Four-wave mixing mitigation by using waveguide-based 4λ-WDM filters for 800 and 400 GbE

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Abstract: We report four-wave mixing mitigation by 4λ-WDM filters fabricated by silica-based planar lightwave circuits for 800- and 400-GbE application. The multiplexing filter integrates a simple polarization-alternating structure on arbitrary lanes for the impairment mitigation.

1. Introduction

Traffic demands are growing in networks such as the Internet as well as in interconnections between datacenter campuses. The Ethernet roadmap claims that the speed will go to 400 Gbps and then 800 Gbps and reach 1 Tbps by about 2030 [1]. Increasing the reach of such high-speed Ethernet to 10 km (LR) to 40 km (ER) is expected accommodate the connections between telecom carriers' offices and between hyperscale datacenters. One strategy for the lengthening it is to apply digital coherent technology; however, IMDD is preferable from an economic standpoint. The 4λ-wavelength division multiplexing (WDM) of 100- or 50-Gbaud PAM4 signals in the O-band has been discussed to realize 800- or 400-GbE using IMDD [2]. So far, channel spacing of 20 nm (coarse-WDM) and 800 GHz (LAN-WDM) has been utilized for, for example, 200 G-FR4 and 100 G-LR4 and lower performance applications. However, when transmitting high baud rate signals such as 100 or 50 Gbaud, the effect of chromatic dispersion becomes pronounced, even if the signals are transmitted at around 1.3 μm, where the zero-dispersion wavelength of single-mode fiber exists. The effect can be more significant for shorter channels of four lanes because the zero-dispersion wavelength is standardized as between 1300 and 1324 nm, with the nominal center at 1312 nm. A solution to this problem under discussion is to narrow the channel spacing of the four signals from 800- to 400-GHz [3] as shown in Fig. 1. However, narrowing the spacing poses a new problem. That is, when high-power transmission signals are introduced for extending the reach, optical nonlinearities, or four-wave mixing (FWM), become an issue, which can degrade transmission performance. It has been suggested that an effective countermeasure to this problem is to orthogonalize the transmit polarization between WDM lanes [4, 5]. For this purpose, two polarization arrangements have been proposed: one that orthogonalizes the polarization of the four adjacent lanes (XYXY) [4] and another that orthogonalizes the center and both sides (YXXY) [5]. In any case, it is necessary to control the transmitter output signal polarizations so that two of them are orthogonalized.

Conventional transceivers are equipped with a WDM filter consisting of dielectric thin film filters (with different wavelength reflectance and transmittance), mirrors, and small lenses. The micro-optics assembly multiplexes signals from four lasers [6]. To mitigate the effect of FWM, it is now necessary to integrate tiny waveplates that control the polarization for each WDM lane, which may be disadvantageous in terms of the number of components and assembly cost. In this study, we developed new 4-λ multiplexer (mux) and demultiplexer (demux) with a frequency spacing of 400 GHz by using silica-based planar lightwave circuit (PLC) technology [7-9]. We integrated a mechanism into the mux to rotate the polarizations of arbitrary lanes with a simple configuration. Transmission experiments using the mux were conducted for polarization combinations (XYXY) and (YXXY). We observed that the degradation of transmission performance due to FWM is similarly improved with either set of polarization configuration.

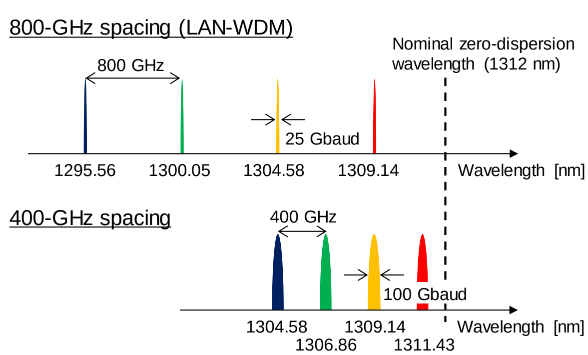

Fig. 1. Wavelength arrangement of 800-GHz spacing (LAN-WDM) and 400-GHz spacing.

2. 4λ-filters for 400-GHz spacing WDM

The 400-GHz spacing WDM being discussed in the standardization requires a wavelength tolerance of about 1 nm (184 GHz) for each lane, which requires a higher wavelength stability for lasers and WDM filters than that required for conventional CWDM and LAN-WDM. Especially for WDM filters, in addition to this wavelength tolerance, it is necessary to provide a wide transmission passband window that allows 100-Gbaud signals to pass through, and this wide window must be realized at a narrow frequency interval of 400 GHz. For the demux filter at the receiver side, an arrayed-waveguide grating (AWG) with multimode output waveguides was used to achieve wide and flat wavelength passbands [8]. At the receiver side, the output of the demux can be directly input to avalanched photodiodes (APDs), and it is not necessary to be concerned about the propagation mode of the light between the demux and APDs. However, even if we use a multimode AWG, achieving sufficient passband for 100-Gbaud signal requires a highly resolved diffraction grating with small crosstalk within the small space of the transceiver. To meet these requirements, we used silica-based PLC technology to fabricate demux filters with a higher relative refractive index difference [9] than previously reported [8]. On the other hand, it is difficult to use a multimode AWG for the mux filter on the transmitter side, because the single-mode light from the lasers must be multiplexed into a single-mode fiber. Therefore, we adopted a filter configuration with multiple stages of Mach-Zehnder interferometers (MZIs). Although the MZI configuration has a narrower transmission passband than the multimode AWG, this configuration exhibits lower insertion loss than the AWG in addition to complying the single-mode requirement. The crosstalk performance of the MZI configuration is inferior to that of the AWG as well; however, low-loss characteristics are preferred for the mux filter at the transmit side rather than crosstalk performance. The essence of the mux filter is that we integrated a lane by lane polarization rotating function in the filter as shown in Fig. 2. On the facet of the mux filter chip, we glued a tiny half wave plate (HWP) at the input waveguides where the input polarization should be rotated. This simple method allows easy optical axis alignment by butting the HWP against the edge of the mux chip, eliminating the need for the precision alignment required with micro-optics.

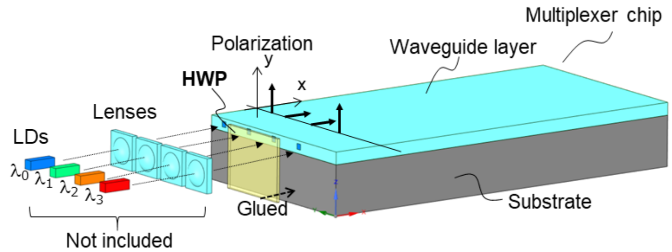

Fig. 2. Mux filter assembly with polarization rotating function.

3. Experiment

Figure 3(a) and (b) show the measured transmittance of the mux and demux filter. We obtained sufficient 3-dB passbands for the demux and mux of 342 and 369 GHz, respectively. The average insertion losses of 2.9 and 2.3 dB were obtained. The chip sizes are 4.5 × 7.3 and 6.9 × 3.8 mm^2, respectively. We also measured the state of polarizations (SOPs) from the mux by inputting a linearly x-polarized continuous-wave lightwave by using free-space polarization analyzer (Thorlabs PAX1000). As shown in the Poincare sphere in the inset of Fig. 3(a), the SOPs are successfully alternated for each lane.

We also performed a signal transmission experiment to assess the feasibility of the mux. To suppress the FWM penalty, it has been suggested that the use of SOPs with orthogonal polarizations of (XYXY) [4] or (YXXY) [5] is effective. The nonlinear polarization in optical fiber [10] is expressed by

$$P_x^{NL} \propto 3x_1x_2x_3^* + x_1y_2y_3^* + y_1x_2y_3^* + y_1y_2x_3^* \tag{1}$$

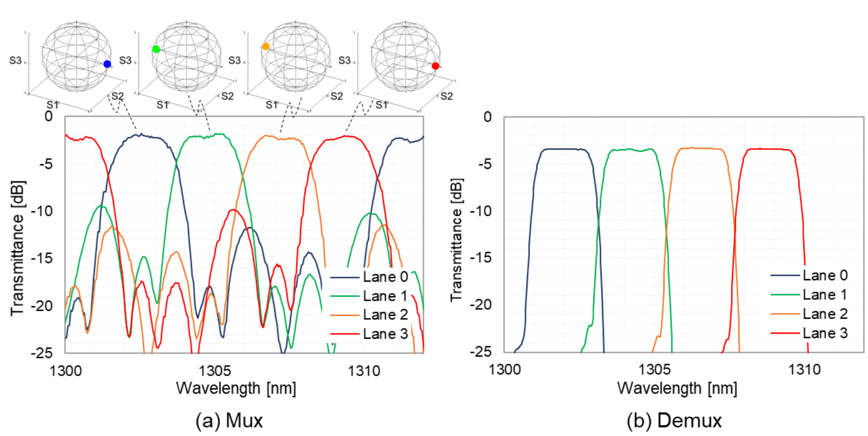

Fig. 3. Measured transmission spectra of fabricated (a) demux and (b) mux filters.

where x_i and y_i are signal and pump polarizations. This equation suggests that nondegenerate FWM can be suppressed when SOPs of four lanes are (YXXY). On the other hand, as regards degenerate FWM, sets of (XYXY) polarizations appears preferable because adjacent lanes have orthogonal polarizations. We experimentally assessed both combinations of polarizations. Figure 4 shows the transmission experiment setup and measured bit error rate (BER) for each lane with sets of polarizations of (XYXY), (YXXY), and (XXXX). We input 400-Gbps signal with 50-Gbaud PAM4 for each lane to four 1-ch SOA-assisted EADFB TOSAs [6]. The wavelengths of the TOSAs are 1302.65, 1304.83, 1307.14, and 1309.45 nm, and each output power is 7.7 dBm. The wavelengths are different from the standards due to design error and can be aligned easily. The TOSAs we used are pigtailed with single-mode fiber; therefore, we connected them to the fabricated mux filter through polarization controllers (PCs). The output of mux was tapped by 1%, and the output polarization was aligned by using a polarization analyzer. SOPs for each lane were controlled by using PCs so that they were aligned in (XYXY) and (YXXY). Measurement was also performed in (XXXX) for comparison with the worst case. The muxed signal was transmitted through a 20-km single-mode fiber (SMF) with a zero-dispersion wavelength of 1308.25 nm. The fiber was prepared so that the zero-dispersion wavelength existed in between the lanes to maximize the effect of FWM. The transmitted signals were detected with a 1-ch APD ROSA [11]. The ROSA was also pigtailed with an SMF. Because we could not directly connect the fabricated demux with multimode outputs, we used a tunable filter instrument with a passband equivalent to that of the demux instead. The measured BER is shown in Fig. 4(b). In the graphs, closed rhombus, circle, and triangle plots represent the case with SOPs with (XYXY), (YXXY), and (XXXX), respectively. We could observe significant improvement when we aligned the polarization to (XYXY) or (YXXY). However, no difference was observed between them. This suggests that we can use a set of SOPs that is convenient for the transceiver configuration. The open circles show the back-to-back (B2B) BERs. Except for lane 3, BER with the countermeasures shows the same performance as that for B2B. The degradation of the B2B BER in lane 3 is assumed to be an effect of the inappropriate driving condition of the electro-absorption modulators in the TOSAs, which is not essential in this experiment.

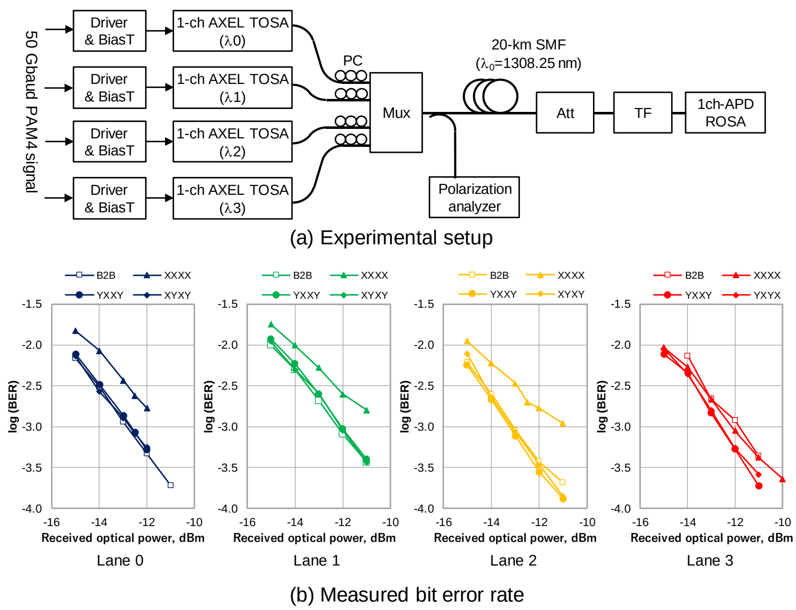

Fig. 4. Transmission experiment.

4. Summary

We reported four-wave mixing mitigation by using silica-based PLC-based 4λ-WDM filters. The mux filter integrates a polarization rotating function with a simple structure. The transmission experiment revealed that both sets of SOPs, (XYXY) and (YXXY), are useful for mitigating the impairment. The proposed filters offer simple transceiver optics for 800G-LR4 and 400G-ER4 application.

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