Silica-PLC based mode-dependent-loss equalizer for two LP mode transmission

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Abstract: A mode-dependent-loss (MDL) equalizer based on silica-PLC is proposed for three-mode transmission and experimentally demonstrated for the first time. By selectively attenuating LP_{01}-mode, 1.5-dB MDL equalization is demonstrated for the setup with large LP_{11}-mode loss.

1. Introduction

A mode-division-multiplexing (MDM) technique has attracted a lot of attentions to increase the capacity of optical fiber transmission system. In MDM system, a MIMO technique is usually used to undo the mode mixing occurred in few-mode fiber (FMF) at the receiver. In MIMO processing, the differences between received modal powers often make it difficult to recover the signals [1]. These differences are caused by the loss difference in FMFs (MDL) and the gain difference in few-mode EDFA (mode-dependent gain, MDG). For MDL (MDG), the loss (gain) of fundamental LP_{01} mode is usually small (large). To equalize MDL or MDG, a mode exchanging or mixing technique at a relay point between two FMFs is useful [2,3], and some mode exchangers based on gratings were proposed in optical fiber [4,5] and silica PLC platform [6,7]. However, these devices themselves have their own MDL due to the loss difference between different modes, and the loss of LP_{01} mode is the smallest. Therefore, if one can increase the loss of LP_{01} mode only, it can act as MDL or MDG equalizer. This is a difficult task than one think, since LP_{01} mode is robust to various waveguide perturbations, such as a corrugation in gratings. To solve these problems, we theoretically proposed PLC based MDL equalizer for two LP mode transmission [8]. The device is based on Mach-Zehnder interferometer (MZI) structure, and the device acts as the MZI for LP_{01} mode, while $LP_{11a,b}$ modes are passed through in a bus waveguide. Thus, we can intentionally attenuate the LP_{01} mode only, while keeping the low insertion loss for $LP_{11a,b}$ modes.

In this paper, we experimentally demonstrate proposed MDL equalizer. It is shown that the power of LP_{01} mode is attenuated due to the interference effect in MZI and the attenuation can be adjusted by changing the length of a delay line waveguide. A FMF-pigtailed module containing the proposed device is fabricated and the LP_{01} mode attenuation is successfully demonstrated. By using the module, 1.5-dB MDL equalization is realized for the transmission in tightly bended FMF, showing the proof-of-concept of the device.

2. Operation principle and device design

Figure 1 shows the schematic of the device. The device consists of bus and delay line waveguides. The relative refractive index difference is 0.55% and the height of core is 9 μm. The widths of both waveguides are 10 μm. To form MZI structure, a directional coupler1, interference waveguides, and a directional coupler2 are concatenated, resulting in 2by2 MZI configuration with four ports. However, we only use Port1 as an input port, and Port3 as an output port. Therefore, the device is basically 1by1 device (Port2 and 4 are not used). The operation principle of the device is as follows. When LP_{01} mode is launched at Port1, it is equally divided by the coupler1 and propagates interference waveguides. Then, the light from these waveguides is interfered at the coupler2 (the same structure with the coupler1), and the power is partially outputted to Port4, depending on the phase difference between the bus and delay line waveguides at the input of the coupler2. The output power to Port4 can be adjusted by changing the parameters of S-bending waveguide, L_d and s_d. For $LP_{11a,b}$ modes, all the light from Port1 is transmitted to the bus waveguide. Then, the propagated light is inputted to the coupler2, and all the light is again transmitted to the upper waveguide. Namely, $LP_{11a,b}$ modes launched to Port1 are transmitted to Por3 and they are not affected by MZI structure. To achieve this function, the design of the coupler is a key component. The length of the coupling region, L_c, has to be carefully determined. For LP_{01} mode, L_c should be (2N-1)/2 multiples of the coupling length to make a 3-dB coupler, where N is an integer. For $LP_{11a,b}$ modes, L_c should be 2N multiples of their coupling length to make the coupler bar-state. After careful design based on finite-element method, the parameters in Fig. 1 are determined as follows: L_c = 5480 µm, *gap* = 3 µm, R_{delay} = 39 mm, L_m = 3000 µm. As stated above, the output power to Port4 for LP_{01} mode can be adjusted by changing L_d and s_d, with keeping the value of R_{delay}. Figure 2 (a), (b), and (c) show the field distributions of the device at 1550 nm for LP_{01}, LP_{11a}, and LP_{11b} modes, respectively, for L_d = 2485 µm and s_d = 39.6 µm. From the Figure, we can see that N values for LP_{01}, LP_{11a}, and LP_{11b} modes are 2, 3, and 1. The transmission powers for LP_{01}, LP_{11a}, and LP_{11b} modes to Port3 are -5.0, -0.61, and -0.02 dB, respectively. Only the output power of LP_{01} mode is greatly attenuated as intended. Figure 3 shows the output power of LP_{01} mode for Port3 at 1550 nm as a function of s_d. Note that, L_d is also changed to keep R_{delay} = 39 mm. By increasing s_d (and L_d), the transmission of LP_{01} mode is decreased due to the phase difference between the bus and delay line waveguides, while the transmission of $LP_{11a,b}$ modes are almost independent to s_d (and L_d). Figure 4 (a) and (b) show the calculated transmission spectra for (L_d, s_d) = (2300 µm, 34.1 µm) and (2485 µm, 39.6 µm). For Fig. 4 (a), all modes are mainly transmitted to Port3. By increasing the length of the delay line by changing L_d and s_d, the transmission of LP_{01} mode is greatly reduced and > 4 dB attenuation is possible in C-band, as shown in Fig. 4 (b).

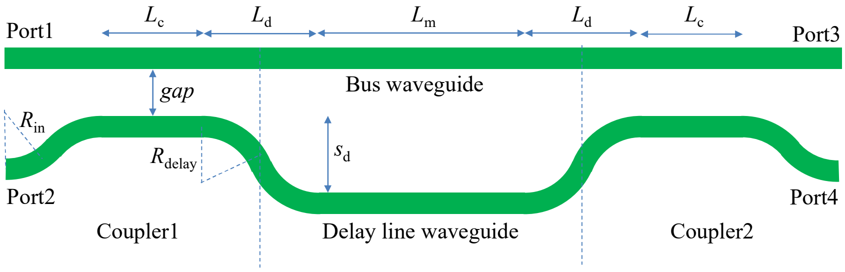

Fig. 1 The schematic of three mode MDL equalizer.

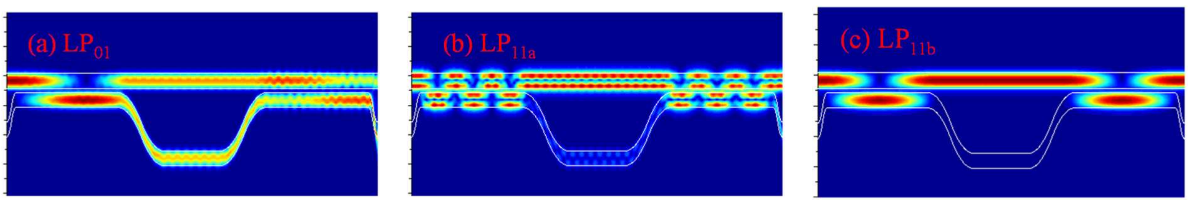

Fig. 2 Field distributions of the device for (a) LP_{01}, (b) LP_{11a}, and (c) LP_{11b} input.

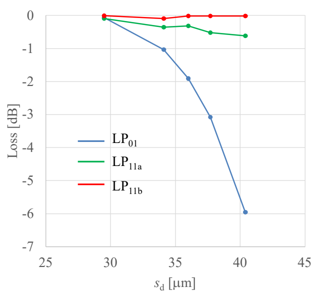

Fig. 3 Calculated loss as a function of s_d at 1550 nm.

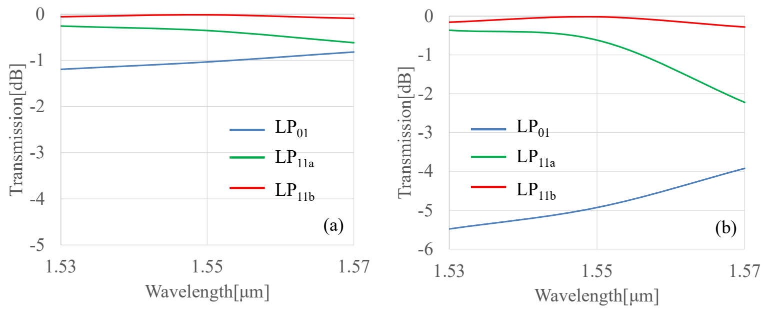

Fig. 4 Calculated transmission spectra of the device with (L_d, s_d) = (a) (2300 µm, 34.1 µm) and (b) (2485 µm, 39.6 µm).

3. Device fabrication and MDL equalization measurement

We fabricated designed chips with some values of (L_d, s_d) and two LP mode FMFs are pigtailed to the chips (hereafter, we call them modules). The picture is shown in the left part of Fig. 5. First, we measured transmission loss of the modules. The right part of Fig. 5 shows the measurement setup. The light from the tunable laser is converted to LP_{01} or LP_{11a} or LP_{11b} mode via mode MUX, and the output power is measured by a power meter. The loss of the mode MUX is subtracted. Figure 6 (a) shows the measured module loss as a function of s_d at 1550 nm. By increasing s_d (and L_d), the loss of LP_{01} mode is clearly increased, while the losses of $LP_{11a,b}$ modes are relatively independent to the value of s_d. However, about -5 dB loss can be seen for $LP_{11a,b}$ modes, which is significantly larger than the calculation. When the input/output FMF is aligned to the input/output waveguides, we used LP_{01} mode because some unstable behaviors were observed for $LP_{11a,b}$ modes. In this condition, the coupling losses between

FMF and chip of $LP_{11a,b}$ modes tend to be larger than that of LP_{01} mode. Also, some additional losses are observed for $LP_{11a,b}$ modes when transmitting isolated S-bending waveguides with the bending radius of 39 mm. These losses are included in Fig. 6 (a). We believe that these losses can be reduced by changing R_{delay} and optimizing pigtailing process. In the fabricated modules, the module with (L_d, s_d) = (2560 µm, 42 µm) have good characteristics for LP_{01} mode attenuation. Figure 6 (b) shows the measured transmission spectra of the module. From Fig. 6 (b), the loss of LP_{01} mode is -8 dB in C-band. The losses of $LP_{11a,b}$ modes are almost the same and between -4 to -6 dB. Since the core of pigtailed FMFs is circular, $LP_{11a,b}$ modes are mixed in FMF, and therefore, we cannot selectively launch $LP_{11a,b}$ modes. Probably, this is the reason for the similar loss for $LP_{11a,b}$ modes. The loss is increased for longer wavelength side, and the tendency agrees well with the calculation (Fig. 4). By using the module, we can add 3 to 4 dB additional loss for LP_{01} mode.

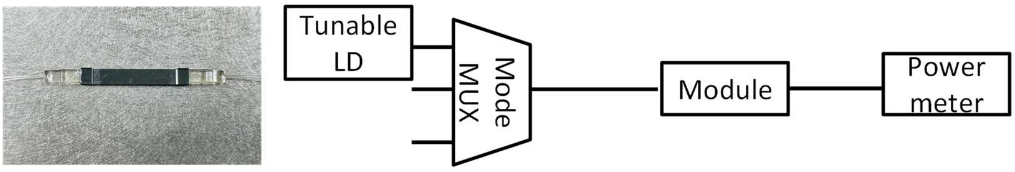

Fig. 5 (left) a picture of the fabricated module and (right) measurement setup of the module loss.

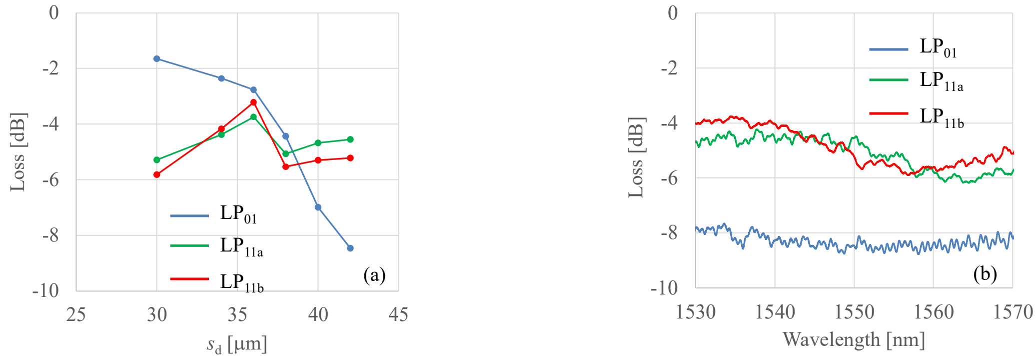

Fig. 6 (a) Measured loss as a function of s_d at 1550 nm and (b) measured loss spectra of the module with s_d = 42 mm.

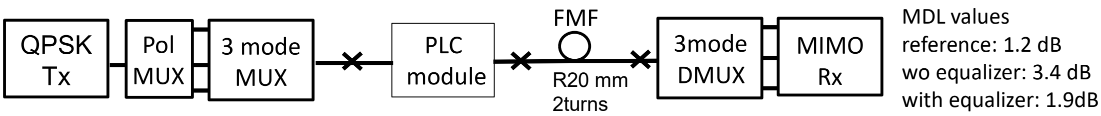

Fig. 7 Experimental setup for MDL measurement and the value of measured MDL.

By using this module, we performed transmission experiment. Figure 7 shows the experimental setup. Three QPSK signals are generated, and they are converted to LP_{01}, LP_{11a}, and LP_{11b} modes via mode MUX. The output of the mode MUX is fusion spliced to the module. The output FMF of the module is also fusion spliced to the mode DMUX and the outputs are processed offline to obtain MDL value. First, we measured the transmission characteristics without the module. Input and output FMFs are straight, and the value of MDL is 1.2 dB (reference). Next, the output fiber is strongly bent with the bending radius of 20 mm, as shown in Fig. 7, for attenuating LP_{11} mode power to make MDL of the setup large. The MDL is increased to 3.4 dB (wo equalizer) due to the loss of $LP_{11a,b}$ modes in the bending fiber. Finally, we insert the module before the bending fiber. The MDL is 1.9 dB (with equalizer) and the value is reduced compared with that for strongly mode mixing condition, showing the MDL equalization concept.

3. Conclusion

PLC-based MDL equalization device was experimentally demonstrated. We reveal that the attenuation for LP_{01} mode can be varied by controlling the parameters of S-bending structure. MDL reduction of 1.5 dB was demonstrated for the setup with large LP_{11}-mode loss condition.

4. Reference

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