Reconfigurable Optical Add-Drop Multiplexer Using a Polymer Integrated Photonic Lightwave Circuit

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We have developed a fully functional reconfigurable optical add-drop multiplexer (ROADM) switch module using a polymer integrated photonic lightwave circuit technology. The polymer variable optical attenuator (VOA) array and digital optical switch array are integrated into one polymer PLC chip and packaged to form a 10-channel VOA integrated optical switch module. Four of these optical switch modules are used in the ROADM switch module to execute 40-channel switching and power equalization. As a wavelength division multiplexer (WDM) filter device, two C-band 40-channel athermal arrayed waveguide grating WDMs are used in the ROADM module. Optical power monitoring of each channel is carried out using a 5% tap PD. A controller and firmware having the functions of a 40-channel switch and VOA control, optical power monitoring, as well as TEC temperature control, and data communication interfaces are also developed in this study.

Keywords: iPLC, ROADM, DOS, VOA, polymer.

I. Introduction

A reconfigurable optical add-drop multiplexer (ROADM) switch module is a key device to selectively add or drop particular channels among multiple wavelength channels in a wavelength division multiplexing (WDM) optical network. In particular, an ROADM module enables the remote control of signal path configuration in a WDM network node, which can enormously reduce the operational expense of a WDM network. The increasing demand for an access optical network accompanied by the recent real-scale spread of FTTH will cause a sharp increase of traffic in metro networks. Therefore, to deal with this traffic increase more efficiently, it is necessary to give a network the flexibility of actively reconfiguring the signal path of various traffic loads in a remote node from the central office. This flexibility of reconfiguring network nodes is essential for the evolution of an existing network into an intellectual optical network, and an ROADM module is the most important device for this purpose.

There are several approaches to developing an ROADM module, of which the one based on silica waveguide optical devices is the most successful. However, there are a few reports on an ROADM module based on polymer optical devices that are regarded as more suitable for mass production, lower cost, and lower power consumption in switching operation. In this study, we report on a fully functional ROADM module based on polymer integrated photonic lightwave circuit (iPLC) technology. A polymer variable optical attenuator (VOA) array and digital optical switch (DOS) array are integrated into a polymer PLC chip and packaged to form a 10-channel VOA integrated optical switch module. Four of these optical switch modules are used in the ROADM module to execute 40-channel

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switching and power equalization. Two C-band 40-channel athermal arrayed waveguide grating (AWG) WDMs are used in the ROADM module. Optical power monitoring of each channel is carried out using a 5% tap PD. A controller and firmware having the functions of a 40-channel switch and VOA control, optical power monitoring, four TEC temperature controllers, and communication interfaces are also developed in this study.

II. The Structure of a Polymer iPLC ROADM

The general structure of an iPLC ROADM module is shown in Fig. 1. As shown in the figure, the iPLC ROADM is composed of two parts. One part is the drop module, which is simply a WDM demux with a tap PD. This part is usually made of a commercial WDM device, so we removed it from consideration in this study. The other part is a rather complex add module which is composed of two WDMs, multiple optical switches and VOAs, tap PDs, and an additional tap coupler. This add module determines the path of signals as PASS or ADD by using 1×2 optical switches and regulates the output optical power of each channel using VOAs. In this study, we used 10-channel VOA-integrated switch modules implemented with polymer iPLC technology, which will be detailed in the next section. The 5% tap PDs are attached to the VOA output to monitor the optical power of each channel and feedback it to the VOA controller. Additional 1% tap PDs are also used to monitor the total input or output power. We used commercial tap PDs in this study [1]. In addition, a commercial fiber fusion 40%:60% tap coupler is used in this study to divide the optical input power into a drop module input (40%) and add module input (60%). In the figure, the optical powers of the COM_IN, EXP_OUT ports are calculated from the DROP_OUT port power by compensating the tapping ratio of the coupler. The COM_OUT port power is also calculated by summing the optical power of each channel and compensating the WDM loss. The WDM devices used in this study were athermal AWG WDMs in which the temperature dependence of the silica AWG WDM chip is mechanically compensated by the thermal expansion of a metal rod [2]. We used athermal AWG WDMs having a semi-flat-top passband fabricated by Fira Photonics Co., Ltd. [3] in this study. A controller and firmware having the control functions of switch states, VOA attenuations, optical power monitoring and closed loop power equalization, TEC temperature control, and I2C/RS232 communication interfaces are also developed in this study using the combination of a microcontroller unit (MCU) and field programmable gate array (FPGA).

III. Design of Polymer DOS and VOA

As seen in Fig. 1, ROADM requires a large number of switches and VOAs, so the power consumption of the switch and VOA units used in the ROADM module can be critical properties. As well-known candidate switches and VOAs for use in an iPLC ROADM module, silica waveguide thermo-optic switches and VOAs are the most popular devices. However, for a small thermo-optic coefficient of the silica material, the silica thermo-optic device generally has high power consumption while in operation. Occasionally, in order to reduce the power consumption, special trench structures are introduced into the device design. On the other hand, polymer is a promising material, especially for thermo-optic devices such as optical switches and VOAs, because of its large thermo-optic coefficient. The thermo-optic coefficient of polymer material is usually 10 times larger than that of silica materials. In this study we used a highly fluorinated UV-curable polymer resin as the base material for optical switches and VOAs with low loss and low power consumption. Its thermo-optic coefficient is -2.5×10^{-4}/°C, and its other material properties can be found elsewhere [4].

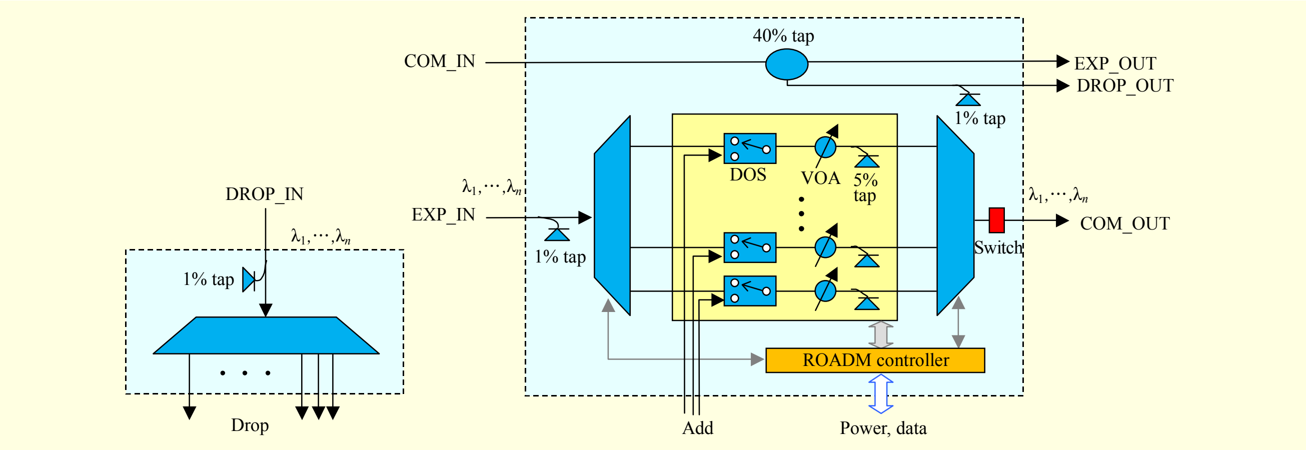


Fig. 1. Structure of iPLC ROADM module.

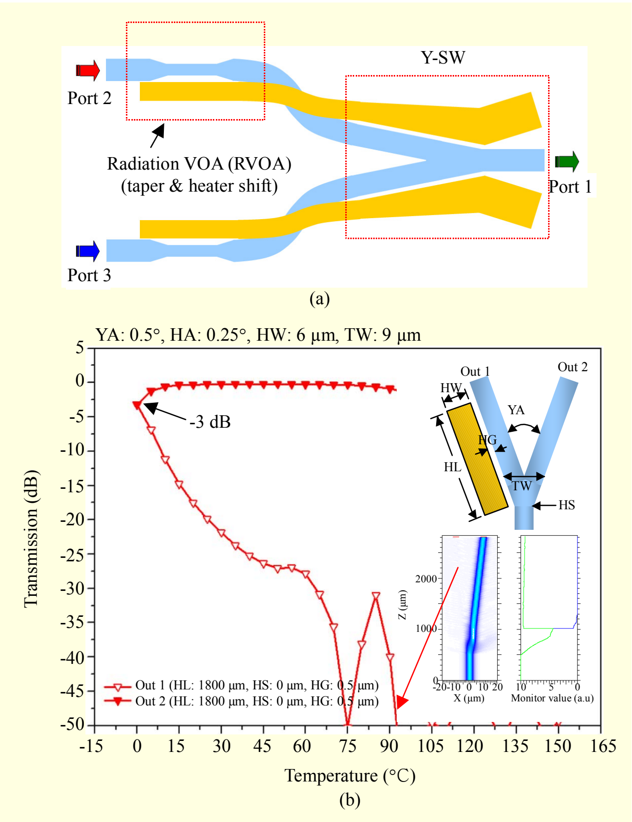


Fig. 2. (a) Basic structure of Y-branch type DOS and (b) BPM simulation result of its Y-branch switching behavior.

Figure 2 shows the basic structure of the Y-branch type DOS used in this study as well as the BPM simulation data of its Y-branch switching behavior [5].

The polymer waveguide for a DOS switch has a core size of 7 µm × 7 µm with a relative index contrast of 0.34%, a bending radius of 25,000 µm, and a Y-branch angle of 0.2°. The heater electrodes in the Y-branch switch section have a width of 6 µm as shown in Fig. 2. When the heater temperature rises, the refractive index of the branch near the heater goes down due to the negative thermo-optic coefficient of polymer material, which forces the optical signal to pass through the opposite branch as shown in the simulation result in Fig. 2(b). In the above DOS design, we used a modified radiation type attenuator at the end of each Y-branch arm to eliminate any residual crosstalk to the blocked port [5], [6]. Therefore, this DOS can operate digitally at a heater temperature at any point above 15°C in a figure in which the optical path has already begun to switch at the Y branch.

Figure 3 shows the structure and calculated attenuation properties of the mode-filtering VOA used in this study [7]. The mode-filtering VOA has a multimode waveguide section between the input and output single-mode waveguides and a heater on the multimode section which is slightly tilted towards the waveguide propagation axis. Both ends of the multimode waveguide have an appropriate taper structure to connect to the single-mode waveguides so that the VOA can transmit optical signals adiabatically without optical loss. When the heater's temperature rises, the refractive index under the tilted heater changes, and many multimode signals are generated in the multimode waveguide section, which can no longer be transmitted adiabatically into the single-mode output waveguide. The number of the multimode signals radiated away at the taper section can be controlled by the temperature of the heater. In this study, we used the same single-mode polymer waveguides as those used in the DOS switch. The multimode waveguide was designed to have a width of 35 µm and a length of 2,000 µm. The width and tilt angle of the heater were optimized as 10 µm and 3°, respectively, from the BPM simulation result. The refractive indexes of the core and cladding at 1,550 nm were 1.393 and 1.388.

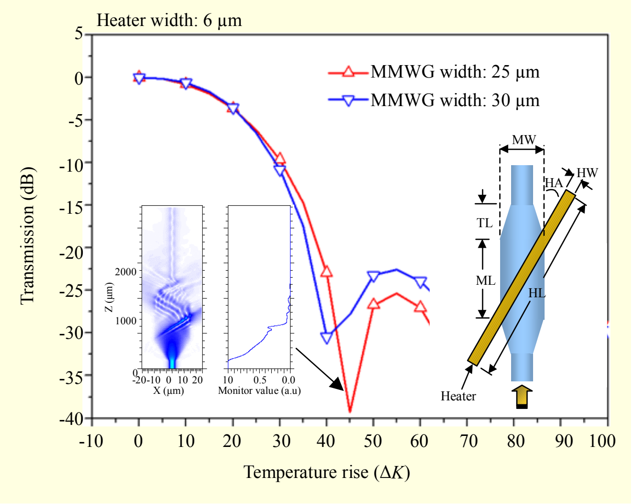


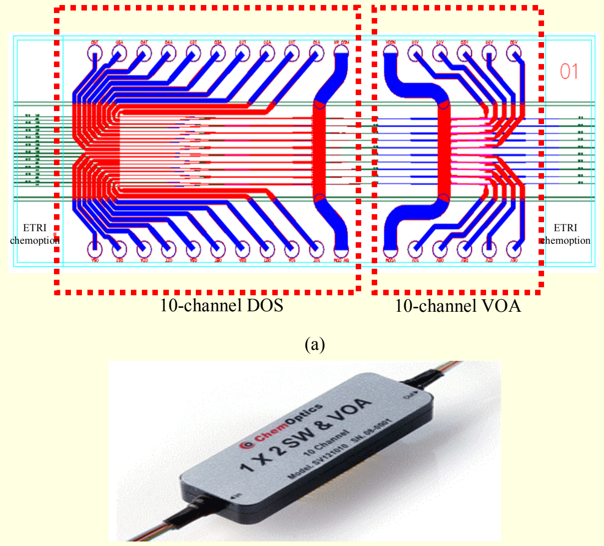
Fig. 3. Structure and properties of the mode filtering VOA.

IV. Integration of DOS and VOA Array

For the first time, to our knowledge, we integrated a 10-channel DOS switch array and mode filtering VOA array into one polymer PLC chip as shown in Fig. 4.

The distance between two adjacent DOS switches and VOAs is 254 µm, so the pitch between the switch input waveguides is 127 µm, which is the same pitch as in commercial fiber blocks. In spite of the relatively low index contrast value of 0.34, the chip size can be minimized by eliminating unnecessary curved waveguides in the chip design. The thermal crosstalk between the adjacent channels is negligible [6].

The heaters were made using a general lift-off process of vapor deposited Cr-Au metal thin films. An additional 4 µm to



(a)

(b)

Fig. 4. (a) Structure of the 10-channel DOS and VOA array integrated into one polymer PLC chip and (b) its packaged module.

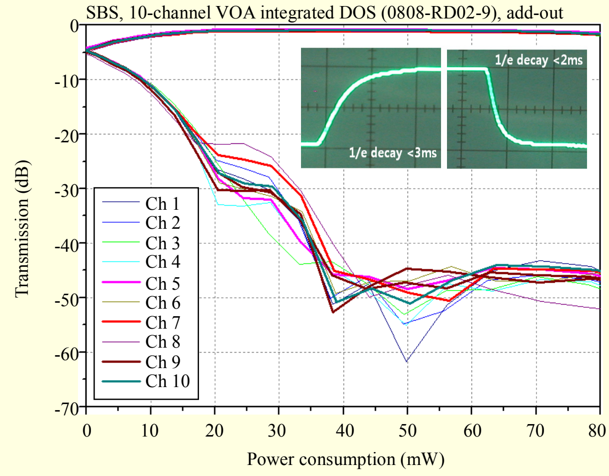


Fig. 5. Switching properties of the DOS array.

6 μm Au metal plating was carried out on the wiring from the heater to the wire bonding pads in the non-waveguide area to reduce the electrical resistance of the wiring, which also helps the wire bonding process. The final chip size was 23.3 mm × 7.7 mm. The heater resistances for the DOS and VOA are directly proportional to their length, showing about 650 Ω and 80 Ω, respectively. This chip is pigtailed with ribbon fibers on both side and then carefully encapsulated in an aluminum case in which a TEC cooler is provided to keep the chip temperature constant during operation. The electrical connections are made by wire bonding from the gold-plated pads on the chip to the terminal pins on the bottom of the aluminum case.

Figure 5 shows the measured switching characteristics of the 10-channel DOS array as a function of applied electrical power with the VOAs in zero attenuation state. The response time of switching operation was less than 5 ms. The insertion losses of the DOS switches were in the range from 1 dB to 1.25 dB when switched at the applied power of 45 mW. This insertion loss includes the propagation loss of the waveguide and the input and output fiber coupling losses. The switching state polarization dependent loss (PDL) was as low as 0.1 dB. The crosstalk to the blocked port continuously decreases to -45 dB when the heater power increases. The saturation decrease of crosstalk for the heater power above 45 mW is thought to be due to the back-coupling of stray lights from outside the waveguide.

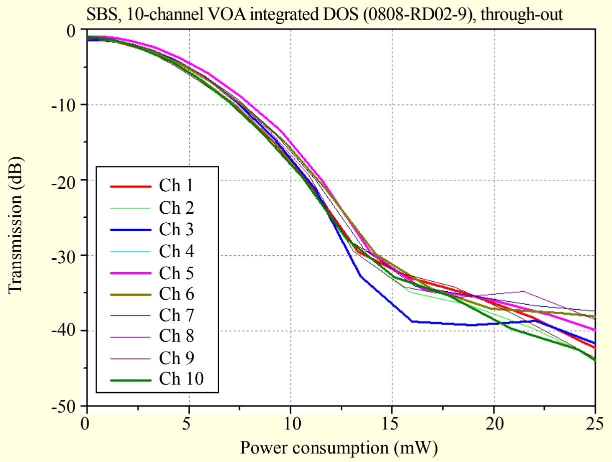


Fig. 6. Attenuation properties of the VOA array.

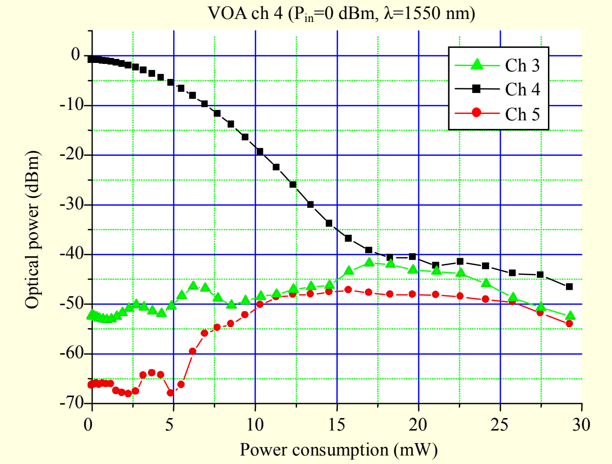


Fig. 7. Crosstalk change due to the attenuation of adjacent channel VOA.

Figure 6 shows the measured attenuation characteristics of the 10-channel VOA array as a function of applied electrical power. In this measurement, the DOS switch was switched to the through state. The attenuation continuously increases with the applied heater power, showing more than 30 dB attenuation

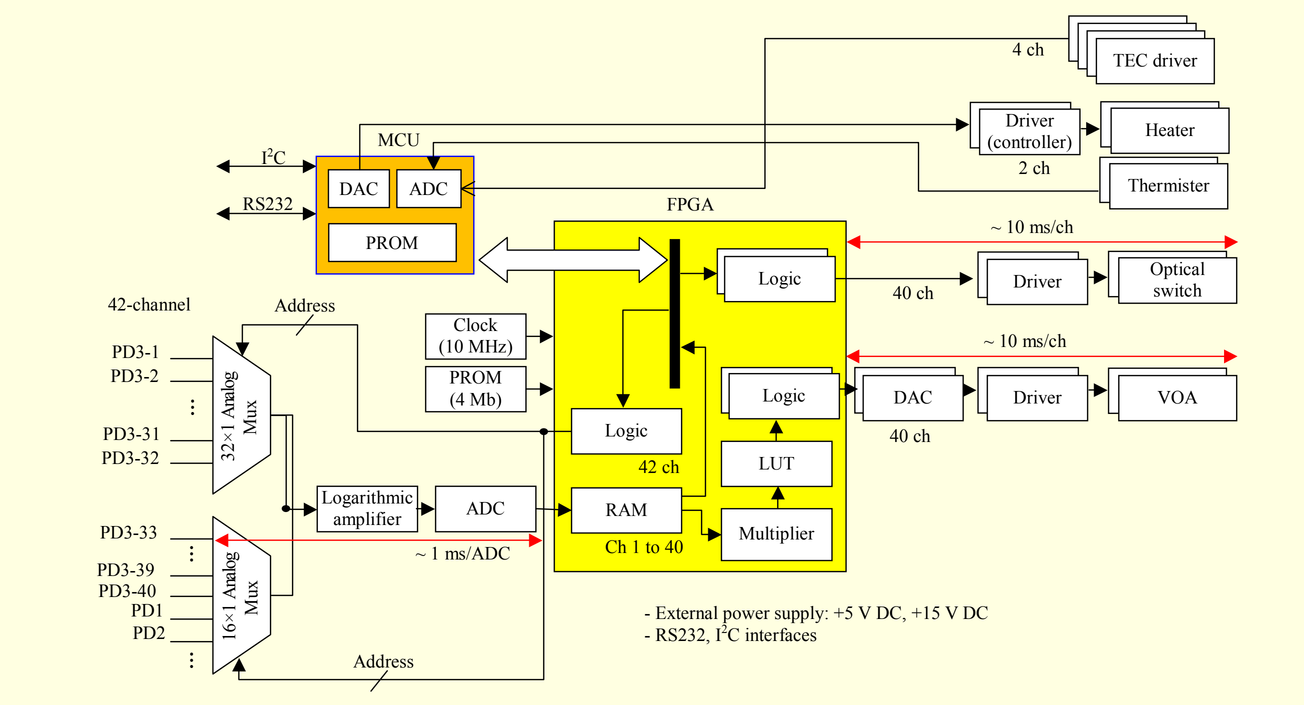


Fig. 8. Block diagram of ROADM controller.

at 15 mW for all channels. The PDL at 10 dB and 20 dB attenuation were about 0.5 dB and 1 dB, respectively.

The VOA operating in a high attenuation state radiates almost all optical power into the cladding layer. This generates stray light, which can cause a serious crosstalk problem for the adjacent channels in array devices. We used borosilicate glass or quartz as the substrate of the integrated polymer PLC chip to help disperse the stray light, and we also designed the module carefully to fully absorb stray light [6]. Figure 7 shows the crosstalk change due to the attenuation of an adjacent channel VOA. As shown in the figure, the crosstalk increases slightly as the attenuation of the adjacent channel VOA increases, but it stays well below -40 dB for all attenuation levels. This proves that the VOA attenuation causes no crosstalk problem at all, even in its compact array structure.

V. Development of the ROA DM Controller

In this study, we also developed a controller circuit for a 40-channel switch and VOA control, optical power monitoring and closed loop power equalization, TEC temperature control, and I2C/RS232 communication interfaces. Figure 8 shows a block diagram of the ROADM controller developed in this study. In the controller, an 8051 series MCU was used to deal with the data communication, command execution, and temperature control. We also prepared a PID temperature control function for thermal AWGs, which was not used in this study. In combination with MCU, we used an FPGA in the

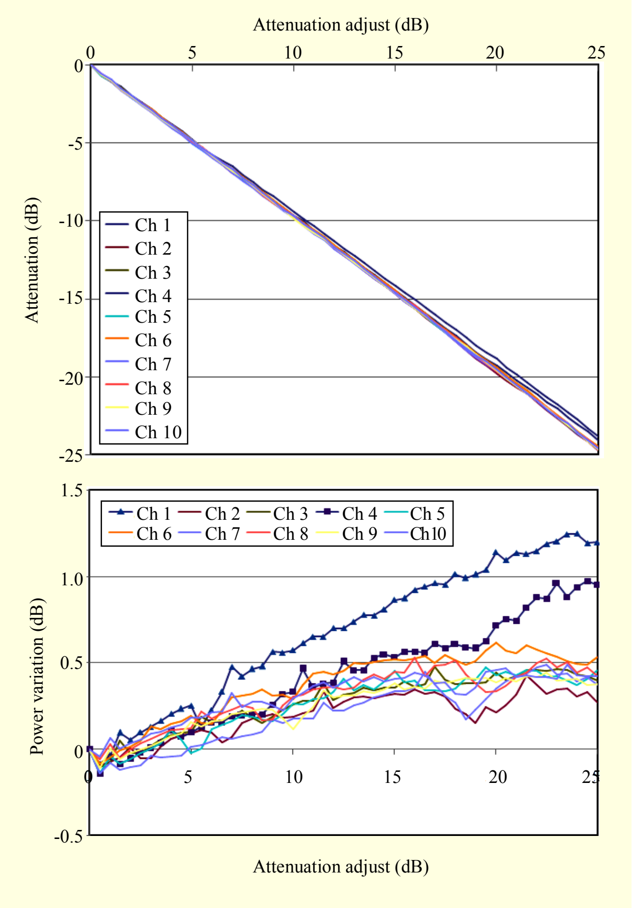


Fig. 9. Linearized attenuation and error curves of VOAs vs. the attenuation set value.

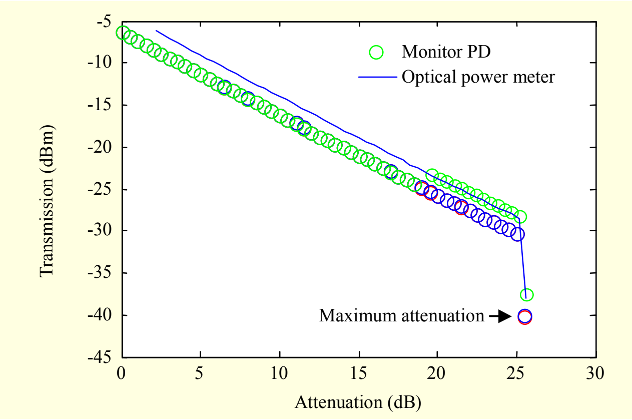


Fig. 10. Monitor PD readout compared with optical power meter.

controller for the simultaneous parallel data process of each channel, which provides much faster control speed than a sequential data process.

All the DOSs and VOAs are controlled by current-based driver circuits, where the DOS drivers are directly controlled via the digital output from the FPGA logic, while the VOAs are controlled through an additional multichannel DAC output set by the FPGA logic.

The mode filtering VOA used in this study shows a non-linear attenuation curve to the heater current. Thus, the controller should linearize the attenuation curve by adjusting the heater current for each attenuation value. We generated look-up tables (LUTs) for each VOA by iteration and implanted them into an FPGA flash memory for the VOA control logic to refer to when calculating the heater current for each attenuation value. Figure 9 shows the linearized VOA characteristics vs. the attenuation setting values, as well as the VOA attenuation errors, which are shown to be less than the 5% of the setting value.

In the controller, the optical power of each channel is continuously monitored by tap PDs for every 10 ms interval. The PD current is converted into voltage data in the logarithmic current-to-voltage converter. Then, it is sampled and digitized at the ADC and sent to the FPGA. For high sensitivity of the tap PDs, particularly for low power detection, noise must be carefully eliminated. We used a two-stage low pass filter and trimmed the filter properties by trial and error to find the best tap PD performance as shown in Fig. 10, where even the maximum attenuation state optical power well below -35 dBm can be easily detected.

VI. Performance of ROADM

In this study, all the components and control boards of the ROADM are packaged into a compact metal housing of 220 mm (L)×135 mm (W)×34 mm (H) size. The performance

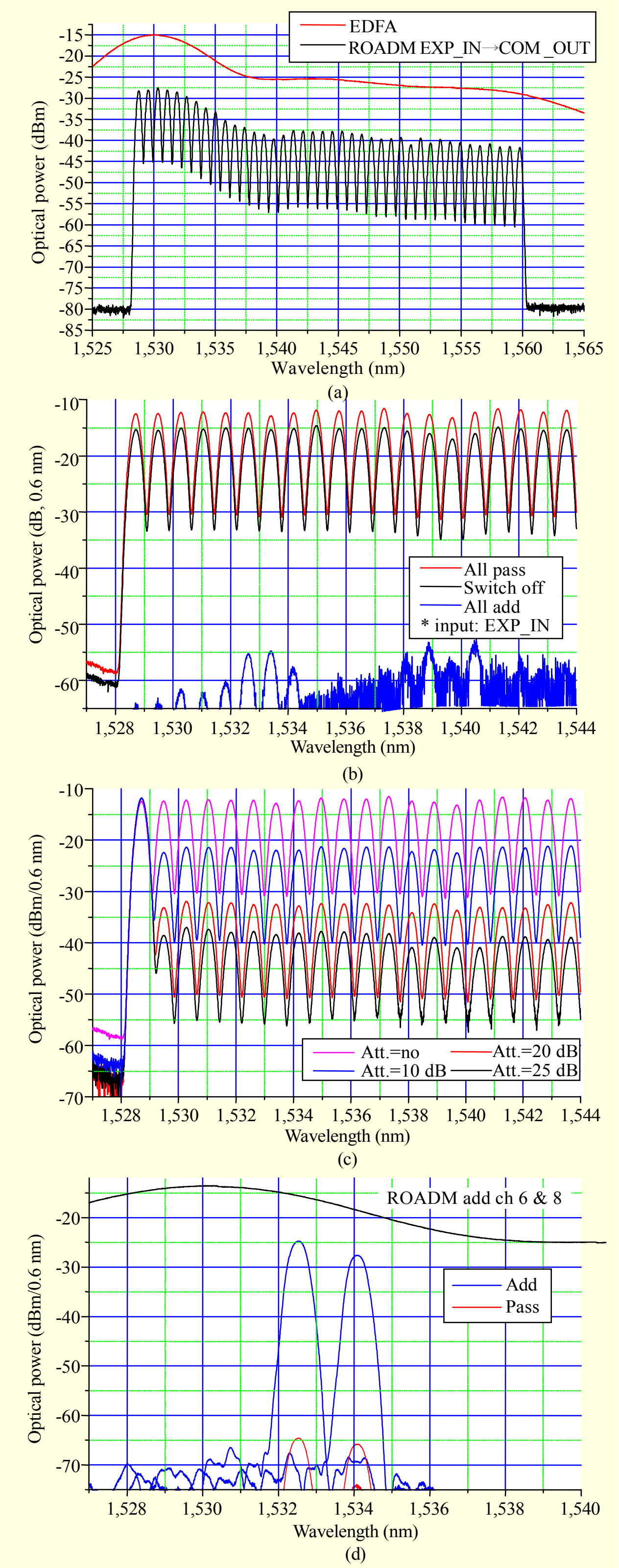


Fig. 11. Transmission properties of the ROADM module: (a) transmission property without control; (b) switching properties showing off, pass, and add states; (c) the VOA attenuation properties; and (d) the add-state spectra of channels 6 and 8.

of the ROADM module was verified under a computer controlled measurement setup, in which the ROADM module was operated by a computer through its own RS232 communication interface, which was also developed in this study.

Figure 11(b) shows the switching properties of the ROADM module. The Y-branch DOS is basically a 3 dB power splitter, so in the switched-off state, the ROADM module shows 3 dB excess optical loss as indicated by the black line in Fig. 11(b). However, when the switch state changes to a pass state, the splitter loss vanishes as indicated by the red line in the figure. If the switch state changes from a pass state to an add state, the optical signal comes in from the EXP_IN port blocked out by the switch as indicated by the blue line in the figure. The switching isolation of the ROADM module (the difference between the red and blue lines) was larger than 40 dB for all channels. Figure 11(c) shows the VOA attenuation properties of the ROADM module at attenuation setting values of 0 dB, 10 dB, 20 dB, and 25 dB for all channels except the first channel, which is uncontrolled for comparison. As shown in the figure, all VOAs operate accurately to the setting attenuation values. The PDL values under attenuation were measured as <0.6 dB at 0 dB attenuation, <1 dB at 10 dB attenuation, and <1.8 dB at 20 dB attenuation.

Figure 11(d) shows the ADD to COM_OUT spectra of channels 6 and 8 when the optical signal comes into the ADD channels, and the switch state varies from the add state to the pass state.

The maximum power consumption of the ROADM was estimated as low as 7.8 W as shown in Table 1, which is less than half the power consumption values of other ROADM module types. Other general properties of the ROADM module developed in this study are summarized as follows:

- number of channels	40 (192.2 THz to 196.1 THz)
- channel spacing	100 GHz
- switching isolation	> 43 dB
- attenuation range	0 dB to 25 dB
- VOA resolution	0.1 dB
- VOA accuracy	±0.6 dB @10 dB attenuation ±1.2 dB @20 dB attenuation

Table 1. Power consumption calculation of the ROADM module.

	Operating power	Number of devices	Maximum power consumption
Controller	0.4 W	1	0.4 W
TEC	0.5 W−0.8 W	4	3.2 W
VOA	0 mW−15 mW	40	0.6 W
DOA	90 mW	40	3.6 W
Sum			7.8 W

VII. Conclusion

In this study, we developed a fully functional ROADM module using a polymer iPLC technology. The polymer mode filtering VOA array and Y-branch DOS switch array are integrated into one polymer PLC chip and packaged to form a 10-channel VOA-integrated optical switch module. Four of these VOA-integrated optical switch modules are used in the ROADM module, as are two C-band 40-channel athermal AWG WDMs. The optical power monitoring of each channel is carried out using 5% tap PDs. A controller and firmware having the functions of a 40-channel switch and VOA control, optical power monitoring, four TEC temperature controllers, two AWG temperature controllers, and data communication interfaces are also developed in this study. We have also reported on the very low power consumption of the ROADM module of 7.8W, which was enabled by using polymer optical devices and athermal AWG WDMs. We also developed a closed loop power equalization algorithm, which we discuss further elsewhere [8].

References

[1] Photonic Solutions, Inc., http://www.photonicsolution.com

[2] L. Leick et al., “Athermal AWGs for Colourless WDM-PON with -40°C to +70°C and Underwater Operation,” *Optical Fiber Commun. Conf.* 2006, paper PDP31.

[3] Fira Photonics Co., Ltd, http://www.fi-ra.com.

[4] ChemOptics, Inc., http://www.chemoptics.co.kr.

[5] Y.T. Han et al., “Crosstalk-Enhanced DOS Integrated with Modified Radiation-Type Attenuators,” *ETRI J.*, vol. 30, no. 5, Oct. 2008, pp. 744-746.

[6] Y.T. Han et al., “Fabrication of 10-Channel Polymer Thermo-Optic Digital Optical Switch Array,” *IEEE Photonics Technol. Lett.*, vol. 21, no. 20, Oct. 2009, pp. 1556-1558.

[7] Y.T. Han, J.U. Shin, and S.H. Park, “10 Channel Polymer Variable Optical Attenuator Array for Power Monitoring and Equalization in Integrated PLC ROADM Module,” *Photonics in Switching*, 4-7 Aug. 2008, pp. 1-2.

[8] S.P. Han, “The ROADM Optical Switch Technology for Metro Optical Network,” *Conf. Optoelectron. Optical Commun.*, May 2009.

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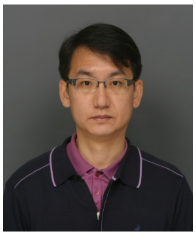

Young-Tak Han received the BS and MS degrees in electronics engineering from the University of Seoul, Seoul, Korea, in 1998 and 2001, respectively. Since 2008, he has been working toward the PhD degree for research in polymeric optical devices at the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea.

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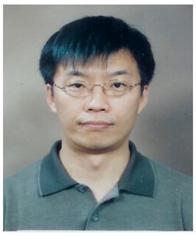

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