55-Spatial-Mode Fiber for Space Division Multiplexing

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Abstract: We report the design and the fabrication of a trench-assisted graded-index-core fiber that supports 55 spatial modes. The fiber is optimized to ensure low macro-bend losses for all the modes, while minimizing the differential-mode-group delays. ©2023 The Authors.

1. Introduction

Multimode Fibers (MMFs) for Space Division Multiplexing (SDM) can be designed to guide a large number of modes (>100), while keeping a standard cladding diameter of 125µm [1]. In contrast, multi-core fibers require enlarged cladding diameters while supporting only few 10s of cores [2]. MMFs with 125µm-cladding diameters not only offer higher spatial density than larger-diameter fibers but also longer-term mechanical reliability [3] and full compatibility with standard connectivity solutions and cabling technology.

Until recently, the largest number of modes reported in SDM transmissions was 45 [4], using a trench-assisted 50µm-diameter graded-index-core MMF [5]. That fiber guided 55 spatial modes (divided into 10 Mode Groups (MGs)), but only 45 spatial modes (9 MGs) could be used because the 10th MG had high macro-bend losses and, to a lesser extent, because its Differential-Mode-Group Delay (DMGD) was higher than those of the lower-order MGs.

In this paper, we report the design and the fabrication of a new trench-assisted 50µm-diameter graded-index-core fiber that is optimized to ensure low macro-bend losses for its 10 MGs, while minimizing the DMGDs for efficient SDM transmission. This fiber was recently used in a 55-spatial-mode transmission demonstration, yielding a record 125µm-cladding capacity of 1.53Pbps and a record spectral efficiency of 332bps/Hz using only C-band channels [6].

2. Design

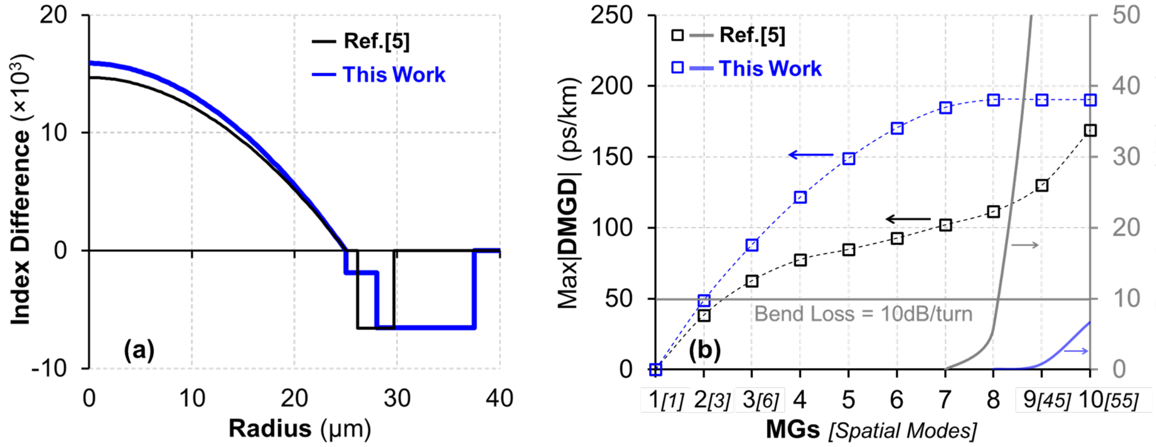

Fig.1: Theoretical targets of index profiles of the 55-spatial-mode fiber [This Work] and of Ref. [5] (a); calculated Max|DMGD| (open squares) and macro-bend losses at 10mm bend radius (solid lines) at 1550nm as a function of the MGs (b). Dashed lines are guides for the eye.

To improve the performance compared to Ref.[5], while keeping a core diameter of 50µm, we made 3 changes in the index profile (see Fig.1(a)): 1st, we increased the core index by 1.2×10^{-3}, which helps to reduce the macro-bend losses; 2nd, we depressed the inner cladding (between the core and the trench) to -1.9×10^{-3} to better confine the 10th MG, which also helps to contain its DMGD [7]; and 3rd, we enlarged the trench to increase its volume and thus reduce the macro-bend losses [8]. The calculated maximum DMGD between all MGs (Max|DMGD|) and the macro-bend losses of the MGs are shown in Fig.1(b) in comparison to those of Ref.[5]. For all DMGDs calculations, we took into account the sensitivity to process variability by simulating Gaussian distributions of index profiles with mean values corresponding to the optimized designs and with standard deviations that match the multimode process tolerances. The resulting mean values of the DMGDs of these profiles are representative of actual manufacturing [1].

The macro-bend losses of the new 55-spatial-mode fiber are drastically reduced compared to those of Ref.[5]. They are below 10dB/turn at 10mm bend radius at 1550nm for all MGs (this upper limit of 10dB/turn is taken as a reference because it corresponds to the maximum value experienced by the fundamental mode of the most deployed fiber worldwide, i.e. the G.652.D step-index single-mode fiber). The calculated Max|DMGD| is slightly higher than that of Ref.[5] (190 vs. 170ps/km at 1550nm) because of the slightly higher core index [9], but this is still acceptable. What is noticeable, however, is that Max|DMGD| reaches a plateau for MGs ≥7 when that of Ref.[5] continues to grow at a faster rate. This is because the highest-order MGs are less confined in the graded-index core of Ref.[5] compared to the new 55-spatial-mode fiber and, as a result, have larger fractions of their fields in the cladding where the lower index increases the speed of propagation and thus increases the DMGDs [7].

3. Fabrication

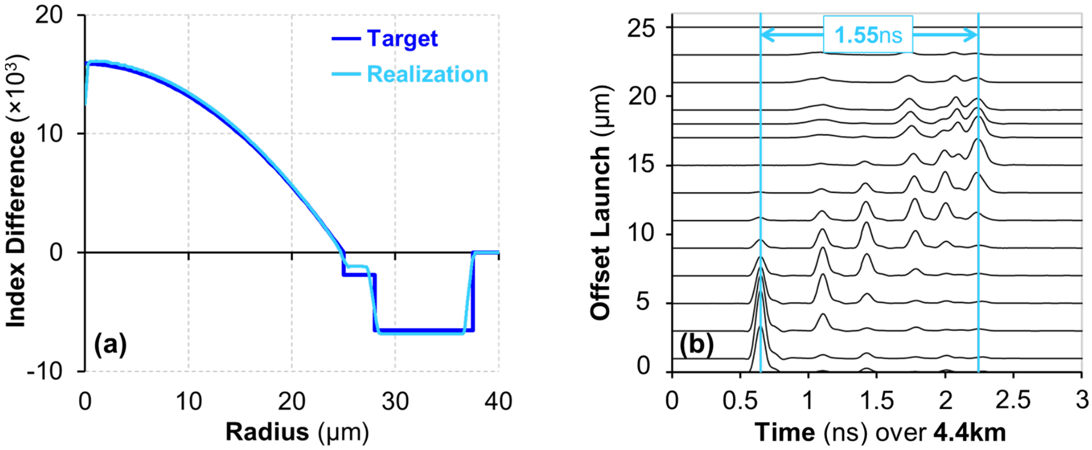

Fig.2: Experimental realization and theoretical target of index profiles of the 55-spatial-mode fiber (a); measured DMGD plot at 1550nm (b).

We fabricated the new 55-spatial-mode fiber with 125µm cladding and 245µm coating diameters using standard multimode production processes. The experimental index profile, measured on preform and set to the scale of the fiber, is close to the target (see Fig.2(a)), except for the Alpha parameter that governs the shape of the graded-index core, as will be explained in the following paragraph. We checked the macro-bend losses according to ITU-T recommendation G.651.1 for MMFs. For ≥2 turns at 10mm bend radius, the losses of the 55-spatial-mode fiber in the C-band were ~17× smaller than those of Ref.[5], confirming the expected macro-bend-loss reduction. DMGDs of several samples were then measured at 1550nm with a standard DMGD setup with input pulse duration of 50ps. The DMGD plot of one sample of 4.4km is shown in Fig.2(b), where the different peaks correspond to different MGs. The results are shown in Fig.3, and a Max|DMGD| of ~350ps/km is obtained for the 10 MGs, in agreement with the impulse response measurements of Ref.[6].

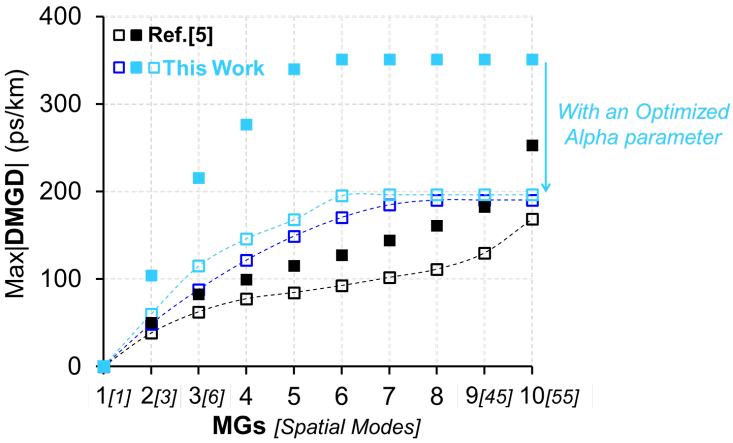

Fig.3: Measured (solid squares) and calculated (open squares) Max|DMGD| at 1550nm as a function of the MGs for the 55-spatial-mode fiber [This Work] and for Ref. [5]. Dashed lines are guides for the eye.

The shape of the Max|DMGD| curve (light blue solid squares in Fig.3), including the plateau for MGs ≥7, is in agreement with our calculations (dark blue open squares) for the 55-spatial-mode fiber. This confirms that the highest-order MGs are better confined than in Ref.[5] (solid black squares) for which the Max|DMGD| significantly increases from ~160 (for 8 MGs) and ~180 (for 9 MGs) to ~250ps/km (for 10 MGs). The DMGDs measurements of the 55-spatial-mode fiber, however, are higher than our calculations. The main reason for this discrepancy is the Alpha parameter that was not optimized in our realization (2.00 vs. optimized value of 1.98). Based on the measured index profile, we calculated that with this optimized value, the Max|DMGD| could be reduced to ~200ps/km (light blue open squares), more closely matching our calculations and suggesting future realizations could reach this value.

We then measured the attenuations of the 10 MGs by the cutback method using a 55-spatial-mode multiplexer [6] at the input side and a free-space power meter at the output side. The results at 1550nm are shown in Fig.4(a). The attenuations are between 0.19 and 0.22dB/km for the 1st eight MGs, and slightly increasing to 0.24dB/km for the 9th MG and significantly increasing to 0.36dB/km for the 10th MG. This steep increase is a sign of micro-bend induced losses. We thus measured these micro-bend losses in the C-band, using the fixed diameter drum Method B of IEC-62221 under multimode launching conditions for the 55-spatial-mode fiber and Ref.[5], and under single-mode launching conditions for a standard G.652.D step-index single-mode fiber, again taken as the reference, (see Fig.4(b)). As expected, the 55-spatial-mode fiber has smaller micro-bend losses (~2.4dB/km) than those of Ref.[5] (~4.3dB/km) because of the improved index profile, but notably higher than those of the reference (~0.5dB/km). These micro-bend losses can be reduced by increasing the effective index difference between this 10th MG and the radiation/leaky modes [10]. This is done by simultaneously increasing the core index and decreasing the core radius, while maintaining a constant normalized frequency <23 to ensure that only 10 MGs are guided. However, we note that this also impacts the DMGDs and the overall attenuation [11]. These aspects need specific investigations that are outside the scope of this paper. Finally, the effective area of the 1st MG was ~170µm² at 1550nm.

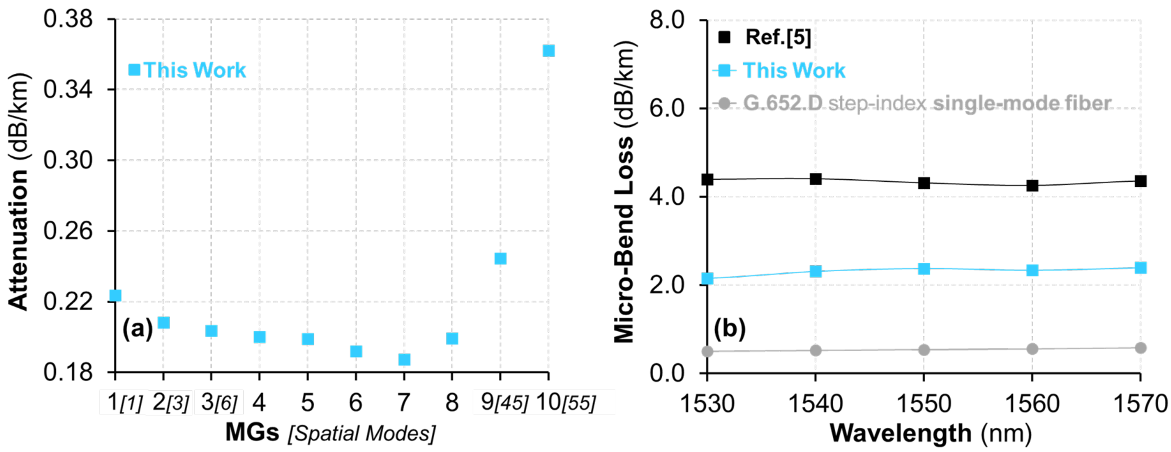

Fig.4: Measured attenuations at 1550nm as a function of the MGs for the 55-spatial-mode fiber [This Work] (a); measured micro-bend losses as function of wavelength for the 55-spatial-mode fiber [This Work], Ref.[5] and a standard G.652.D step-index single-mode fiber (reference) (b).

4. Conclusion

We designed and fabricated a trench-assisted 50µm-diameter graded-index-core fiber with low macro-bend losses for its 55 spatial modes. DMGDs ≤350ps/km at 1550nm were obtained with potential to reduce to ~200ps/km by adjusting the Alpha parameter. The attenuation was low (≤0.24dB/km at 1550nm) with the exception of the 10th MG (0.36dB/km at 1550nm) due to micro-bend induced losses. It is believed that this micro-bending sensitivity may be reduced by redesigning the graded-index core.

This fiber was successfully used to transmit 1.53Pbps with 332bps/Hz spectral efficiency over 25.9km, record achievements in any 125µm-cladding diameter fiber and achieved using only C-band channels.

5. References

[1] P. Sillard, “Few-Mode Fibers for Space Division Multiplexing,” OFC’16, paper Th1J.1.
[2] Y. Sasaki *et al.*, “Single-mode 37-core fiber with a cladding diameter of 248 µm,” OFC’17, paper Th1H.2.
[3] S. Matsuo *et al.*, “Large-effective-area ten-core fiber with cladding diameter of about 200µm,” Opt. Lett. **36**, 4626–4628 (2011).
[4] R. Ryf *et al.*, “High-spectral-efficiency mode-multiplexed transmission over graded-index multimode fiber”, ECOC’18, paper Th3B.1.
[5] P. Sillard *et al.*, “50µm Multimode Fbers for Mode Division Multiplexing,” J. Light. Technol. **34**, 1672–1677 (2016).
[6] G. Rademacher *et al.*, “1.53 Peta-bit/s C-Band Transmission in a 55-Mode Fiber,” ECOC’22, paper Th3B.2.
[7] R. Olshansky, “Effect of the cladding on pulse broadening in graded-index optical waveguides,” Appl. Opt. **16**, 2171–2174 (1977).
[8] D. Molin *et al.*, “Trench-Assisted Bend-Resistant OM4 Multi-Mode Fibers,” ECOC’10, paper P1.12.
[9] D. Gloge and E. A. J. Marcatili, “Multimode theory of graded-core fibers,” Bell Syst. Tech. J. **52**, 1563–1578 (1973).
[10] R. Olshansky, “Mode coupling effects in graded-index optical fibers,” Appl. Opt. **14**, 935–945 (1975).
[11] P. Sillard *et al.*, “Micro-Bend-Resistant Low-Differential-Mode-Group-Delay Few-Mode Fibers,” J. Light. Technol. **35**, 734–740 (2017).