Optical Fiber Bendable at 3-mm Diameter for Optical Transceivers and Silicon Photonic Packaging

Xin Chen, Jason E. Hurley, Yin Shu, and Ming-Jun Li
Corning Incorporated, 1 Riverfront Plaza, Corning, NY 14831, USA
chenx2@corning.com

Abstract: A 3-mm diameter bendable and mechanically reliable fiber for both O- and C-band wavelength windows is designed and fabricated. Bending losses of 0.036 dB/turn at 1310 nm and 0.39 dB/turn at 1550 nm are demonstrated. © 2024 The Author(s)

1. Introduction

As the transceiver technology move toward very high data rate, more components are packaged into a tight space with compact form factor. Optical fiber is used to route between different components and the fiber can be wrapped in even smaller space with lower bending diameter. In certain applications, optical fiber is needed to be bent at a bend diameter as small as 3 mm, which poses challenges for both the bending performance and long-term mechanical reliability. The bending requirements exceed those for bending insensitive fibers (BIF) for 10 mm bend diameter that have been used in fiber-to-the-home applications [1]. Although a fiber that is bendable to around 5 mm diameter was designed, fabricated and demonstrated [2], the bending loss of that fiber is still too high for 3 mm bend conditions.

In this paper, we explore the feasibility of making an optical fiber that can be used inside optical transceivers and silicon photonic packaging with bending diameters as low as 3 mm to further push the boundaries of optical fibers used inside transceivers. We have taken into account the needs in both O-band and C-band, two dominant wavelength windows for optical transceivers. In particular, we studied the feasibility of using such fiber in O-band below the cable cutoff wavelength of the fiber for single mode operations.

2. Fiber design

There are several factors to consider when designing fibers for 3 mm bend diameters. The fiber needs to have mode field diameter (MFD) similar to BIFs used in this type of application with an MFD of 8.6 μm +/- 0.4 μm at 1310 nm. However, since the fiber is only used for very short lengths from a few centimeters to a meter, the chromatic dispersion requirements, in particular the zero-dispersion wavelength requirement to be within 1300 nm and 1324 nm can be lifted. The most important factor is the bending loss. New profile designs target to reduce bending loss at 1310 nm below 0.1 dB/turn and at 1550 nm below 0.5 dB/turn at 3 mm bend diameter.

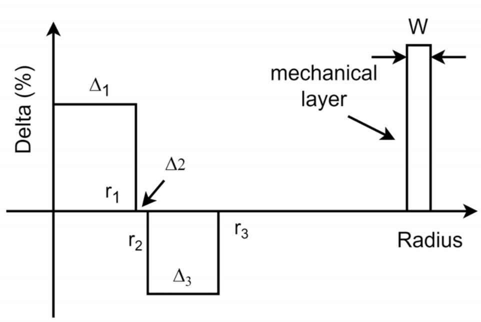

Fig. 1 The schematic of optical fiber refractive index profile design for low bending loss at 3 mm bend diameter.

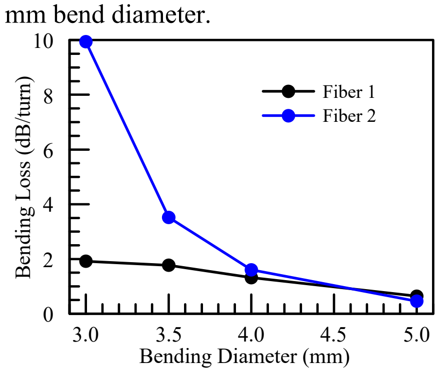

Fig. 2. Modelled bending loss vs bending diameter for two fibers: Fiber 1 and Fiber 2.

To design a fiber with low bending loss at 3 mm bend diameter, the optical power should be strongly confined in the fiber core region. We adopt the design strategy for BIFs using a low index trench [2]. Fig. 1 shows schematically the profile design based on the index contrast or delta to the cladding. The fiber consists of a step-index core with a delta of Δ_1, and core radius r_1. Following the inner cladding with $\Delta_2 = 0$ % between radius r_1 and r_2, there is a low index trench with a delta of Δ_3 from radius r_2 to radius r_3. An outer cladding follows the low index trench. It is desirable that the MFD of the 3 mm diameter bendable fiber is still compatible with other BIFs so that the MFD should be greater than 8.2 μm at 1310 nm, and 9.1 μm at 1550 nm. The low index trench reduces the amount of power in the cladding, resulting in less power leaking into the cladding and polymer coating when bending is applied. However, in order to have strong bending performance the trench needs to move very close to the fiber core, closer than the conventional BIF. We have done modeling to illustrate this through a fiber having a step-index core with Δ_1 of 0.35% and r_1 of 4.1 μm and a trench with width of 7.5 μm and depth of -0.4% using the method in [3] and COMSOL Multiphysics software 5.4. Fiber 1 has a r_2 of 4.8 μm close to the edge of the core while Fiber 2 has a r_2 of 9.0 μm, similar to conventional BIFs. The bending performance at 1550 nm is shown in Fig. 2. Both have good bending performance at 5 mm bending diameter. But when the trench is close to the core, the fiber has much better bending performance at 3 mm bending diameter. The trench parameters also affect the fiber MFD compared to the case without a trench. The core parameters were further adjusted to yield the desired MFD for the fiber.

Another requirement is mechanical reliability under 3 mm bending diameter. Although theoretically perfect silica fiber without any flaws can survive such bending condition, practical fibers can have various flaws due to manufacturing and fiber handling, such as coating stripping. Therefore, they cannot meet the long-term reliability requirement. The reliability of a bent fiber with respect to time is a function of fatigue, the flaw distribution and stress level at each small element area around the fiber surface [4]. Our reliability model shows that assuming a typical fatigue parameter n=20 for silica and a requirement of >5 years failure probability, a silica fiber with 125 μm cladding diameter can only be bent to 5 mm diameter as shown in Fig. 3. The long-term mechanical performance under tight bending can be enhanced by adding a mechanical reliability layer that is doped with Titania at outer cladding [5] as shown in Fig. 1. The Titania layer has a width of *w* and higher relative refractive index. The optical parameters of fiber are primarily determined by the core, the inner clad and the trench. Although the refractive index change of the mechanical layer is higher than the core, its effect on fiber optical properties is negligible because it is far away from the core. With the fatigue parameter n>=33 for the Titania layer and the requirement of >5 years failure probability, the fiber with 125 μm cladding diameter can be bent to 3 mm diameter as shown in Fig. 3.

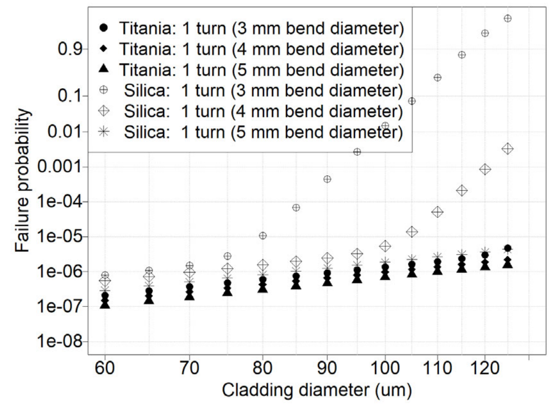

Fig. 3. Fiber > 5years failure probability under different bending diameters for silica cladding and Titania cladding.

3. Fiber properties and O-band use

3.1 Optical properties

Following the design considerations in Section 2 we have designed and fabricated a fiber with 125 μm cladding diameter targeting 3 mm bending. The fiber has a MFD of 8.93 μm at 1310 nm and 9.54 μm at 1550 nm, compatible with other BIFs typically used in these environments. The attenuation is 0.347 dB/km at 1310 nm and 0.216 dB/km at 1550 nm. The cable cutoff wavelength is around 1540 nm. Modeling based on the measured refractive index profile of the fiber indicates that it has a zero-dispersion wavelength of 1265 nm, which is outside of standard single mode fiber, but has little effects at short length.

Table 1. Measured bending loss at 1310 nm and 1550 nm.

Bending Diameter (mm)	Bending Loss at 1310 nm (dB/turn)	Bending Loss at 1550 nm (dB/turn)
2	0.59	4.30
3	0.036	0.39
4	0.01	0.18
5	0.006	0.015

Table 2. Modeled bending loss for LP01 and LP11 modes.

Bending Diameter (mm)	1310 nm LP01 Bending Loss (dB/turn)	1310 nm LP11 Bending Loss (dB/ turn)	1550 nm LP01 Bending Loss (dB/turn)
3	0.053	2.47	0.41
5	0.0029	0.16	0.038

We measured fiber bending loss, which was the most important optical property to study. As the bending diameter was very small, we had to handle the fiber careful by wrapping the fiber around a rod with diameters of 2 mm, 3 mm, 4 mm and 5 mm. Measurement results are shown in Table 1. At 3 mm bending diameter, the bending loss at 1310 nm is 0.036 dB/turn while at 1550 nm is 0.39 dB/turn. Both meet our design target. The 1310 nm bending performance is better than 1550 nm. As the bending diameter is reduced to 2 mm, the bending losses increased further, more at 1550 nm. Modeling was also conducted using COMSOL Multiphysics software following the method described in [3] with results shown in Table 2. The bending losses for the LP01 mode are consistent with the experimental results within reasonable variability. Modeling revealed additional insight on LP11 bending loss at 1310 nm at 3 mm bending diameter. It can be observed that at 1310 nm the bending loss is 2.47 dB/turn, much higher than the loss of LP01 mode at the same bending. It would be more desirable that LP11 bending loss can be even higher as the bending can then help to strip out LP11 mode at this wavelength. It is feasible to fine tune the fiber refractive profile to slightly weaken the bending performance to achieve this goal.

3.2 Use of the fiber in O-band

Since the fiber has a cable cutoff wavelength above 1500 nm, at 1310 nm, the fiber supports two modes. However, the fiber can still be used at 1310 nm, or more broadly at O-Band between 1260 nm to 1360 nm if the alignment between the single mode fiber from other components and this fiber is sufficiently good. One measure for higher order modes is the multi-path interference (MPI) [6]. We define MPI loss to gauge the penalty of such effect in short distance transmission. Since MPI power penalty results from the reduction in the detected optical power due to interference, the ratio of the lowest received power P_{low} detected from the distribution to the average received power P_{avg}, converted into dB units defines the MPI loss for a given link realization:

$$MPI\ Loss = -10 \cdot \log_{10}\left(\frac{P_{low}}{P_{avg}}\right) \tag{1}$$

To measure MPI loss, we used a measurement setup that is shown in Fig. 4(a). We fusion spliced 2 m of 3 mm bendable fiber with SMF pigtails in both ends and measured the optical power with the fiber under test shaken and input state of polarization scrambled. The measured optical power over time is shown in Fig. 4(b). It can be found that the MPI loss is only 0.09 dB. Therefore, with a good alignment of fibers, the 3 mm bendable fiber can be used in 1310 nm or O-band with minimum MPI penalty.

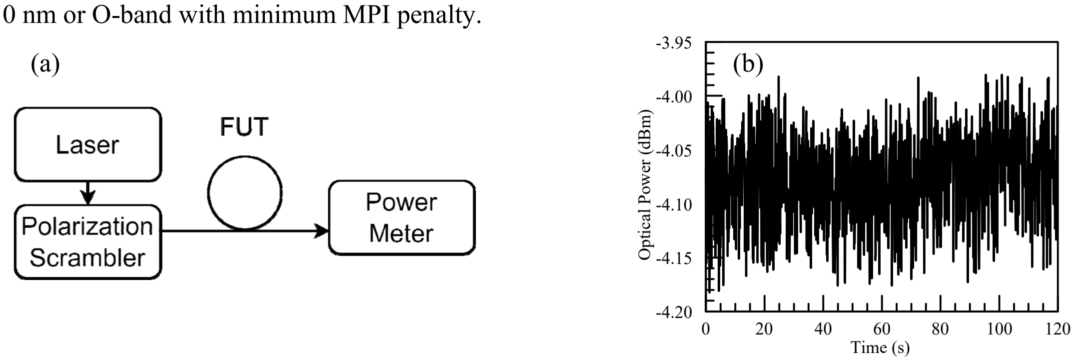

Fig. 4 (a) Experimental setup for MPI measurement; (b) The measured optical power as a function of time.

4. Conclusions

Fibers with bendable diameters of 3 mm have been designed and fabricated for use inside optical transceivers and silicon photonic packaging. The fiber shows MFD compatible with other BIFs while having excellent bending performance of better than 0.1 dB/turn at 1310 nm and better than 0.5 dB/turn at 1550 nm. We also show that it is feasible to use such fiber in O-band, in addition to C-band if good fiber alignment can be achieved.

5. References

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