a synchronous recovery of wavelength identification, wavelength power, and control data using a common circuit and requires only a single laser at each users transmitter and a single photodetector at each monitoring or detection point. The subcarrier portions of the transmitters and receivers can be fabricated using low cost monolithic-microwave integrated circuit (MMIC) technology that has been developed for wireless communications [13].

Potential limitations to OSCM include fiber nonlinearities and dispersion and detector saturation. Crosstalk due to fiber four-wave mixing [14] is low as there is a single subcarrier per wavelength and the relative power of the subcarrier component is much less than the baseband component of the optical signal. Signal cancellation and fading due to dispersion can be overcome using single sideband subcarrier modulation techniques as demonstrated in [15]. Monitoring of many subcarrier channels using a single photodetector can be achieved with new high power traveling wave photodetector designs [16].

B. ADM Node Architecture

The main ADM components are shown in Fig. 2(a) and (b) and are outlined below.

1) The WDM Optical Crossconnect (WDM-OXC): Used in both Type A and B bypass states, the WDM-OXC consists of four subsystems: an in-line optical amplifier, a WDM input channel state monitor, a WDM optical switch, and a WDM channel equalizer. All wavelengths at the node input are amplified using an erbium doped fiber amplifier (EDFA). The WDM input channel state monitor is used to determine the set of wavelengths present at the ADM input and to decode channel control information. Individual wavelengths are tagged with a subcarrier frequency that corresponds to that particular wavelength. A portion of the optical input is tapped at the WDM-OXC input, photodetected, and demodulated using a parallel channel subcarrier receiver to recover network and channel control information. Type I and II ADM's use the WDM dilated 2 × 2 acoustooptic switch architecture reported in [17] and [18]. Type III ADM uses a broadband optical circulator and wavelength selective filter to drop a single wavelength and bypass the remaining wavelengths. The channel equalizer measures the power per wavelength at the ADM output and adjusts AOTF RF drive power per channel.

2) The OEO Crossconnect (OEOXC): The OEO crossconnect (OEOXC) is used to implement a Type B bypass with the capability of bit-rate independent optoelectronic wavelength translation with 2R signal regeneration or add/drop with the local host. The Type I and II OEOXC's contain an analog electronic crossbar switch with output thresholding (2R), a photodetector array, and a WDM laser array configured similar to [7]. The OEOXC in the Type III ADM uses a wide wavelength tunable laser transmitter [19] and single photodetector in place of the multiwavelength laser array and arrayed receiver. The 2R electronic crossbar switch is an $(N+M) \times (N+M)$ strictly nonblocking bit-rate transparent switch with N input and N output ports interfacing to a $1 \times N$ photodetector array and a $1 \times N$ multiwavelength laser array, respectively. The remaining M input and M output ports are used to interface to the local host. For the Type I and II ADM's, $N = W$, the number of network wavelengths; for the Type I ADM, $N = M = 1$. The electronic crossbar switch used in our experimental demonstration is a 2R reconfigurable regenerator that is digitally transparent up to 2.5 Gbps.

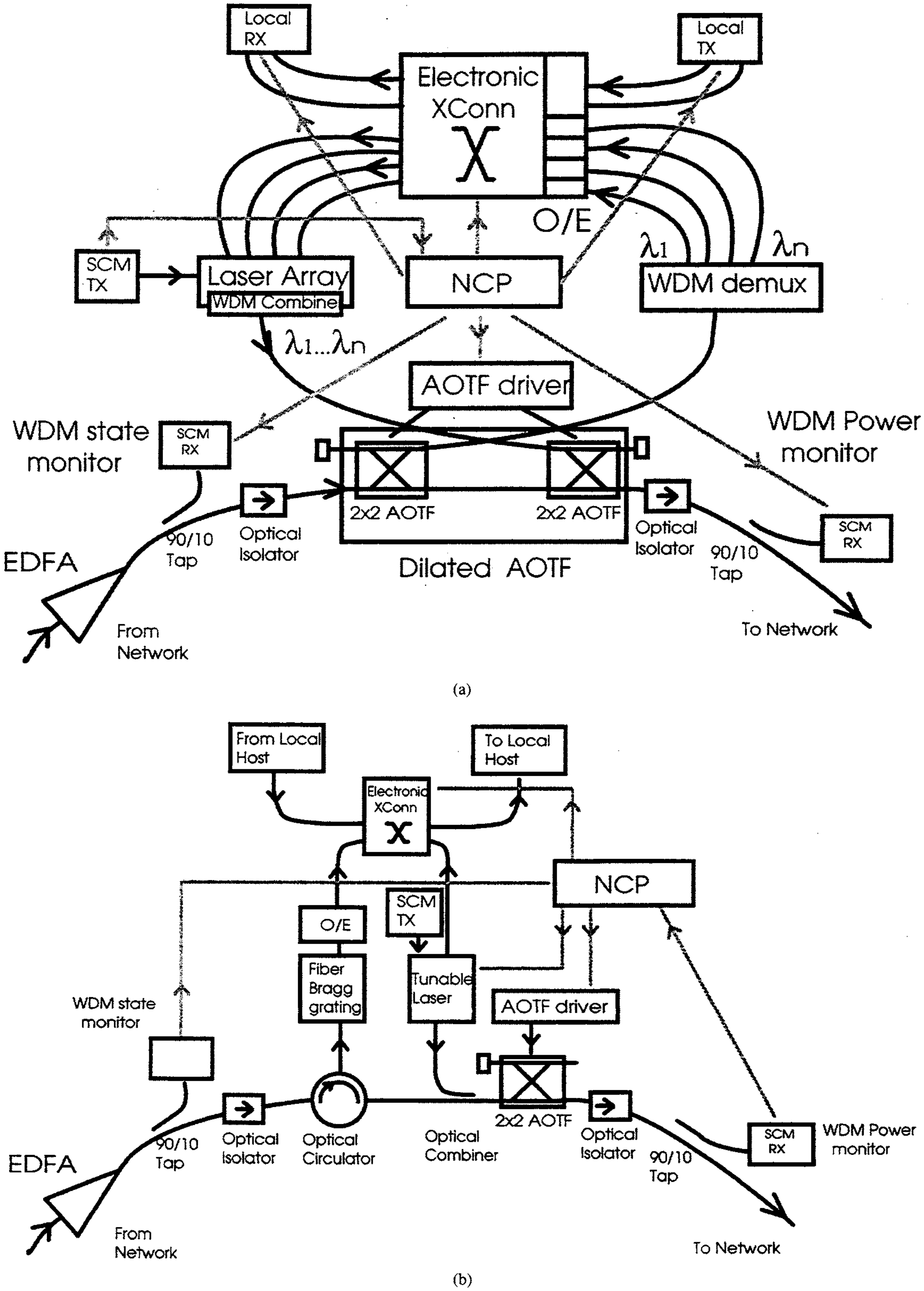
3) The WDM Multiplexer and Demultiplexer: The WDM multiplexer and demultiplexer is responsible for separating and combining lightpaths in add/drop or bypass paths. In the Type I ADM node, the number of inputs/outputs to the mux/demuxes are equal to the number optical inputs to the OEOXC. For a Type II ADM, the mux/demux size is greater than the OEOXC optical inputs so that a subset of lightpaths may be remultiplexed and forwarded to another network or subnet as shown in Fig. 1. The Type III ADM utilizes a filter that routes one wavelength into the node and passes or reflects the remaining wavelengths to the ADM output.

4) The ADM Node Control Processor (NCP): The NCP coordinates all functions within an ADM node and processes network management and control information. The NCP coordinates signal connection requests, keeps track of the ADM input state, acknowledges availability of local lightpath resources, and controls the state of the WDM-OXC and OEOXC. Network signaling is carried out using optical subcarrier multiplexing where an RF subcarrier is modulated onto each wavelength in addition to the baseband information. Each wavelength contains a unique subcarrier used for wavelength identification [20] and carries low bit rate (order 100 Mbps) data for network and channel control information.

C. Optical Layer Implementation

The MOSAIC ADM node structure can be mapped onto the International Telecommunication Union (ITU) recommended optical layer for second-generation optical networks [2], [3], [8]. In this model, the optical layer provides lightpaths to higher protocol layers (e.g., SONET/SDH, ATM). We have established the relationship between the three optical layers and MOSAIC node functions as shown in Table I.

The optical channel (OC), or lightpath layer, is responsible for end-to-end routing of lightpaths. The OC layer determines the best paths for a given lightpath including combinations of bypass modes and controls the optical multiplex section described below. The optical multiplex section (OMS) layer is responsible for configuring the node in an add/drop or bypass state for each lightpath. This layer is also responsible for separating and combining wavelengths and performing the wavelength translation function. The optical amplifier section (OAS) layer handles the link level functions of data transmission and ensures the necessary SNR is delivered between lightpath end points. This layer can also decide on optimal combinations of optical and OEO bypass to maximize the lightpath SNR.



(a)

(b)

Fig. 2. ADM node subsystems and components: (a) Type I: multichannel add/drop with wavelength translation and optical and 2R OEO switching and (b) Type III: single channel drop with single tunable wavelength add and 2R OEO wavelength translation.

An example of how the MOSAIC optical layer supports two simultaneous lightpaths is shown in Fig. 3. Lightpaths A and B, indicated in the figure, are add/dropped at different nodes and traverse a different combination of network elements (NE's). For each lightpath, the OM section is configured as a Type A or Type B bypass. In each case, the originating and

TABLE I
OPTICAL LAYERS

Layer	Functions	Physical components
Optical Channel OC	• End to end routing of lightpaths • Signaling connection requests • Monitoring connection requests • Monitoring network state • Acknowledge of lighpath availability • Control of resources to set lightpath • Establish routing map	• Network controller • Baseband transmitter and receivers • Subcarriers transmitter and receivers • Input channel state monitor
Optical Multiplex Section OMS	• Configure mux section as bypass Type A or B, add or drop • Wavelength conversion • Wavelength separation	• Dilated AOTF • Electronic cross-connect • Optical Mu/Demultiplexers
Optical Amplifier Section OAS	• Optical amplification • Channel equalization • SNR quality monitoring • Transmitter • Receiver • Regeneration (level and/or timing restoration, OEO and all-optical)	• EDFA • Dilated AOTF • Baseband transmitter and receivers • Subcarrier transmitter and receivers • Electronic cross-connect

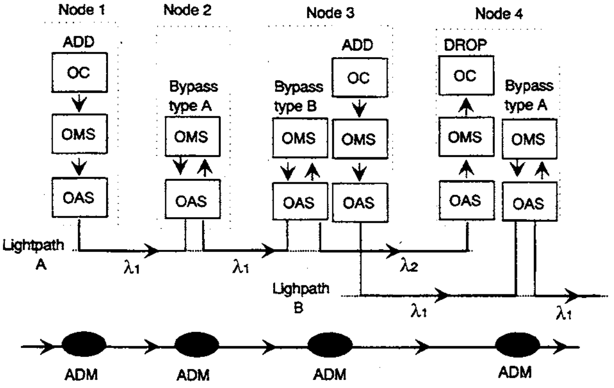


Fig. 3. Example of MOSAIC supporting two lightpaths using ITU optical layer model.

terminating NE's pass the lightpath through the OC section and in all cases the lightpath passes through the OM and OA sections. In this example, lightpath A is added to the network on λ_1 at node 1 and lightpath B is added to the network on λ_1 at node 3. Lightpath A traverses one node in the Bypass A state and one node in the Bypass B state that is used to convert the wavelength to λ_2. This wavelength translation is needed prevent blocking of lightpath A. Node 3 is configured as a bypass Type B node for lightpath A and an add node for lightpath B. Lightpath A is dropped at node 4, and lightpath B is Type A bypassed at node for further routing in the network.

III. MOSAIC SUBSYSTEMS

In this section we describe in more detail the WDM-OXC and OEOXC subsystems and present experimental results. The optical multiplexer is internal to the laser array chip, while a Lucent 1 × 8 silica on silicon integrated optic router was used as the wavelength demultiplexer and is shown in Fig. 5.

A. WDM Optical Crossconnect (WDM-OXC)

Type I and II OXC's allow reconfigurable WDM add, drop, and bypass functions. The Type III OXC provides similar functions using fixed wavelength drop, and single tunable wavelength add and translation. Subsystem implementations and demonstrations are described below:

1) Optical WDM Channel Monitoring: With OSCM, only a single photodetector is required to monitor the state and control information of all incoming channels. A fiber tap is used to direct a fraction of the input optical power to the photodetector as shown in Fig. 4. The recovered electrical signals are demultiplexed using heterodyne frequency down conversion and amplitude detection as shown in Fig. 4. The four-channel subcarrier receiver is shown in the experimental ADM node in Fig. 5. Local VCO's provide continuous tuning from 4.8 to 6.2 GHz. MMIC mixers are used to down-convert RF channels to 300 MHz. Bit recovery of 100 Mbps control and detection of average subcarrier power is achieved using LPF's.

2) Multichannel Dilated WDM Optical Switch for Type I and II ADM's: The multichannel WDM-OXC is based on a novel dilated switch constructed from two cascaded 2 × 2 AOTF switches [18] and is shown in Fig. 6. AOTF technology has evolved significantly over the last several years [21]. Primary limitations in dense WDM systems are related to bit errors induced during multichannel exchange/bypass operations [22], [23] and may be overcome using techniques like spatial and/or wavelength dilation [24]. The MOSAIC dilated optical switch consists of cascaded, polarization independent, fully integrated apodized AOTF's made by Pirelli Cavi S.p.A [17] with filter bandwidth and sidelobe suppression designed for a 3.2 nm spaced WDM network. The first stage independently routes wavelengths $[\lambda_i, \cdots, \lambda_j]$ to the second stage or to the wavelength demultiplexer. The second stage is used to improve the signal extinction ratio, decrease inter- and intrachannel crosstalk from the first stage, and to route $[\lambda_n, \cdots, \lambda_m]$ from the OEOXC to the network. The switching state of the dilated AOTF switch is determined by the applied RF frequencies $[f_i, \cdots, f_j]$ to both AOTF switches. This configuration exhibited better than 30 dB rejection on the dropped channel and a suppression of more than 18 dB on the sidelobes at the drop port. This rejection is further improved by the WDM

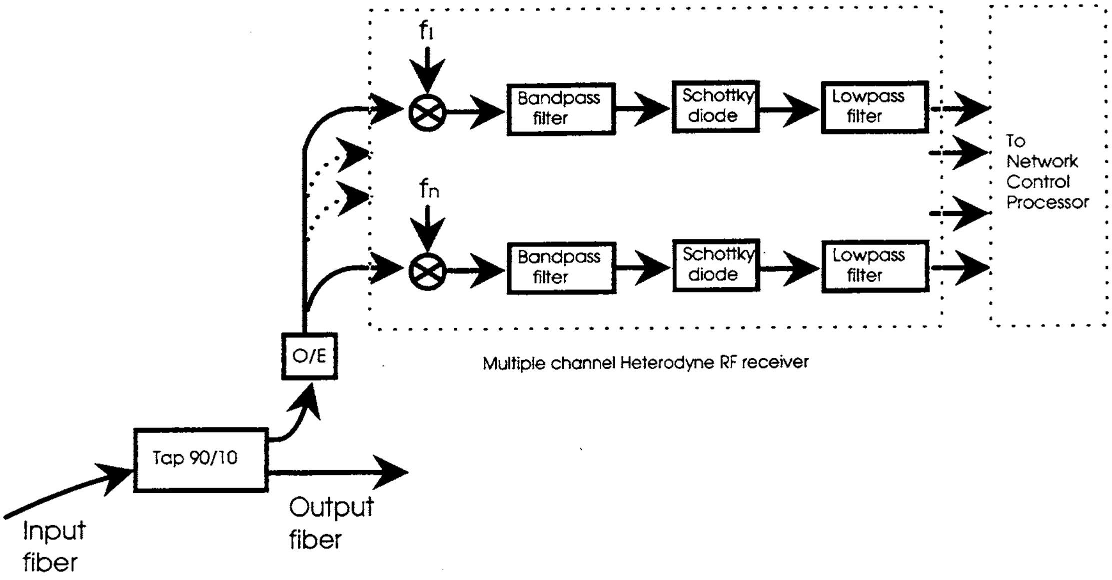


Fig. 4. Schematic for subcarrier-based WDM channel monitoring and channel equalization subsystems.

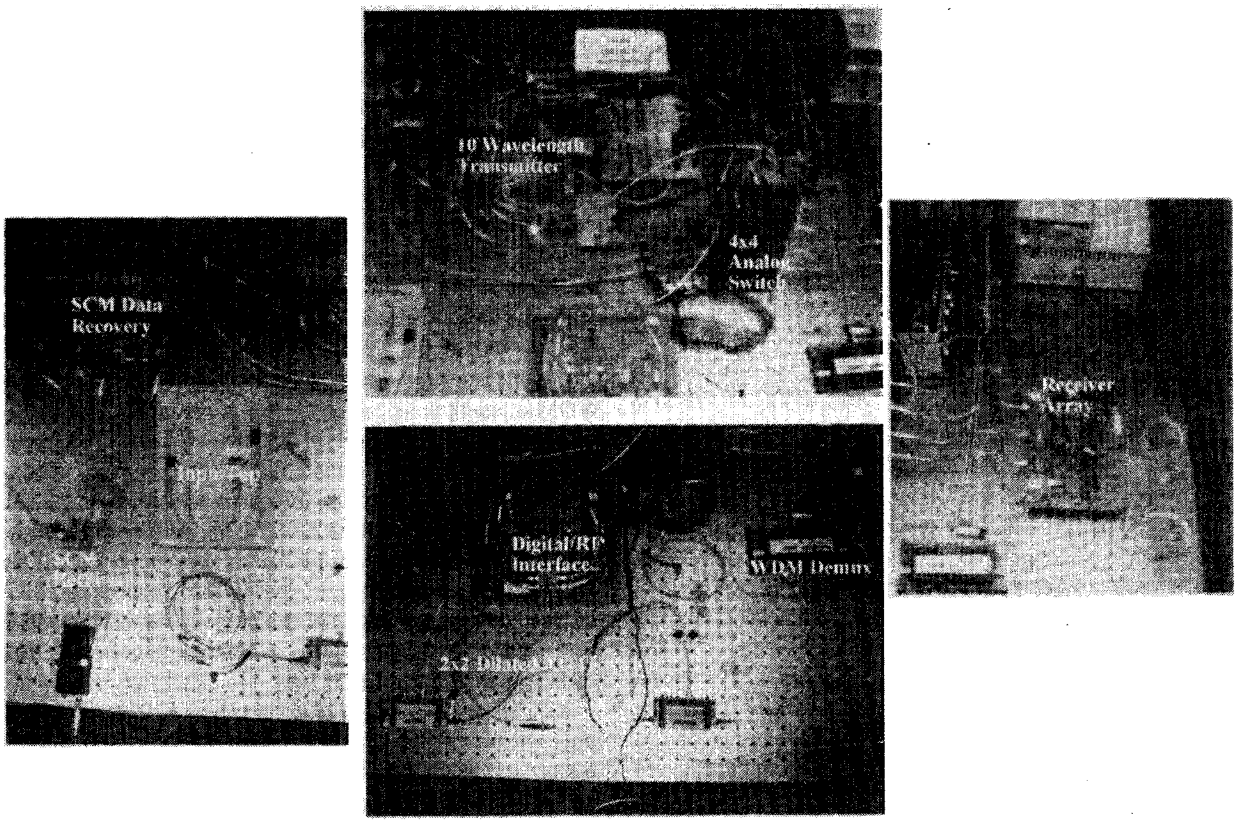


Fig. 5. Photograph of experimentally demonstrated Type II ADM.

demux with a measured power penalty less than 0.3 dB at $P(e) = 10^{-9}$ for coherent and incoherent crosstalk.

Demonstration of multichannel add/drop is shown in Fig. 7. Four WDM channels were applied at the input [Fig. 7(a)] and channels 1 and 3 were dropped. The optical signals at the second stage output are shown in Fig. 7(b) with the dropped channels rejected by more than 30 dB. The dropped channels after the demux are shown in Fig. 7(c) and (d) demonstrating better than 30 dB isolation.

The performance of an AOTF switch that is controlled with multiple RF frequencies [22], [23] is a key issue for multichannel ADM's. Fig. 8(a) shows the measured BER as a function of power at the drop port when a signal at $\lambda_0 = 1556.8$ nm was dropped by applying an RF signal at