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Low Insertion Loss 3D Waveguide-based Fan-in/Fan-out For a 12-Core Fiber

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Abstract: *We fabricated a laser inscription 3D waveguide-based fan-in/fan-out for a 12-core fiber and achieved an insertion loss of less than 0.51 dB over both the O-band and C-band across all 12 cores.*
Keywords: *Fiber based devices for space division multiplexing*

I. INTRODUCTION

In recent years, the demand for data communication has been expanding, leading to a growing need for increased communication capacity. Space Division Multiplexing (SDM) systems have emerged to cope with the need. In particular, multi-core optical fibers (MCF), which have multiple cores within a single optical fiber, are expected to be a promising means of increasing transmission capacity. 2-core fiber for submarine cables is becoming the first commercial application of MCF [1]. 4-core fiber has also been developed, as a subsequent step[2]. Due to constraints in cable installation space, MCF is also being anticipated for data center and terrestrial transmissions. Among these, a 12-core fiber (12CF) with a coating diameter of 250 μm has been proposed [3], which can achieve more than ten times the spatial utilization efficiency while maintaining a standard coating diameter.

In connecting existing single-core fiber (SCF) based transmission systems with MCF, a Fan-in/Fan-out (FIFO) that branches the MCF to SCFs is an essential device. Various types of FIFOs have been proposed, including bundle types [4, 5], fused taper types [6], and spatial coupling types [7, 8].

Recently, a technology that uses femtosecond laser inscription (FLI) to make three-dimensional optical waveguides (3D waveguide) for FIFO has seen significant improvements [9, 10, 11]. This technology offers a high flexibility in core arrangement and can accommodate many cores in a small glass substrate. Therefore, even as the number of cores increases, the device size can be kept compact. To the best of our knowledge, there have been no reports of low-loss FIFO with a 3D waveguide that have achieved insertion loss (IL) of less than 1 dB in both the C and O-bands.

In this study, we have developed a compact and low-loss 3D waveguide-based FIFO for 12CF, achieving an IL of less than 0.51 dB across all 12 cores over both the O-band and C-band.

II. OPTICAL DESIGN AND STRUCTURE

The overall configuration of the FIFO using a 3D waveguide is shown in Fig. 1. It consists of a 3D waveguide using FLI technology, a 12CF and a 12-chanenel SCF array.

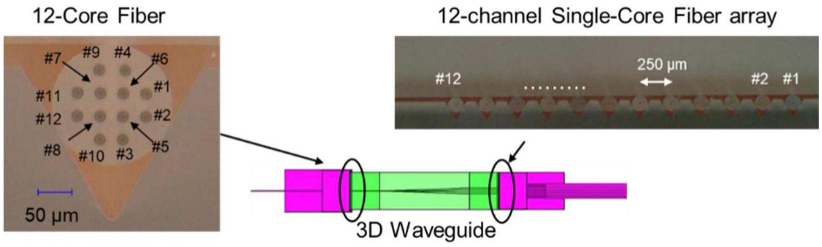

Fig. 1 Schematic structure of 3D Waveguide based FIFO, an end face photo of the 12CF in a V-groove, and an end face photo of the 12-SCFs in a V-groove array.

A. 12-Core Fiber

An uncoupled 12CF [3] with a cladding diameter of 180 μm was used in this FIFO. Its characteristics are listed in Table. 1. The core-to-core pitch is 35 μm, while cores #4 and #9 have a wider pitch of 42 μm to identify the top and bottom. The mode field diameter (MFD) at a wavelength of 1310 nm is 8.8 μm. It features a trench-assisted design that allows transmission in both the O and C-bands while minimizing inter-core cross talk (XT). It was fixed on the V-groove substrate with the identification cores positioned at the top of the core arrangement area.

Table. I Characteristics of 12CF

Number of cores	12
Cladding diameter	180 μm
Coating diameter	250 μm
MFD	8.8 μm
Core to core pitch	35 μm
Type of fiber	Trench assisted

B. 12-channel Single-Core Fiber Array

The SCFs have an MFD of 8.6 µm at 1310 nm, similar to that of the 12CF. A 12-fiber ribbon was utilized and each SCF was arranged on a V-groove substrate with a pitch of 250 µm, consistent with the configuration used in conventional two-dimensional waveguide devices.

C. 3D Waveguide

The 3D waveguide has been developed based on FLI technology [9, 10, 11]. The 3D waveguide we used was designed to match the pitch of the 12CF and the 12-SCF array at each end. Each waveguide core was inscribed with an appropriate bending radius to minimize bending loss. Images of the connection surfaces to the 12CF and SCFs are shown in Figs. 3 (a) and (b), respectively. A top view image showing the 12-waveguide-core paths is shown in Fig.3 (c). This is a mock-up sample photo to visualize paths more clearly. An image of the measured near field pattern of the waveguide, which has a design MFD of 8.6 µm equivalent to those of the fibers, is shown in Fig. 4. The beam has a Gaussian shape profile with small distortion and has a beam diameter of 8.5 µm in $1/e^2$ width at 1310 nm.

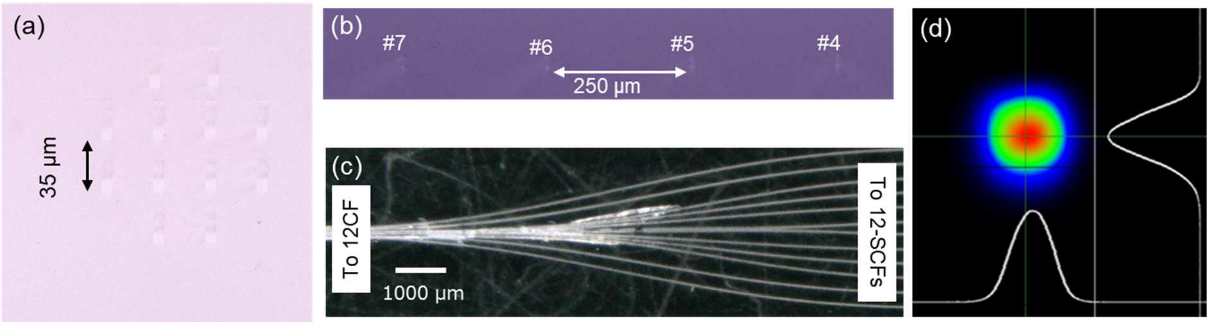

Fig. 3 Microscopic image of 3D waveguide.(a)End face to be connected to 12CF, (b) End face to be connected to 12-SCFs (a part of 12 cores), (c) Top view image of overall 3D waveguide substrate.(A mock-up sample with core paths visible), (d)Near Field Pattern of a 3D Waveguide core.

The length of the waveguide substrate in the propagation direction is 20 mm. Fig. 4 shows 3D waveguide ILs individually measured by using the fibers at each optically optimal alignment position. The measured ILs are all approximately 0.3 dB, comprising a propagation loss of around 0.1 dB/10 mm and a coupling loss of around 0.05 dB per facet.

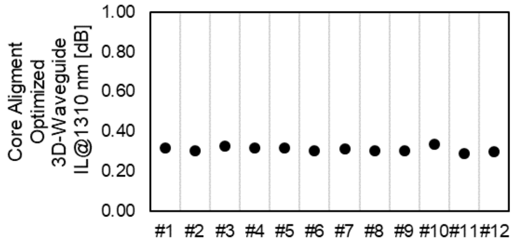

Fig. 4 IL of 3D Waveguide at 1310 nm when each core was individually optimally aligned with fibers.

III. Fabrication

To suppress back reflections at the ends of the fibers and waveguide, they were polished at an angle of 8 degrees. The 12CF and the 12-SCF array were coupled with each end face of the 3D waveguide, respectively by the use of optical power monitoring active alignment, and subsequently secured with a UV curable adhesive. The assembled FIFO was housed in a plastic package as illustrated in Fig. 5 (a). The dimensions of the packaged FIFO are 50 mm × 8 mm × 4.3 mm. A whole view of the packaged FIFO with pigtails is illustrated in Fig. 5 (b).

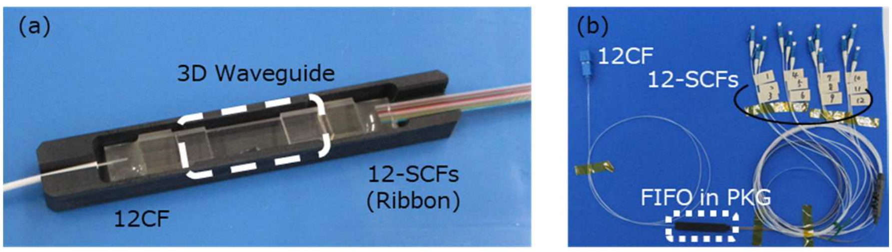

Fig. 5 Photos of fabricated FIFO (a) zoomed in PKG, (b) overall FIFO.

IV. Optical Characteristics

The results of the IL and polarization dependent loss (PDL) measurements for the FIFO in both the O and C-bands are shown in Fig. 6. In the O-band, the average IL and maximum IL of the 12 cores were 0.34 dB and 0.45 dB, respectively. In the C-band, they were 0.40 dB and 0.51 dB, respectively. The PDL of all cores in both the O and C-bands was less than 0.1 dB.

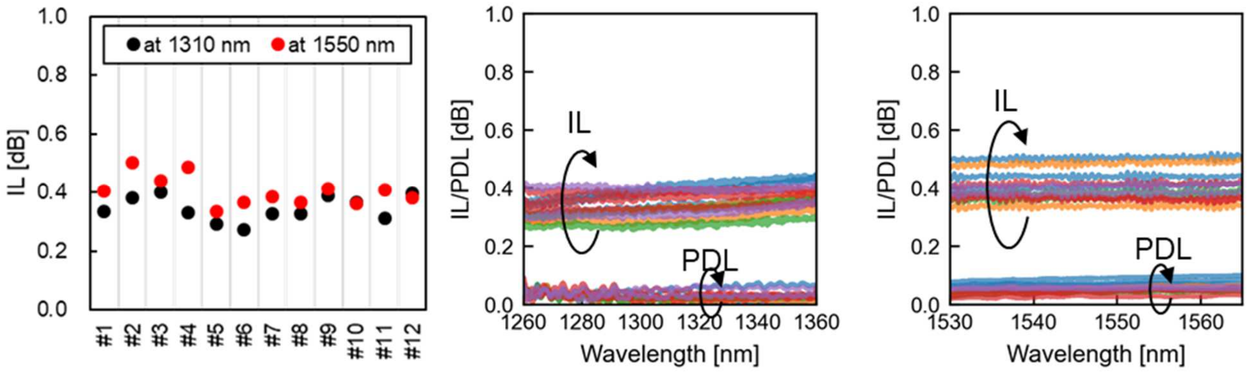

Fig. 6 (a) Measurement IL of the fabricated FIFO at 1310 nm & 1550 nm. Measured IL/PDL spectrums of fabricated FIFO at O-band (b) and at C-band (c) .

The propagation loss of the 20 mm long waveguide was approximately 0.2 dB, while the connection loss to the fiber was about 0.1 dB at the two bonding points, resulting in a total loss of approximately 0.3 dB. This indicates that an almost ideal alignment state was maintained even after bonding. Cores #5, #6, #7, and #8, which are closer to the center of the fiber, have lower ILs, while some of the other cores have slightly higher ILs. This non-uniformity was caused by a core positions misalignment between the 12CF and the waveguide. Lower IL and higher IL uniformity can be expected by improving the misalignment. The small ripples observed in each spectrum are due to multiple reflection interference between the 12CF connector end face and the optical power sensor window. We measured the XT of the FIFO pair at 1550 nm, and the results between the nearest neighboring cores are shown in Fig. 7. The maximum XT was below -40 dB. At 1310 nm, the XT was even lower. The return loss (RL) measured with an optical time domain reflectometer is shown in Fig. 8. The result excludes the reflection from connectors. They are over 65 dB at both 1310 and 1550 nm. The results of temperature-dependent loss measurements are shown in Fig. 9. During temperature cycling between -40 °C and 85 °C, the change in IL of all cores was less than 0.1 dB.

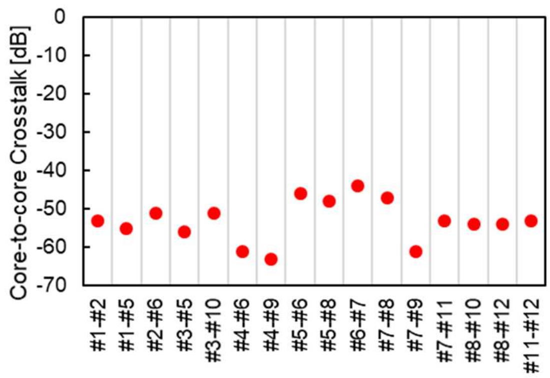

Fig. 7 Measured core-to-core XT between the nearest neighboring cores in the fabricated FIFO pair at 1550 nm.

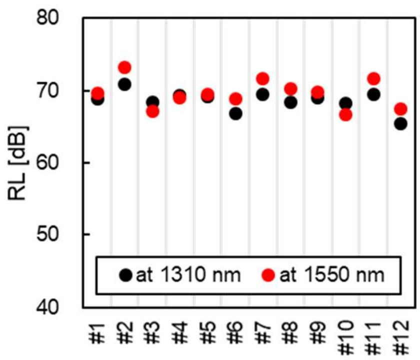

Fig. 8 Measured RL of the FIFO

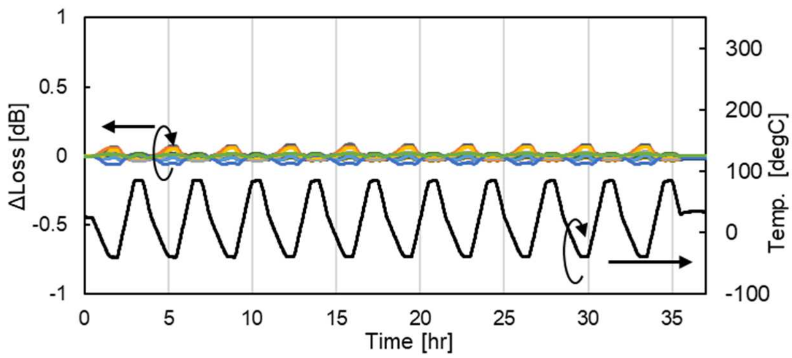

Fig. 9 Measured thermal dependent loss at 1310 nm over a temperature range of -40 to 85°C in the FIFO

V. Conclusions

We fabricated a 3D waveguide-based FIFO for uncoupled 12CF. In all 12 cores, the insertion loss was less than 0.51 dB over both the O and C-bands, with an average IL of 0.34 dB at 1310 nm and 0.40 dB at 1550 nm. Improving the core position alignment will enable lower IL. The FIFO size was 50 mm × 8 mm × 4.3 mm. This compact and low loss FIFO employing a laser inscription 3D waveguide demonstrates a potential solution for next generation high-density SDM fiber networks.

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