Trench-Assisted Bend-Resistant OM4 Multi-Mode Fibers

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Abstract *The trench-assistance concept has proven its efficiency for bend-insensitive single-mode fibers. Here, we show how it applies to multi-mode fibers for which bend losses can also be significantly decreased while ensuring full compliance with OM3 and OM4 standards.*

Introduction

Power margins of 850nm Gigabit Ethernet (GbE) systems decrease with increasing bit-rates and distances. The penalties are basically split into power penalties induced by the modal dispersion, mainly Inter Symbol Interference, and losses that are caused by material attenuation, macro- and micro-bends and connector losses.

The power penalties due to modal dispersion have been reduced to 3dB after 300m with OM3 Multi-Mode Fibers (MMFs) in the beginning of the 00's, and to less than 1.5dB with the recently standardized OM4 MMFs, providing better tolerance to losses for such a long link.

MMFs have been used for almost a decade in environments where bends were not a major issue, mainly because of their low bending sensitivity under 10GBASE-S sources launches used in 10GbE applications[1].

In Data centers, MMFs are subject to harsher environments (massive cabling, plurality of connectors, reduced footprint). This has recently fostered investigations on bending behaviors of MMFs[1-6].

In this paper, we show how trench-assisted graded-index profiles can efficiently be used to decrease the macro-bend losses of MMFs, while ensuring full compliance with OM3 and OM4 standards, including Numerical Aperture (NA), core size, Differential Mode Delays (DMDs) and bandwidths attributes.

Reducing Macro-Bend Losses

Standard MMFs have very similar index profiles: a 50µm-diameter α-parameterized graded-index core ended by a constant cladding, with a standardized NA of 0.200±0.015. The α parameter is tuned around the value of 2 to provide the highest possible bandwidth at 850nm, which is the typical operating wavelength of 10GbE applications. At 850nm, hundreds of modes are allowed to propagate in a standard 50µm MMF, and they usually have their own characteristics, such as group velocity, chromatic dispersion, attenuation, and macro- & micro-bend losses.

For a given bend radius, macro-bend losses are proportional to the power fraction of the mode that propagates after the radiation caustic, i.e. the radius for which the effective index of the mode intersects the index of the cladding of a tilted profile representing the bent fiber[7]. As a result, the highest-order modes, that have the lowest effective indices, are the most bend sensitive and exhibit bend losses of several hundreds of dB/m at 10mm bend radius, while the lowest-order modes are extremely bend resistant with negligible macro-bend losses down to 5mm bend radius[4]. This also explains why the bending behavior of MMFs greatly depends on the launching conditions.

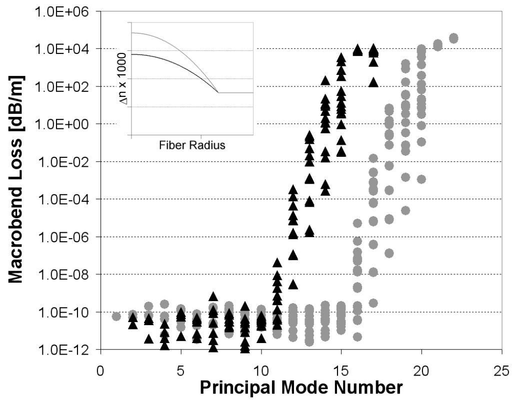

Fig. 1: Profiles and modeled bend losses[2] of guided modes at 10mm bend radius at 850nm for a 50µm MMF with NA=0.250 (grey line & circles) and for a standard 50µm MMF with NA=0.200 (black line & triangles).

One way to lower the bending sensitivity of a mode is to decrease the power fraction that propagates after the radiation caustic without changing the shape of its power profile. For graded-index cores, this means higher index differences, which results in higher numbers of modes and in higher NAs, which is critical for backward compatibility with standard MMFs (see Fig 1).

The other and much more efficient way to reduce macro-bend losses is to change the shape of the power profiles of the modes. This can be achieved by adding a depressed-index area in the cladding[8] close to the graded-index core, as shown in Fig.2. This depressed-index area, if well designed, confines the tails of the modes without modifying their intrinsic nature. As a result, bend losses can be significantly reduced (factor of ~10 compared to standard MMFs) without impacting the NA, and the compliance with OM3 and OM4 standards.

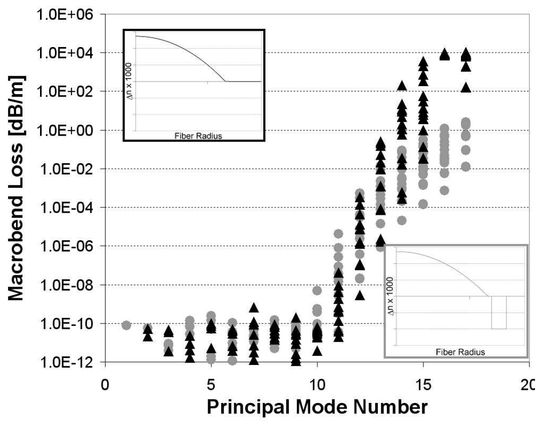

Fig. 2: Profiles and modeled bend losses[2] of guided modes at 10mm bend radius at 850nm for a trench-assisted 50µm MMF (grey line & circles) and for a standard 50µm MMF (black line & triangles) with same NA=0.200.

Trench-Assisted Fiber Design

As in the single-mode world[8], the larger the trench volume (i.e. the integral of the trench index over its cross-section) is, the smaller the macro-bend losses are. Fig.3 shows macro-bend-loss measurements of several trench-assisted MMFs with different trench volumes, made with the PCVD process. The measurements have been performed according to the latest G.651.1 recommendations that specify the proper launching conditions to be applied[9].

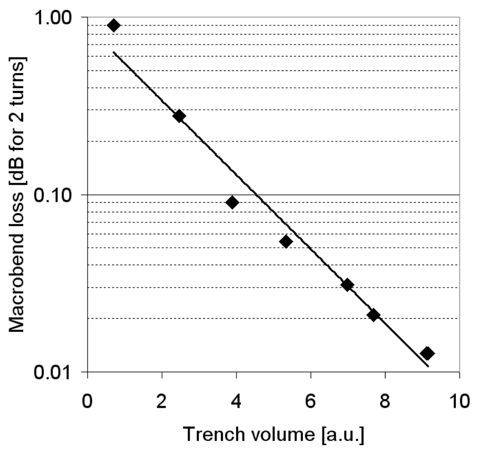

Fig. 3: Macro-bend losses for 2 full-turns at 7.5mm bend radius at 850nm as a function of the trench volume, measured according to G.651 launching conditions.

The width, index and position of the trench required to reach a desired volume have to be carefully chosen to meet the stringent OM3 and OM4 standards. Fig.4 shows, for a trench with given width and index, the impact of its position on the outer DMD, the OverFilled Bandwidth (OFL-BW) and the calculated Effective Modal Bandwidth (EMBc) at 850nm. For α close to the optimum, calculations show that the outer DMD is the most impacted by the presence of the trench. If the trench is too close to (resp. too far from) the core, the DMD plot exhibits outer pre- (resp. post-) pulses that degrade the outer DMD[10], as shown in Fig.5. An accurate control of the trench position is thus required to fulfill the OM4 DMD masks recommendations, which is easily achievable with the PCVD process.

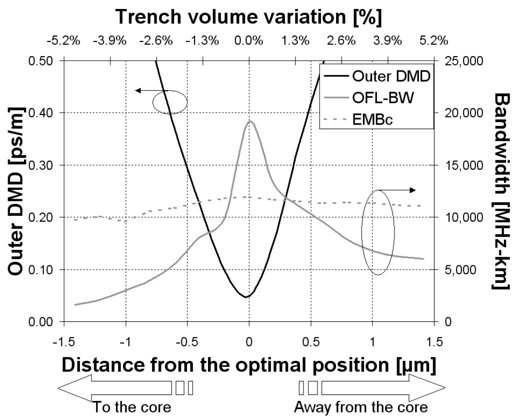

Fig. 4: Modeled outer DMD, OFL-BW and EMBc at 850nm as a function of the trench position and of the trench volume variation.

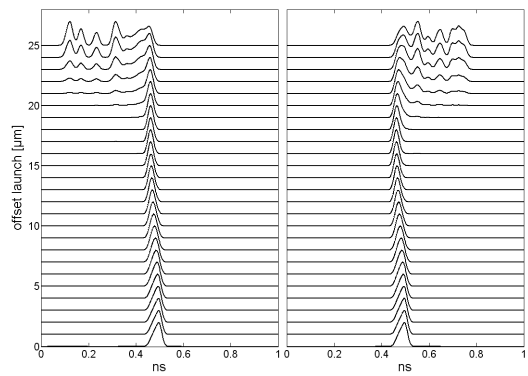

Fig. 5: Modeled DMD plots at 850nm when the trench is too close to the core (left) and too far from the core (right).

Because the outer highest-order modes are mainly responsible for the quality of the OFL-BW at 850nm, it is also maximized when the outer DMD is optimal. Note that the requirement of 3,500MHz-km for this OFL-BW is less stringent than that of the outer DMD (<0.30ps/m)[10].

The EMBc exceeds the OM4 recommendation of 4,160MHz-km whatever the position of the trench. This is because offset launches greater than 22µm count for less than 3% in its computation. DMD recommendations are thus much more stringent than that of EMBc.

As a final comment, it should be noted that within the tolerance of the trench position given by these DMD constraints, the trench volume does not significantly change (as illustrated in Fig.4) and as a result the macro-bending performances are not impacted.

Experimental Results

Based on these considerations, we have designed and fabricated trench-assisted graded-index 50µm MMFs. For this type of profile, the PCVD process demonstrated its high efficiency. Fig.6 shows the macro-bend losses of such a MMF with NA=0.205 compared to those of standard graded-index 50µm MMFs[11]. The macro-bend losses are 10 times lower with equivalent NAs for bend radii down to 5mm and for 8-quarter turns.

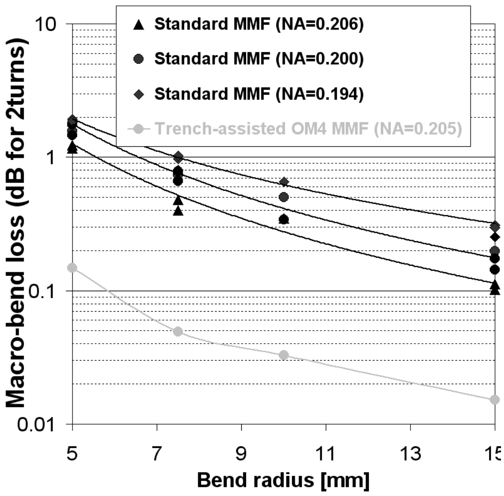

Fig. 6: Macro-bend losses of trench-assisted 50µm MMF at 850nm (gray circles) compared to standard 50µm MMFs (black circles, triangles & diamonds), measured according to G.651.1 launching conditions.

The OFL-BWs at 850nm & 1300nm are well above 3,500MHz-km and 500MHz-km respectively. In addition, high-resolution DMD measurements show that OM4 recommendations are perfectly fulfilled. Performances of such a trench-assisted bend-resistant 50µm OM4 MMF are summarized in Table 1.

As expected, the bandwidths of these MMFs are not impacted by the bends contrary to what is observed in standard MMFs for which the critical highest-order modes disappear[1].

Tab. 1: Main characteristics of a single-trench-assisted bend resistant 50µm OM4 MMF

DMD Inner	0.032	ps/m
DMD Outer	0.149	ps/m
DMD Sliding	0.035	ps/m
OFL-BW 850nm	6300	MHz-km
OFL-BW 1300nm	620	MHz-km
EMBc	>10,000	MHz-km
Core size	50.4	µm
Numerical Aperture	0.205	-

Conclusion

We have demonstrated how trench-assisted graded-index profiles can efficiently be used to design bend-resistant MMFs. Such profiles allow to reach macro-bend losses that are one order of magnitude lower than those of graded-index profiles of standard MMFs, while ensuring full compliance with OM3 and OM4 Standards.

This trench-assistance concept appears as a simple and robust solution that can be made with standard PCVD and drawing processes.

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