PLC Mode-control Device for Mode-division-multiplexing Transmission

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1. Mode-division-multiplexing transmission

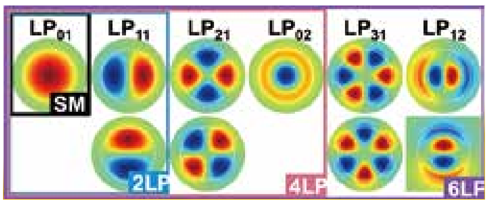
One of the elemental technologies in space-division multiplexing (SDM) optical transmission is mode-division multiplexing (MDM), which multiplexes optical signals with multiple stationary states (namely, modes). Optical fibers with circularly symmetric cores have linear polarization (LP) modes as shown in Figure 1. An optical fiber designed to support a limited number of propagation modes is known as a few-mode fiber (FMF). (The subscripts of LP_{ml} modes represent the azimuthal (m) and radial (l) orders, respectively. For $m > 0$, two modes with different phases degenerate and are distinguished as LP_{11a} and LP_{11b} modes.) FMF achieves higher spatial multiplicity compared to multi-core fiber (MCF), where multiple cores propagating through a single mode (SM) are arranged to achieve spatial multiplicity. FMF, however, exhibits significant differences in transmission characteristics between modes, which can degrade signal recovery accuracy in MIMO signal processing-based transmission systems. This becomes a limiting factor for maximizing transmission distance, making it challenging to extend the number of modes for long-distance transmission. Therefore, in long-distance transmission systems, as shown in Figure 2, it is effective to not only perform optical amplification, but also to implement mode switching and reduce mode loss differences in the repeaters, thereby homogenizing the transmission characteristic differences between modes. This paper introduces a device using a silica planar lightwave circuit (PLC) that performs such mode control.

2. PLC mode multiplexer/demultiplexer

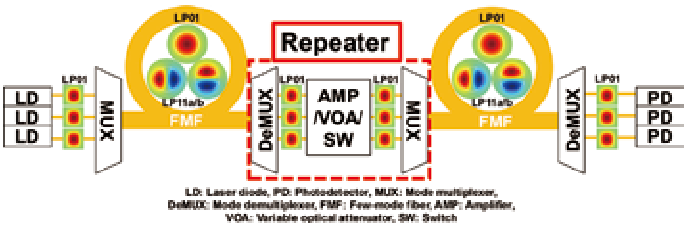
A mode multiplexer (MUX) is required to excite each mode of the FMF with light waves from the semiconductor laser. Due to the reciprocity of light, a mode MUX can also function as a mode demultiplexer (DeMUX) when light is injected in the inverse direction, except in special cases. The PLC mode MUX/DeMUX is highly integrated and enables flexible mode control as described below.

Figure 3(a) shows a cross-sectional view of a quartz-based PLC optical waveguide. The core and its surroundings are made of glass like in optical fibers, and light waves travel by total reflection within the high-refractive-index core. Made of the same material as optical fibers, it enables low-loss interconnection. By forming a Y-shaped core (hereinafter referred to as a Y-junction waveguide) as shown in Figure 3(b), it can function as an optical splitter. (Though not strictly accurate, the explanation here is in accordance with the terminology used for fiber modes). Additionally, not only the LP_{01} mode, as shown in Figure 3(b), but also the higher-order LP_{11a} mode, as shown in Figure 3(c), split evenly. The output phases of these modes correspond to the symmetry of the incident modes. Due to the linearity and reciprocity of light, both the superposition state and the

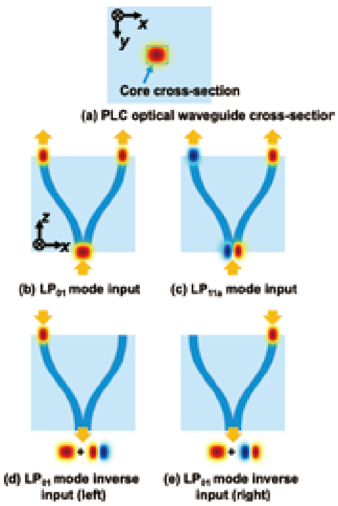
■ Figure 1: Field distribution of LP modes propagating through fiber



■ Figure 2: Example configuration of a long-distance transmission system using FMF



■ Figure 3: Light propagation in a PLC Y-junction waveguide



backward propagation state as shown in Figure 3(b) and Figure 3(c) are valid. In other words, as shown in Figures 3(d) and (e), it means that the LP_{01}/LP_{11a} modes are excited in the lower trunk waveguide when the LP_{01} mode is injected on one side of the upper branch waveguide. Thus, the Y-junction waveguide functions as a type of mode MUX/DeMUX.

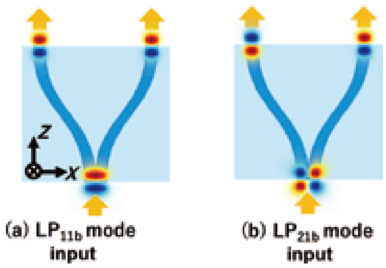
Further, even though equal splitting can be performed with higher-order modes, due to the nature of PLC (as long as processing is done in a single layer), branching can only occur in the x-direction, leaving the order in the y-direction unchanged. Specifically, as shown in Figure 4, the LP_{11b}/LP_{21b} modes are converted to the LP_{11b} mode on the branch waveguide side. However, for mode MUX/DeMUX operations, it is necessary to output the LP_{01} mode at the end. Therefore, a mode rotator (LP_{11a}/LP_{11b} mode switcher) using an L-type waveguide as shown in Figure 5 is useful. By placing this before and after the Y-junction waveguide, the order in the y-direction can be reduced. Consequently, in principle, even when modes of any order are injected, combining the Y-junction waveguide with the mode rotator allows for the output of the LP_{01} mode. Figures 6(a) and (b) show examples of configuration for higher-order modes, and as shown in Figure 6(a), even when the LP_{11b} mode is injected, it is converted to the LP_{01} mode. When injected from the opposite side, it is converted to a superposition of the LP_{01}, LP_{11a}, LP_{11b}, and LP_{21b} modes.

3. PLC-mode-control device

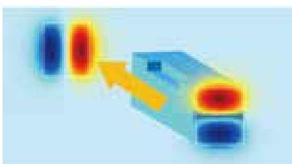
The 4-mode MUX/DeMUX shown in Figure 6 is an example of a specific device that can be used as a mode MUX/DeMUX in the repeater shown in Figure 2. However, simply amplifying each of the LP_{01} modes demultiplexed by the mode MUX cannot compensate for the mode delay differences and loss differences that occur in the FMF before and after the repeater. Therefore, what has been recently considered is an optical matrix multiplier (OMM) circuit for matrix multiplication operations on optical mode amplitudes. Figure 7 shows the basic configuration of OMM, which can obtain the output of four input amplitudes multiplied by an arbitrary unitary matrix U. Although omitted in the figure, a phase-control device and a splitting-ratio-control device are included in addition to the Y-junction waveguide, and arbitrary unitary conversion can be performed by controlling these devices. As shown in Figure 8, by inserting an optical amplifier and attenuator between two OMMs (Figure 7), the transfer matrix can be represented by $T = USV^{\dagger}$. This is a matrix representation of the singular value decomposition, which means that optical amplitude conversion by arbitrary matrices is possible. Appropriately setting the transfer matrix makes it possible to arbitrarily control mode switching and gain/loss differences, thereby enabling compensation for mode transmission characteristic differences corresponding to the FMF links in the preceding and subsequent stages. However, in this configuration, only a simple linear conversion is performed, and the delay cannot be compensated by the repeater alone. Averaging the difference in mode delay by switching modes in multiple repeaters is effective in compensating for the difference in delay between modes.

Thus far, six-mode MUXs have already been reported, and we will focus on studying mode MUX/DeMUX and mode-control devices for further expansion of the number of modes going forward.

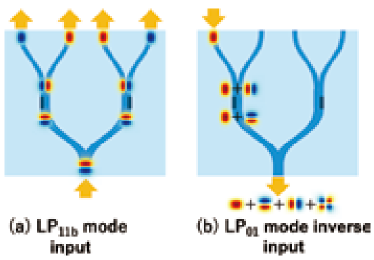
■ Figure 4: Higher-order-mode light propagation in a PLC Y-junction waveguide



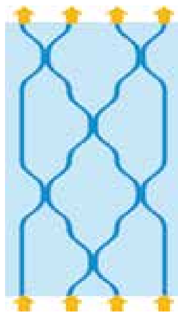
■ Figure 5: Mode rotator using an L-type waveguide



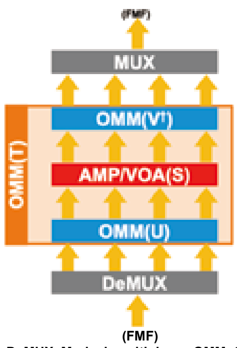
■ Figure 6: Example configuration of 4-mode MUX/DeMUX



■ Figure 7: Example configuration of a 4x4 optical unitary converter



■ Figure 8: Example configuration of an arbitrary mode-control device in a repeater



MUX: Mode multiplexer, DeMUX: Mode demultiplexer, OMM: Optical matrix multiplier, AMP: Amplifier, VOA: Variable optical attenuator
U, V†: Unitary matrix, S: Real diagonal matrix,
T: Arbitrarily configurable conversion matrix