# Designs of Bend-Insensitive Multimode fibers

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**Abstract:** New designs of bend-insensitive multimode fibers are proposed. The bending loss can be reduced by a factor of 10 while meeting all other standard requirements. The design concept is validated by actual fiber results.

**OCIS codes:** (060.2280) Fiber design and fabrication; (060.2270) Fiber characterization

## 1. Introduction

Recent years have seen increased interest in bend-insensitive fibers for applications in challenging environments with tight bends [1-4]. Significant progress in bend-insensitive single-mode fibers has been made for fiber to the home applications. In particular, standard compliant single-mode fibers with bending loss of 0.1 dB/turn at a bend radius of 5 mm and wavelength of 1550 nm has been demonstrated [1]. For enterprise network applications, bend-insensitive multimode fibers (MMF) are attractive because they offer improved spare operating margins, and enable smaller cable, hardware and equipment designs that can deliver space savings, easy handling for frequent changes and better cooling efficiency, and better overall connection and cable management.

In this paper, we propose new designs for making bend-insensitive MMF and report experimental results.

## 2. Fiber Designs

To design bend-insensitive MMF, we consider placing a low index ring in the cladding similar to designing bend-insensitive single-mode fibers. Figure 1 shows two bend-insensitive MMF designs. Both designs have alpha graded index core with a low index ring in the cladding. In Design (a) of Figure 1, the alpha-profile extends into the low index ring. Design (b) in Figure 1 has an offset between the core and the low index ring. In both designs, the low index ring reduces the optical power of guided modes in the cladding region outside the ring, thus improving their bend performance. The design task would be simple if only the bend loss requirement were considered. However, other requirements for MMF need to be considered as well such as numerical aperture (NA), optical core diameter (CD) and more importantly the bandwidth (BW), making the design task much more complicated. Care must be taken in designing both the core and the ring to satisfy all these requirements.

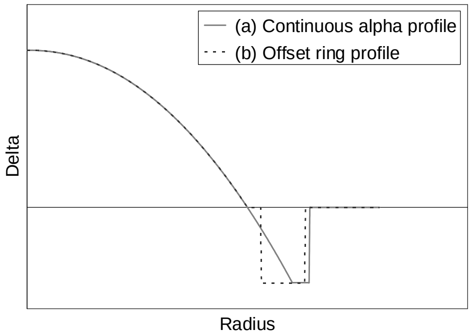

Figure 1. Bend-insensitive MMF profile designs. (a): continuous alpha profile in the ring, and (b): offset ring profile,

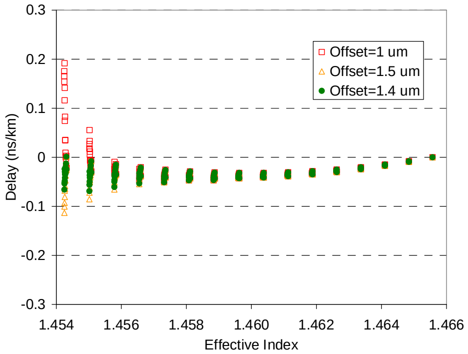

Figure 2. Effects of ring offset on time delays.

The fiber bend performance is linked to the “volume” of the ring defined by

$$V = \int_{r1}^{r2} |\Delta(r)| r dr \tag{1}$$

where $\Delta(r)$ is the relative refractive index change in the ring, and $r_1$ and $r_2$ are the inner and outer radius of the ring. Increasing the ring volume will increase the bend performance, but will increase the core NA and CD. In order to keep the NA and CD compatible with the specifications of the standard MMF fiber, the ring volume has to be small enough to allow the unwanted higher order modes to tunnel into the cladding. At the same time, the core delta and core radius need to be adjusted to achieve the design targets. For MMF, BW is a very important parameter. To achieve high BW, the core profile needs to be carefully designed with the correct alpha value. Any deviation from the optimum alpha profile will result in degradation in fiber BW. For standard MMF without the low index ring, the outermost mode groups tend to have shorter time delays. However these outer mode groups are not observed in a practical fiber as they are bend sensitive and can be easily stripped. For bend-insensitive MMF, the bending loss of these modes is decreased and the profile needs to be carefully designed to correct any delay problem associated with these modes. In Design (a) shown in Figure 1, this problem is solved by extending the alpha profile into the low index ring region. The outer mode groups of the core see an ideal alpha profile and their delays are not affected by the ring. In Design (b) shown in Figure 1, an offset is placed between the core and the ring. If the offset value is properly selected, the outer mode group delays can be corrected. Figure 2 shows the effect of offset on time delays of the outer mode groups. The core delta is 0.936%, the core radius is 24.5 µm, the ring delta is -0.45% and the ring width 5 µm. For an offset of 1 µm, the two outer mode groups travel slower, but for an offset of 1.5 µm, the two outer mode groups travel faster. The optimum offset value in this case is about 1.4 µm.

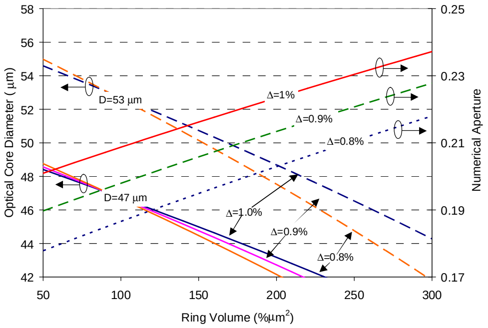

Figure 3. Design diagram for numerical aperture and optical core diameter. The ring delta is between -0.5 to -0.3%.

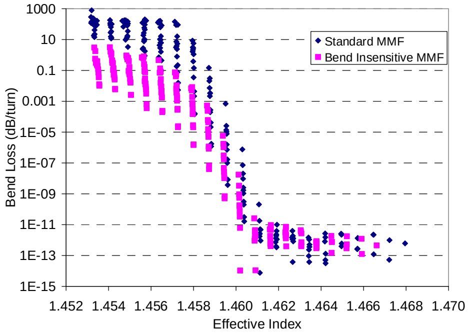

Figure 4. Comparison of bending loss for standard MMF and bend-insensitive MMF.

To model fiber bend loss, we use a full vectorial finite element method. In our modeling, a bent fiber is transformed into a straight fiber with an equivalent refractive index distribution as suggested in Ref. [5],

$$n_{eq}(x,y) = n(x,y)\exp(\frac{x}{R}) \tag{2}$$

where $R$ is the bending radius, and the fiber is bent in the x-axis. The numerical modeling is based on a finite element method solving the fully vectorial Maxwell equations used in a previous study [6]. A circular perfectly matching layer (PML) is implemented at the fiber surface to emulate the effect of an infinite domain in the finite element model. With the PML, the propagation constant $\beta$ of a mode becomes complex with the real part related to the effective index and the imaginary part related to the bending loss. The bending loss of the fiber ($\alpha_B$) in a particular mode can be calculated from the imaginary part of the propagation constant $\beta$ so that,

$$\alpha_B = \frac{20}{\ln(10)}\mathrm{Im}(\beta) \approx 8.686\,\mathrm{Im}(\beta) \tag{3}$$

A similar approach can be used to calculate tunnelling loss of leaky modes below the index of the outer cladding by setting the bend radius to infinity. Below the cladding index, the propagation constant $\beta$ of a leaky mode is complex. Its imaginary part contributes to the tunneling loss.

The tunneling losses of leaky modes allow us to determine the fiber NA and CD for bend-insensitive fiber designs. Figure 3 is a design diagram for NA and CD of Design (a), showing how ring volume, core delta (Δ) and core physical diameter (D) change the two parameters.

Figure 4 compares the bend loss of each mode of a standard 50 mm MMF and a bend-insensitive MMF. The ring volume for the bend-insensitive fiber is 101 % µm$^2$. It can be seen that the low index ring reduces bend losses of the outer mode groups while the bend losses of the inside mode groups remain the same. As a result, the bend loss of a MMF depends on launch conditions. However, even if only the inner mode groups are excited, discontinuities such as connectors, splices, and small perturbations along the fiber, will cause mode coupling, spreading the power into outer mode groups. A bend-insensitive fiber will show benefits in these practical deployment conditions. Figure 5 plots calculated overall bend loss as a function of bend radius for a standard MMF and a bend-insensitive MMF under an encircled flux launch (EFL) condition by using a 2 m length of standard MMF with a 25 mm diameter mandrel in the middle. It's clear that the bend-insensitive MMF has a bend loss more than 10 times lower compared to standard MMF in the bend radius range studied.

## 3. Experimental results

We made bend-insensitive MMF using the conventional outside vapor deposition (OVD) process. Bend losses were measured using mandrels with different radii. Figure 6 shows measured bend loss for a bend-insensitive fiber compared to a standard MMF. The bend loss of the bend-insensitive MMF is more than 10 times lower than the standard MMF, which is in excellent agreement with the modeling results shown in Figure 5. Typical fiber profile design parameters and measured optical properties at 850 nm are summarized in Table 1. In addition to the excellent bend performance, the bend-insensitive fiber is fully compatible with the MMF standard. In particular the bandwidth can meet the OM3 and OM4 requirements (as detailed in ISO/IEC 11801), suitable for high data rate applications. The bend-insensitive MMF non-standard in Figure 6 has a larger ring volume of 200 % μm$^2$. It has a bend loss less than 0.1 dB even for a bend radius as small as 3 mm. Although this fiber is not fully standard compliant, it can be used for special applications that demand very low bend loss.

Table 1. Typical profile design parameters and measured optical characteristics of bend-insensitive MMF at 850 nm

| | Core Alpha | Core Delta | Core Radius | Ring Delta | Ring Thickness | Ring Volume |
|---|---|---|---|---|---|---|
| Profile Parameters | 2.12 | 0.93 % | 24.5 μm | -0.31 % | 5.8 μm | 102 % μm$^2$ |
| | Optical Core Diameter | NA | Bandwidth | Attenuation | Bend Loss at 2x7.5 mm radius | Bend Loss at 2x15 mm radius |
| Optical Properties at 850 nm | 50.1 um | 0.208 | OM3 and OM4 Compatible | 2.184 dB/km | 0.112 dB | 0.060 dB |

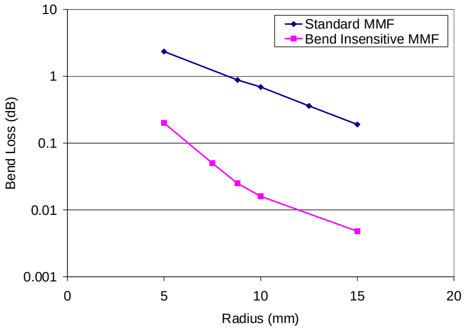

Figure 5. Calculated bending loss for standard and bend-insensitive MMF

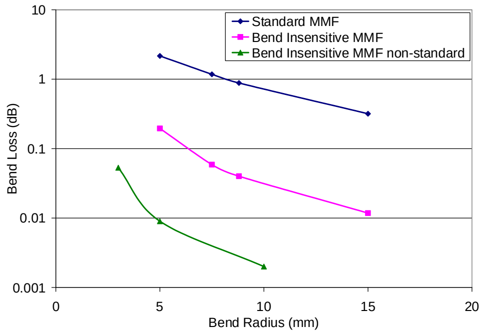

Figure 6. Comparison of bending performance of standard and bend-insensitive MMF.

## 4. Conclusions

We have proposed new designs for making bend-insensitive MMF. The new designs offer bend loss improvement by a factor of more than 10 and are fully compliant with the existing MMF standards. We have made bend-insensitive MMF using the OVD process and demonstrated excellent fiber bending performance, which validate the design concept. The excellent bending performance of new bend-insensitive MMF, plus their standards compliance, make this fiber particularly well suited to data center applications with more protection against downtime and more efficient space usage and cable and connection management.

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