Low Loss Optical Switch with Precisely Rotationally-aligned Multi-core fiber Array

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Abstract: We propose a 1×4 optical switch with coupled-core multi-core fiber (MCF) array. An image processing allows MCF to be precisely rotationally-aligned. It enables the IL less than 0.6 dB with the uniformity of 0.04 dB.

1. Introduction

The data traffic in optical communication networks has been increasing exponentially ever since the deployment of dense wavelength division multiplexing system in the 1990s. However, according to the study of practical single-mode-fiber optical communication systems [1], transmission capacity limits would come in the next decade. Under these circumstance, the spatial division multiplexing (SDM) technologies using multi-core fibers (MCFs) have been studied as a promising approach to overcome these limits. Many kinds of MCFs have been reported such as uncoupled-core MCFs (UC-MCFs), coupled-core MCFs (CC-MCFs), and multi-mode MCFs [2-5] up to now. CC-MCFs in particular are better than others for arranging more cores in a standard 125 um cladding fiber, under the condition that crosstalk (XT) among cores are compensated for by multiple-input-multiple-output (MIMO) digital signal processing (DSP). They also have the prominent characteristics of a low differential group delay between spatial modes to reduce MIMO DSP load [3]. Consequently, CC-MCFs are expected to be used for next generation long-haul transmission systems.

In an MCF transmission system, the 1 × N optical switches for MCFs would be necessary to monitor optical performance in each MCFs. They can also play an important role in making optical networks more reliable by constructing redundant optical path architectures [6]. Although micro-electromechanical system (MEMS) based 1 × N switches using single-core-fibers (SCFs) [7] are widely used in current networks, they are not available for MCFs. One of the challenges in realizing MCF switches is rotational alignment between MCFs.

In this paper, firstly, we propose a 1 × 4 switch with 4-core CC-MCFs and a 2D-MEMS mirror. Rotational MCF alignment with minor misalignment is achieved by image processing of the MCFs end faces. Measurements of the characteristics of the fabricated switch are given. Secondly, we discuss the port count scalability of switches using not only CC-MCFs but also using UC-MCFs

2. Structure and optical design

An optical path schematic of the 1 × 4 switch is shown in Fig. 1 (A). It consists of a CC-MCF array with five CC-MCFs, a lens and a tilt mirror. Each CC-MCF is kept in a glass ferrule and their end faces are polished at an angle of 8°. A CC-MCF has four cores with a nearest core pitch of 25 μm and has a mode field diameter (MFD) of 10 μm at a wavelength (λ) of 1.55 μm [5]. The core is designed to be coupled at the C and L bands. The lens has aspherical surfaces and an AR-coating on both sides. The focal length *f* is 3 mm. The Au-coated mirror is driven in θ_x and θ_y tilt axes by a 2D-MEMS comb actuator.

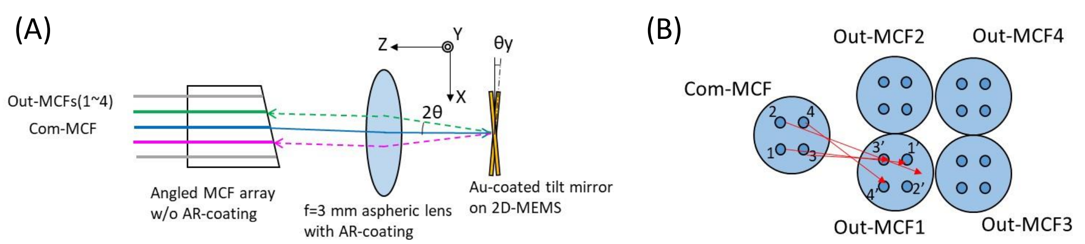

Fig.1. (A) A schematic of the optical paths in a switch. (B) An end face image of an MCF array.

As shown in Fig. 1 (A), a beam leaves the common MCF (com-MCF) end face, and goes through the lens. The beam is collimated by the lens and reflected on the surface of the Au-mirror that is aligned at the tilt direction. Then, it goes back to the lens and is refocused again at the MCF end face. After that, it couples with one of the out-MCFs. The com-MCF can be coupled with each out-MCF by individually adjusting the driving voltages of the MEMS actuators. It should be noted that the four cores of the com-MCF are coupled with four cores of an out- MCF not with a parallel shift but with just a half-turn shift as shown in Fig. 1 (B). Therefore, each MCF demands precise rotational alignment in order to achieve low insertion loss (IL).

3. Rotational alignment of MCF

One of the important points in assembling this switch is a rotational alignment of MCFs as described in the last paragraph. Rotational alignments of one MCF per one hole or one V-groove have been reported in the connector field [8], whereas alignment of plural MCFs is a new challenge. In this fabrication, four out-MCFs need to be aligned simultaneously, because they are kept in one square shaped hole in a ferrule and the rotation of adjacent MCFs is influenced. Though separating MCFs by the use of a ferrule with as many holes as the MCF count is one idea, fiber density in the MCF array decreases and loss increases because the increase in the mismatch in the optical path distance due to the 8 ° angle of the MCF array. As a result, it prevents port count scalability and low IL. We utilized image processing to allow the MCF array to have precise angle alignment. Com-MCF and each out-MCF whose cores were input with a visible light were continuously monitored by a camera as shown in Fig. 2 (A). Each MCF was able to be actively aligned since their angles were calculated in real time. The angle of an MCF is defined as the difference in the angle between white lines drawn on two cores and a horizontal green line in the background as shown in Fig. 2 (B). Figure 2 (C) shows the assembled MCF array. MCFs are fixed by a UV curable adhesive just after alignments are completed.

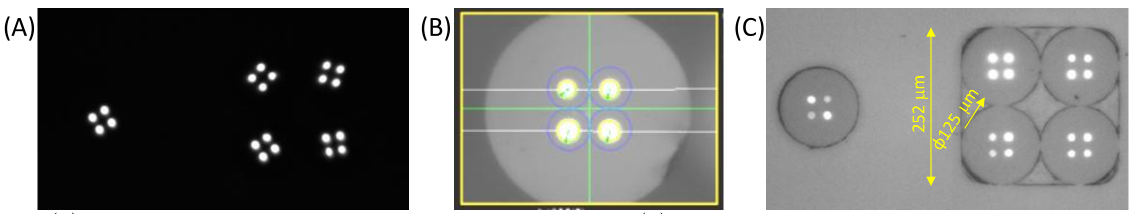

Fig.2. (A) An end face photo of the MCF array before alignment. (B) End face photo of the MCF during rotational alignment. (C) End face photo of an aligned MCF array after it is polished.

Three MCF arrays were assembled, and the angle shifts of out-MCF from com-MCF were measured. All angle shifts were smaller than 1 ° as shown in Fig. 3. This is equivalent to a loss increase of less than 0.02 dB assuming the MFD of 10 µm. Even if the core pitch is 50 µm, the loss increase is still less than 0.07 dB.

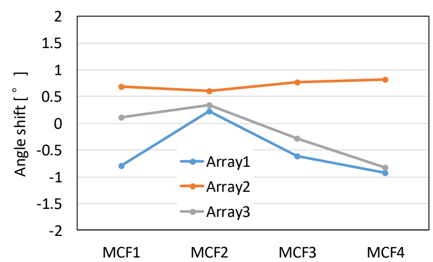

Fig.3. Angle shift of the out-MCFs from the com-MCFs

4. Fabrication and optical characteristics

The lens was passively positioned in front of an Au-coated mirror. Then, the assembled MCF array was actively aligned with the mirror-and-lens subassembly by the use of light power monitoring at λ of 1.55 µm. The assembled switch is shown in Fig. 4.

Fig.4. Photo of the assembled optical switch.

Insertion loss was measured with the light source at λ of 1.55 µm. The light was equally split into four and simultaneously input to the four cores of the com-MCF. Light power from the out-MCFs was measured. The result is shown in Fig. 5 (A). All four ILs were less than 0.6 dB and IL uniformity was 0.04 dB. The ILs included a Fresnel round trip reflection loss of 0.3 dB due to no AR-coating on the end face of the MCF array. The other major loss of 0.3 dB came from the reflection efficiency of the Au-coating mirror and optical pass distance difference due to the 8 ° angle of the MCF array end face. Inter-fiber XT at λ of 1.55µm was also measured. The result is shown in Fig. 5 (B). There are twelve cases of XT and all of them were less than -61 dB. IL repeatability over 500 times at λ of 1.55µm was measured. Tuned voltages for the 2D-MEMS actuator were applied and released alternately while the measurement was taken. The IL fluctuation range through the test was 0.002 dB as shown in Fig. 5 (C). This still included a variation due to light source. A wavelength dependent loss from λ of 1.53 to 1.625 µm was 0.2 dB as shown in Fig. 5 (D).

The 1 × 4 switch can be used as a switch of 4 groups of 1 × 4 (or 4 × 1 × 4) as shown in Fig. 5 (E) when each core in the MCF is used as an independent path with fan-in/out. IL of the 4 × 1 × 4 switch is shown in Fig. 5 (F). An average IL is 0.58 dB. This is almost the same level with that of the 1 × 4 switch. On the other hand, IL uniformity of 0.18 dB is larger than that of the 1 × 4 switch. This is due to the inter-core XT of CC-MCF. Therefore, smaller uniformity is possible by the use of UC-MCF.

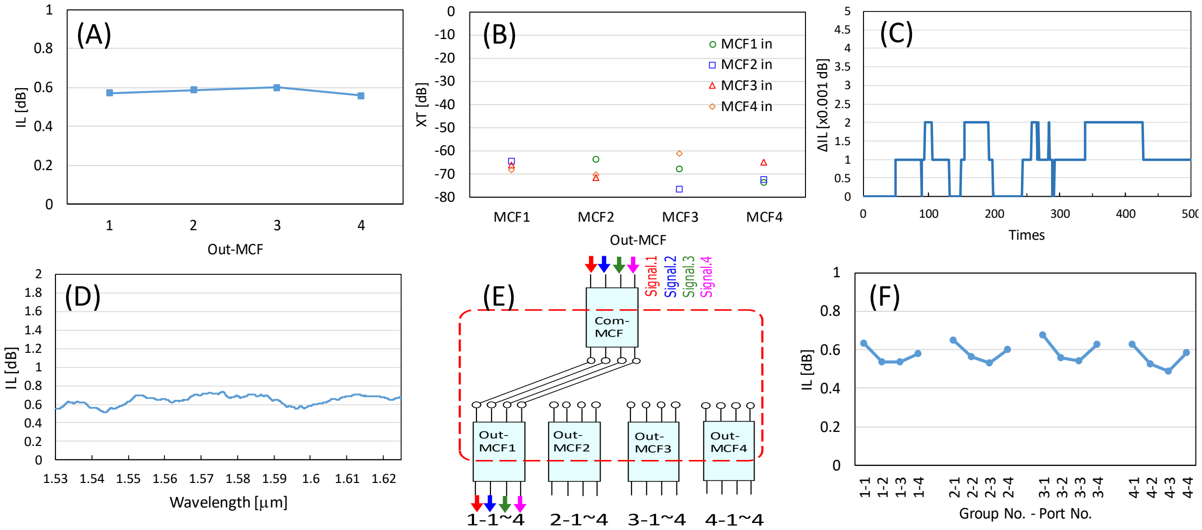

Fig.5. The optical characteristics of a 1×4 switch for a 4-core CU-MCF. (A) IL at 1.55µm. (B) XT at 1.55µm. (C) IL repeatability at 1.55µm. (D) Wavelength dependent loss at C and L bands. (E) A schematic of the 4×1×4 switch. (F) IL of individual cores at 1.55µm.

5. Port count scalability by MCF

The use of UC-MCF instead of CC-MCF is effective to realize large port count $1 \times N$ switches. When SCF is used as a common port and m MCFs whose core count is n are used, the switch can be used as a $1 \times (m \times n)$ switch. A simulation result between fiber cladding diameter and port count in switches is shown in Fig. 6. Assuming that an Au-mirror tilt range θ is ±3°, f of a lens is 3 mm, core count per MCF is 4 and inter-core pitch is 45µm, out-core can be located in a square of $4f\theta \times 4f\theta$ (628 µm × 628 µm) as a light scanning area. MCF can achieve a 100 port count with 25 fibers (not including a common fiber) whose cladding is 125µm in diameter. On the other hand, an SCF's switch has only 36 ports. To achieve a 100 port count, their cladding must be around half of a standard fiber in diameter.

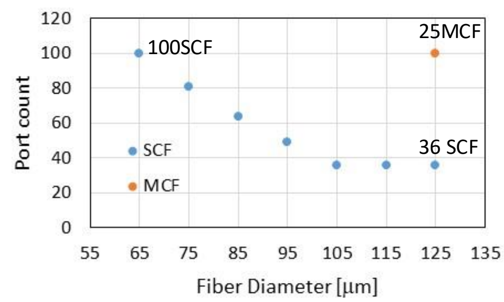

Fig.6. Relation between fiber diameter and port count in switches.

6. Conclusion

We have developed a 1×4 optical switch for the C/L band using coupled-core MCFs. An MCF array with angle misalignments between MCFs of smaller than 1 ° thanks to image processing enabled an IL less than 0.6 dB and its uniformity of 0.04 dB. The IL will be reduced to 0.3 dB by applying an AR-coating on the MCF end faces. This switch also can be used as a 4 group 1×4 switch by replacing CC-MCF with UC-MCF. Another advantage of UC-MCF switches is port count scalability.

7. References

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