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Variable Mode-dependent-loss Equalizer based on Silica-PLC for Two-LP-mode Transmission

Takayoshi Mori(1), Takeshi Fujisawa(2), Junji Sakamoto(3), Yoko Yamashita(1), Taiji Sakamoto(1), Ryota Imada(1), Ryoto Ima(2), Takanori Sato(2), Kei Watanabe(3), Ryoichi Kasahara(3), Toshikazu Hashimoto(3), Kunimasa Saitoh(2) and Kazuhide Nakajima(1)

(1) Access Network Service Systems Laboratories, NTT Corporation, Tsukuba, Ibaraki, 305-0805 Japan, takayoshi.mori.sf@hco.ntt.co.jp
(2) Graduate School of Information Science and Technology, Hokkaido University North 14, West 9, Kita-ku, Sapporo 060-0814, Japan
(3) Device Technology Laboratories, NTT Corporation, Atsugi, Kanagawa, 243-0198 Japan

Abstract *We present a low loss silica PLC based mode dependent loss equalizer with a 2.5-dB variable range. A variable differential modal gain equalization in a two-LP-mode EDFA was demonstrated over the entire C-band for the first time. ©2022 The Author(s)*

Introduction

Mode-division multiplexing (MDM) technology has received much attention for increasing the capacity of optical fibre transmission systems. In MDM systems with non-negligible mode coupling, multiple-input and multiple-output digital signal processing (MIMO-DSP) is mandatory. A mode dependent loss (MDL) in a link severely affects the MIMO-DSP [1]. An MDL is caused by the differential-modal-attenuation (DMA) of the few-mode fibres, which increases along the transmission distance. A few-mode amplifier also causes a differential-modal-gain (DMG), which varies with the amplification conditions. Therefore, it is important to minimize an MDL in an MDM link. A spatial optical device was proposed for realizing a few-mode variable optical attenuator (VOA) [2]. However, it attenuates all transmission modes in principle, and the device size tends to be large. In our previous work, we demonstrated a compact silica planar lightwave circuit (PLC) based fixed MDL equalization device [3].

In this paper, we propose a PLC-based variable MDL equalizer with two-LP-mode operation, which can selectively vary the attenuation of the LP_{01} mode. The proposed equalizer achieves a 2.5-dB variable range with a 2-dB insertion loss. For the first time, a variable DMG equalization in a two-LP-mode EDFA is demonstrated over the entire C-band without significantly affecting gain and flatness.

Properties of variable MDL equalizer

Figure 1 shows a schematic of the proposed equalizer. The device is based on the Mach-Zehnder interferometer structure and contains two cascaded couplers with the same structural parameters [3]. Both LP_{01}- and $LP_{11a,b}$-mode lights are guided into port 1, and coupler 1 acts as a 3-dB coupler only for the LP_{01}-mode by adequately designing a gap and coupling length L_c. The coupled LP_{01}-mode light is guided into coupler 2 via a delay line waveguide, and a part of the LP_{01}-mode light is re-coupled into a bus waveguide in accordance with the phase difference between the delay line and bus waveguides. Then, the LP_{01}-mode light with designed attenuation and the $LP_{11a,b}$-mode light without attenuation ideally are output from port 3. In our previous study [3], we proved our concept by fabricating multiple non-variable PLCs with different S-bending waveguide parameters, namely s_d or L_d. In this present study, we controlled the phase difference of the LP_{01}-mode light guided in the delay waveguide by introducing a heater. The height, width and relative refractive index difference of the waveguide were set at 9 μm, 10 μm, and 0.55%,

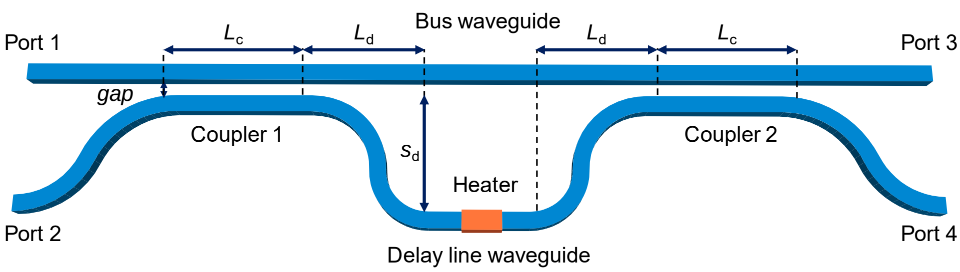

Fig. 1: Schematic of proposed two-LP-mode variable MDL equalizer.

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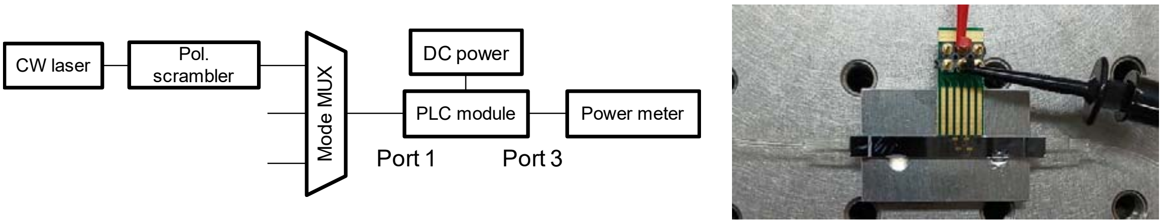

Fig. 2: Experimental setup for measuring modal loss property of fabricated PLC module shown in inset photo.

respectively. The L_c, gap, L_d and s_d were set to 5480, 3.0, 4756, and 145 μm, respectively.

Figure 2 shows the experimental setup for evaluating the loss property of the fabricated PLC module of the proposed equalizer. The continuous wave (CW) light at 1550 nm was polarization scrambled at 20 kHz. The LP_{01}, LP_{11a}, or LP_{11b} modes were launched into the PLC module selectively using a 3D waveguide-type mode multiplexer (MUX) with a 21-dB extinction ratio. Two-LP-mode step-index fibres (SIFs) with a core radius of 6.0 μm and relative refractive index difference of 0.5% were connected to the input/output ports of the chip using a fibre block. The mode MUX and an SIF were fusion spliced. An inset photo shows the fabricated PLC module. The chip size is 3.0 mm wide × 35 mm long × 1.0 mm high. The heater is mounted in the middle of the delay line, and the temperature is controlled by changing the direct current (DC) power. The output power of port 3 was measured using an optical power meter via an SIF. The loss per mode was determined by measuring the reference input power at the SIF inserted between the mode MUX and PLC.

Figures 3(a) and (b) show the measured loss and DMA at 1550 nm as a function of applied power to the heater, respectively. The DMA is derived as the loss difference between the LP_{01} and LP_{11} modes, and the LP_{11}-mode loss was assumed as the average of the LP_{11a} and LP_{11b} modes. In Fig. 3(a), the black, red and blue symbols show the losses for the LP_{01}, LP_{11a} and LP_{11b} modes, respectively. The insertion losses of the LP_{01}, LP_{11a}, and LP_{11b} modes were 2.1, 2.4, and 2.2 dB, respectively. It is confirmed that the attenuation of the LP_{01} mode changes by 3.5 dB when the applied heating power is changed from 0 to 170 mW, while the attenuation change in the LP_{11a} and LP_{11b} modes is 0.8 dB or less, indicating that the LP_{01} mode was selectively attenuated. Assuming the temperature coefficient of the silica as being on the order of 10^{-5} /°C, a loss change of about 3 dB was expected numerically for a temperature change of 10 °C. Figure 3(b) also shows that the DMA can be varied by about 2.5 dB by adjusting the heating power, and the required heating power was 170 mW. These results indicate that the proposed equalizer successfully works as designed.

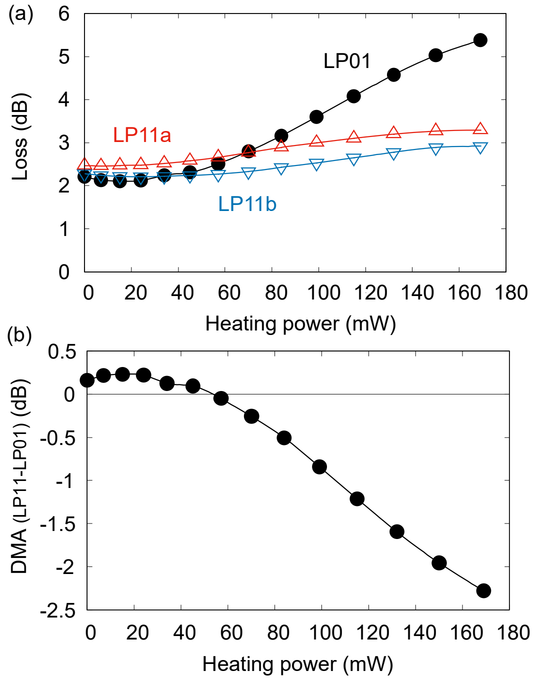

Fig. 3: Measured (a) loss and (b) DMA at 1550nm as function of applied power to heater.

Variable DMG equalization for two-LP mode EDFA

We used a two-LP mode erbium-doped fibre amplifier (EDFA) previously reported [4]. This EDFA achieves a relatively low DMG of about 2 dB in the C-band due to a specially designed ring-core EDF and an LP_{11}-mode-based pumping scheme. Figure 4 shows the experimental setup for variable DMG equalization in the two-LP mode EDFA. A tunable laser was used as a signal light source, and we evaluated the gain and DMG at 1530, 1540, 1550 and 1565 nm. The signal light was modulated at 20 Gb/s with the QPSK format. The modulated signal was polarization scrambled at 20 kHz, and the output power after mode MUX was set to –25 dBm/mode by adjusting three VOAs. Four WDM lights at 1535, 1545, 1555, and 1563 nm were combined with the signal light via an optical coupler, and the output power of the mode MUX was set at –15 dBm/mode/λ assuming a 40-λ WDM. All WDM lights were guided into the two-LP mode EDFA, and its output was fusion spliced with the variable PLC module. The gain of each mode was then evaluated by measuring the output intensity of each mode at a wavelength

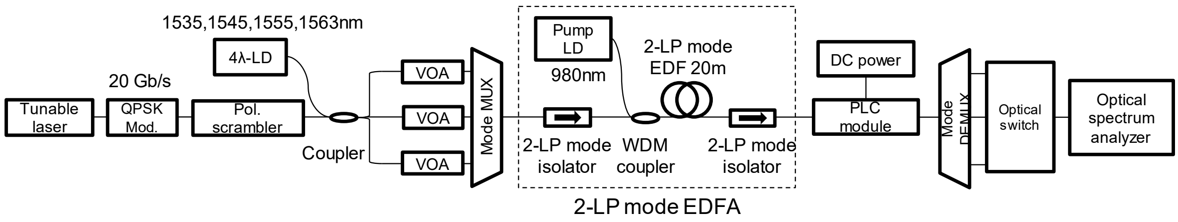

Fig. 4: Experimental setup for variable DMG equalization of two-LP mode EDFA.

under test by using a mode demultiplexer (DEMUX), optical switch, and optical spectrum analyser.

Figure 5 shows the pump-power dependence of (a) gain and (b) DMG measured at 1550 nm. Open and filled symbols correspond to with and without PLC, respectively. In Fig. 5(a), circles and triangles show the results obtained for the LP_{01} and LP_{11} modes, respectively. For the LP_{11} mode, the LP_{11a} and LP_{11b} modes were averaged. Figure 5(a) shows that the gain of the two-LP mode EDFA can vary about 10 dB by changing the pump power. It also shows that the pump-power dependence of the gain differs between modes. This results in the pump-power dependence of DMG. As shown in Fig. 5(b), the DMG increased from 1.6 to 2.3 dB when we did not use the PLC module. Figure 5(a) also reveals that we can minimize the difference in pump-power dependence between modes using the PLC module. Thus, the pump-power dependence of DMG at 1550 nm were successfully reduced to less than 0.05 dB, as shown in Fig. 5(b). Figure 6 shows wavelength dependence of DMG. Open and filled symbols show the results obtained with and without the PLC module, respectively. A DMG of less than 0.5 dB was achieved in the entire C-band independent of the pump power by using the PLC module. Moreover, there was no significant effect on the wavelength dependence. Figure 7 shows the time variation of the output power of the PLC module measured at 1550 nm. Black and blue lines correspond to the LP_{01} and LP_{11} modes (as the average of degenerative modes). The standard deviation of the variation ranged from 0.2 to 0.6 dB. There was no significant time variation, although it varied slightly depending on the heating power applied to the PLC module. These results reveal that the PLC module can precisely minimize the DMG and its pump-power dependence in the entire C-band.

Conclusion

We proposed a low-loss and compact silica-PLC-based MDL equalizer with a 2.5-dB variable range. The pump-power dependence of DMG in the two-LP mode EDFA was successfully equalized to less than ±0.5 dB over the entire C-band without significantly affecting the wavelength dependence. Our proposed equalizer will be beneficial for achieving an MDL-minimized MDM transmission link.

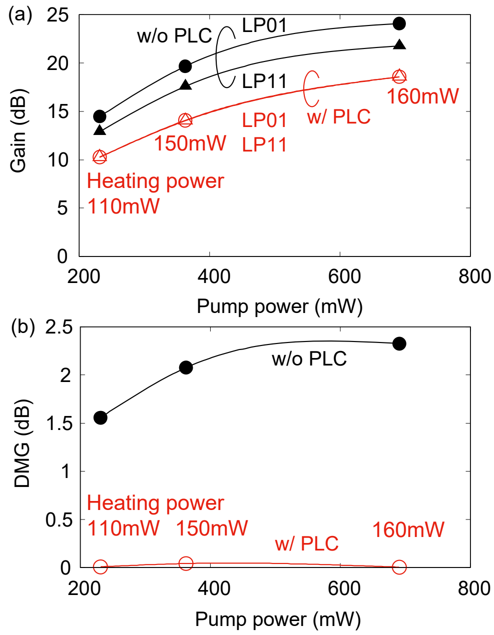

Fig. 5: Pump-power dependence of (a) gain and (b) DMG measured at 1550 nm.

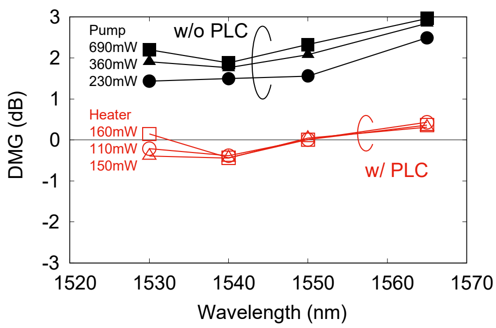

Fig. 6: Wavelength dependence of DMG.

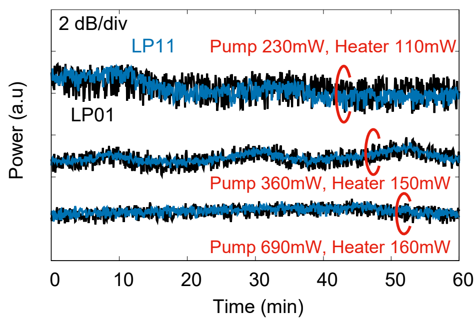

Fig. 7: Time variation of output power of PLC module measured at 1550 nm.

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References

[1] Peter J. Winzer and Gerard J. Foschini, "MIMO capacities and outage probabilities in spatially multiplexed optical transport systems," Optics Express, vol.19, no. 17, pp. 16680-16696, 2011, DOI: 10.1364/OE.19.016680

[2] Miri Blau, Israel Weiss, Jonathan Gerufi, David Sinefeld, Moran Bin-Nun, Robert Lingle, Lars Grüner-Nielsen, and Dan M. Marom, "Variable optical attenuator and dynamic mode group equalizer for few mode fibers," Optics Express vol. 22, no. 25, pp. 30520-30527, 2014, DOI: 10.1364/OE.22.030520

[3] T. Fujisawa, T. Mori, J. Sakamoto, Y. Yamashita, T. Sakamoto, R. Imada, R. Ima, T. Sato, K. Watanabe, R. Kasahara, T. Hashimoto, K. Nakajima and K. Saitoh, " Silica-PLC based mode-dependent-loss equalizer for two LP mode transmission," Optical Fiber Communications Conference and Exhibition (OFC) 2022, M4J.4, 2022.

[4] M. Wada, T. Sakamoto, T. Mori, T. Yamamoto, N. Hanzawa, and F. Yamamoto, "Modal gain controllable 2-LP-mode fiber amplifier using PLC type coupler and long-period grating," Journal of Lightwave Technology, vol. 32, no. 24, pp. 4694–4700, 2014, DOI: 10.1109/JLT.2014.2361675