Few-Mode Fibers for Mode-Division-Multiplexed Systems

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(Invited Paper)

***Abstract*—We describe the design trade-offs that are at stake when optimizing few-mode fibers (FMFs) that support a high number (≥ 6) of LP modes. We particularly detail the design of 6-LP-mode fibers that allow to multiply the capacity by a tenfold factor (two modes being spatially non-degenerate and four modes being two times spatially degenerate). For low-differential-mode-group-delay (low-DMGD) FMFs adapted to strongly-coupled mode-division-multiplexed systems, trench-assisted graded-index-core profiles can be optimized to have Max|DMGD| <10 ps/km and undesired leaky LP modes appropriately cut off, while all guided LP modes show good robustness (Bend Losses <10 dB/turn at 10 mm bend radius). Such low-DMGD FMFs being sensitive to process variability, we show how fiber concatenations can efficiently compensate for this issue and that values <25 ps/km can realistically be reached. For weakly-coupled FMFs adapted to weakly-coupled mode-division-multiplexed systems, step-index-core profiles can be optimized to have large effective index differences, $\Delta n_{\rm eff}$, between the LP modes (Min$|\Delta n_{\rm eff}|$ >1.0 × 10^{-3}) to limit mode coupling and $A_{\rm eff}$ >∼100 μm^2 to limit intra-mode non-linearity with good mode robustness. For such weakly-coupled FMFs, sensitivity to process variability is small and main characteristics do not significantly change when variations are within the manufacturing tolerances. We also briefly discuss experimental validations.**

***Index Terms*—Optical fiber communication, optical fibers.**

I. Introduction

Mode-division-multiplexed systems using few-mode fibers (FMFs) [1] have recently received considerable attention because of their potential to overcome the capacity limits of single-mode systems.

A first strongly-coupled approach [2]–[5] consists of minimizing the differential mode group delays (DMGDs) so that all modes can be simultaneously detected using complex 2 N × 2 N (2 polarizations × N spatial modes (including LP modes degeneracies)) multiple-input multiple-output techniques, regardless mode-coupling phenomena. This requires a careful design of the FMF [6]–[10] in order to reduce the DMGDs that is the limiting factor to bridge long distances.

A second weakly-coupled approach [11]–[14] consists of minimizing mode coupling so that each LP mode can be separately detected using simple 2 × 2 (nondegenerate LP modes) or 4 × 4 (two-time degenerate LP modes) multiple-input multiple-output techniques, regardless the number of LP modes. Here, a careful design of FMF is also required [15]–[17] in order to reduce mode coupling that will ultimately limit the reach of the transmission.

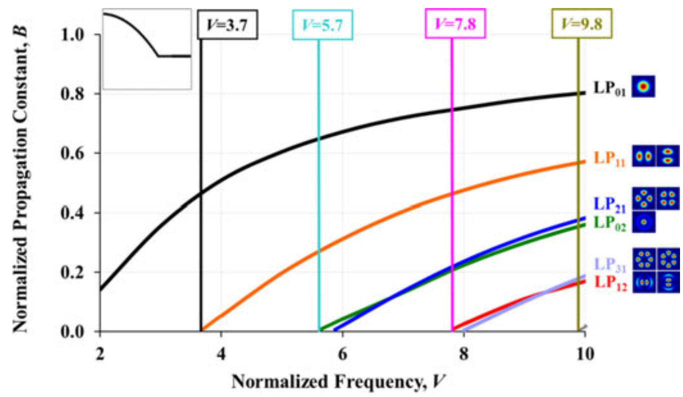

Fig. 1. Normalized propagation constant, B, versus normalized frequency, V, for graded-index-core profiles with $Alpha$ = 2.00 (inset).

Since the first FMFs demonstrations of early 2011, impressive progresses have been made [18], but increasing the number of LP modes that can actually be used is still a challenging issue. So far, only 4-LP-mode fibers with low DMGDs [5], [10] and with low mode coupling [15] have been reported.

In this paper, we describe the design trade-offs that are at stake when optimizing low-DMGD FMFs and weakly-coupled FMFs that support a high number (≥6) of LP modes. These fibers allow to multiply the capacity of mode-division-multiplexed systems by more than a tenfold factor (≥2 modes being spatially non-degenerate and ≥4 modes being two times spatially degenerate) compared to single-mode systems. We particularly detail the design of 6-LP-mode fibers that show good mode robustness (*Bend Losses* <10 dB/turn at 10 mm bend radius) with low DMGDs on the one hand and with low mode coupling on the other hand. And we briefly discuss experimental validations.

II. Low-DMGD FMFs

A. Design Strategy

Graded-index-core profiles are currently used to design high-bandwidth 50 μm-diameter-core multi-mode fibers. These 19-LP-mode-group fibers can have low DMGDs (<50 ps/km at 850 nm for best OM4 fibers) but it is at the expense of high bend losses for the highest-order LP mode groups [19].

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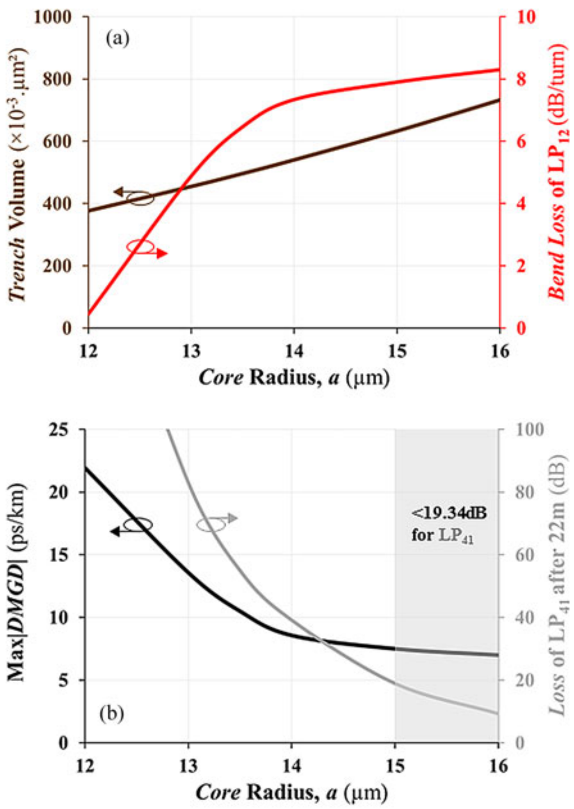

Fig. 2. Trench-assisted graded-index-core 6-LP-mode fibers with $V = 9.65$: trench volume and *Bend Losses* of the most bend sensitive LP_{12} mode at 10 mm bend radius (a), and Max|DMGD| and *Losses* of the least leaky LP_{41} mode after 22 m with two 40 mm-radius loops (b) as a function of the core radius, a.

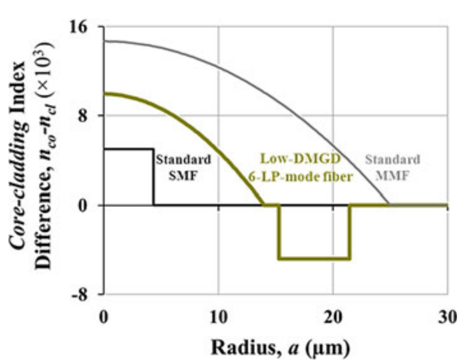

Fig. 3. Index profile of the optimized low-DMGD 6-LP-mode fiber. The index profiles of standard single-mode and 50 μm-diameter-core multi-mode fibers are added for sake of comparison.

Graded-index-core profiles are nevertheless well adapted to low-DMGD FMFs [7]–[10], [18], [20]. Fig. 1 shows, for this profile type, the dependence of the normalized propagation constant $B = (n_{\text{eff}}^2 - n_{cl}^2)/(n_{co}^2 - n_{cl}^2)$ on the normalized frequency $V = 2\pi a/\lambda\sqrt{n_{co}^2 - n_{cl}^2}$, where n_{eff} is the effective index of the LP mode, n_{co} and n_{cl} are the indexes of the core and of the cladding, respectively, a is the core radius, and λ is the wavelength. For any p-LP-mode fiber, one simply chooses V to be close to the highest possible value that allows for the first p LP modes to propagate while cutting off the next higher-order LP modes. This way, the p LP modes have B close to their highest possible values and are thus less bend sensitive [15].

Once V is set, one has then to optimize the core radius, a, that will give this value (the core-cladding index difference, $(n_{co}-$ $n_{cl})$, being subsequently derived from the V formula) and the *Alpha* parameter that governs the shape of the graded-index core and that may slightly differ from 2.00 in order to minimize the DMGDs. This optimization, however, becomes more and more difficult when the number of LP modes increases and when one wants to ensure low bend losses ($<$10 dB/turn at 10 mm radius). We have found that DMGDs become $>$100 ps/km as soon as the number of LP modes is $\geq$4 [18].

Adding a trench in the cladding reduces the bending sensitivity and thereby allows to overcome this limitation. The design strategy thus slightly changes. For each core radius, first, one has to adjust the trench volume to maintain *Bend Losses* $<$10 dB/turn at 10 mm bend radius (the trench volume is the integral of the trench-cladding index difference over its cross-section and it is directly linked to bend losses [19]) and, second, one has to optimize the *Alpha* parameter. Finally, to best choose the core radius, one has to find the optimum trade-off between DMGDs, that have to be as small as possible (Max|DMGD| $<$50 ps/km, preferably $<$25 ps/km, between any 2 LP modes), and the losses of the undesired leaky LP modes, present because of the trench [21], that have to be kept $>$19.34 dB on a 22 m-long sample with two 40 mm-radius loops (the rest with a bend radius $\geq$140 mm) to ensure effective cut-off, as described in the IEC 60793-1-44 document. This is illustrated below for 6-LP-mode fibers but this can be applied to any p-LP-mode fiber ($p \geq 6$).

B. Optimizing 6-LP-Mode Fiber

For 6-LP-mode fibers, V is set at 9.65. Results are summarized in Fig. 2. When the core radius increases at constant V the core-cladding index difference decreases. As a result, the LP modes become less guided and their bend losses increase significantly. To compensate for this degradation, the trench volume is increased [19], as shown in Fig. 2(a). This is very effective. When the trench volume reaches $\sim$0.50 μm^2 for a core radius of 13.5 μm, the bend losses of the most bend-sensitive LP_{12} mode show a clear curvature and can be kept $<$10 dB/turn at 10 mm bend radius.

Increasing the trench volume, however, comes at a price: the undesired leaky LP modes become more robust, i.e. their losses become smaller. One has thus to find the optimum trade-off between Max|DMGD| that decreases when the core radius increases and the losses of the least leaky LP_{41} mode that increases when the core radius decreases. From 12 to $\sim$14 μm, Max|DMGD| steeply decreases from 22 ps/km [18] to 8.6 ps/km; then, it decreases at a much more moderate rate and reaches 7.5 ps/km at 15 μm. Above this core radius, the LP_{41} mode have losses that become $<$19.34 dB after 22 m with two 40 mm-radius loops, and can no longer be considered as cut off (see Fig. 2(b)).

An optimized profile is thus obtained for a core radius $a =$ 14 μm (yielding a core-cladding index difference $(n_{co} - n_{cl}) =$ 10×10^{-3} for $V = 9.65$ at 1550 nm), a trench volume of 0.54 μm^2 and an *Alpha* $= 1.95$ (see Fig. 3). The main characteristics of this optimized 6-LP-mode fiber are given in Table I at 1550 nm. We note that the effective areas, A_{eff}, of all the guided

TABLE I
CHARACTERISTICS OF THE OPTIMIZED TRENCH-ASSISTED GRADED-INDEX-CORE LOW-DMGD 6-LP-MODE FIBER AT 1550 nm

		LP_{01}	LP_{11}	LP_{21}	LP_{02}	LP_{31}	LP_{12}
n_{eff} - n_{cl}	($\times 10^{-3}$)	7.71	5.62	3.54	3.55	1.46	1.48
Bend Loss	(dB/turn)	<<1	<<1	<<1	<<1	<10	<10
DMGD vs. LP_{01}	(ps/km)	/	-7.6	-6.5	-7.8	0.8	-7.5
Max|*DMGD*|	(ps/km)	8.6 (LP_{31} vs. LP_{02})					
A_{eff}	(μm^2)	126	169	227	256	273	274
Dispersion	(ps/nm/km)	20.1	20.4	20.6	20.6	20.9	20.9

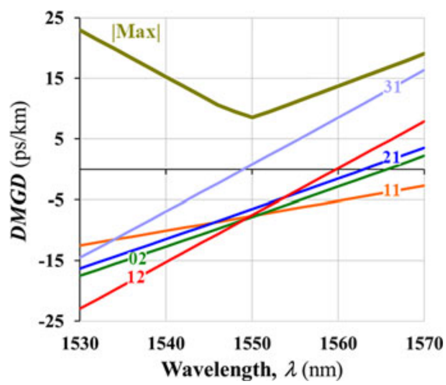

Fig. 4. Optimized trench-assisted graded-index-core 6-LP-mode fiber: DMGDs of all guided LP modes and resulting Max|DMGD| as a function of wavelength, λ.

LP modes are well above 100 μm^2 (between 126 and 274 μm^2), which ensures small intra-mode non-linearity. LP modes with A_{eff} >160 μm^2 might be sensitive to micro-bends [22]. However, current solutions used to reduce this sensitivity (optimization of glass and dual-coated diameters, use of a softer primary coating) can readily be used for such FMFs. Finally, chromatic dispersion, that is between 20 and 21 ps/nm/km for all modes, will be compensated for at reception by digital signal processing [23].

The DMGDs of the guided LP modes, and the resulting Max|DMGD|, are plotted as a function of wavelength in Fig. 4. Max|DMGD| remains $\leq$23 ps/km from 1530 to 1570 nm with a |slope| $\leq$0.77 ps/km/nm.

Such low-DMGD FMFs, however, are known to be sensitive to profile variations that can occur during the manufacturing process [8], [18]. As expected, *Alpha* is by far the most critical parameter. Variations of $\pm$1% from its optimum value, i.e., $\pm$0.02 in absolute value, which is within the manufacturing tolerance, lead to Max|DMGD| of $\sim$100 ps/km. Variations of the other core parameters have less impacts: $\pm$4%, i.e., $\pm$0.5 μm, and $\pm$5%, i.e., $\pm 0.5 \times 10^{-3}$, for core radius and for core-cladding index difference, respectively, lead to Max|DMGD| of $\sim$50 ps/km.

One way to compensate for these variations is to concatenate fibers. This technique, proposed in the beginning of the 80's for standard multi-mode fibers [24], works very well here [6]–[10], [18]. Low-DMGD FMFs with parameters lower and higher than their optimum values can have LP modes with DMGDs with opposite signs, which makes possible the realization of DMGD-compensated links. A 4-LP-mode link with Max|DMGD| as low as 6 ps/km has recently been demonstrated [5]. Here, we have concatenated 6-LP-mode fibers with non-optimum core parameters (within the manufacturing tolerances) and we have found that links always had Max|DMGD| <25 ps/km. The worst possible concatenation of these fibers corresponds to an *Alpha* and a core radius being +1% above and −4% below their optimum values, respectively. Adjusting the lengths of these two fibers with a ratio $L_{\text{Alpha}+1\%}/L_{\text{Radius}-4\%}$ of 0.58 yields a DMG-compensated 6-LP-mode link with Max|DMGD| of 23.6 ps/km (see Fig. 5).

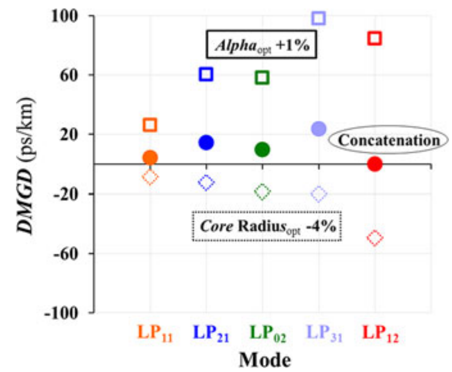

Fig. 5. Optimized trench-assisted graded-index-core 6-LP-mode fiber: DMGDs for *Alpha* (open squares) being +1% above its optimum value and for *Core* Radius (open diamonds) being −4% below its optimum value, and for their resulting concatenation with a length ratio, $L_{\text{Alpha}+1\%}/L_{\text{Radius}-4\%}$, of 0.58 (solid circles).

We have fabricated a first prototype of this optimized 6-LP-mode fiber using our standard manufacturing processes [25] and we have obtained Max|DMGD| of 85 ps/km at 1550 nm. This is one order of magnitude higher than the theoretical value but, given the fiber sensitivity, this is still a low DMGD value for a first trial. The attenuation of the fundamental LP_{01} mode was measured at 0.207 dB/km at 1550 nm. Calculating the different mode power distributions and attenuation contributions (guiding, scattering, and absorption phenomena), we have found the attenuation differences between all guided LP modes to be <0.01 dB/km, which notably limits mode-dependent-loss impairments. New realizations should allow to reduce Max|DMGD| and to make DMGD-compensated links.

III. WEAKLY-COUPLED FMFS

A. Design Strategy

Step-index-core profiles have proven to be very well adapted to weakly-coupled FMFs [16]. It is well known that they present large DMGDs (>1 ns/km), but this is not an issue for this approach; on the contrary, large DMGDs can be advantageous to limit inter-mode non-linearity [26]. In addition, this profile type offers simplicity in terms of design and manufacturing.

The same design strategy as for the low-DMGD FMFs can be applied for the choice of V (see Fig. 6). Once V is set, one has only to optimize the core radius. First, bend losses have to be kept below 10 dB/turn at 10 mm bend radius. Then, one has to find the optimum trade-off between the effective index differences between the LP modes, that have to be as high as

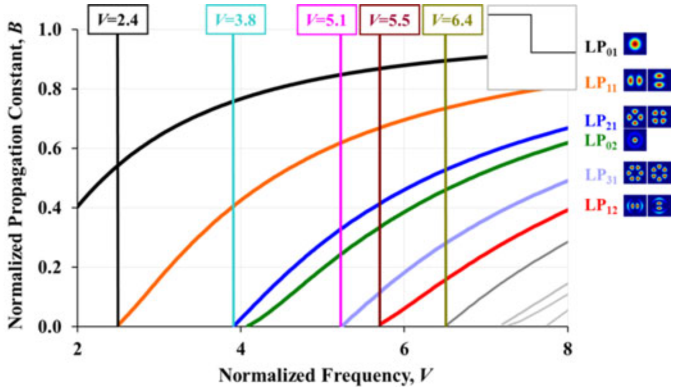

Fig. 6. Normalized propagation constant, B, versus normalized frequency, V, for step-index-core profiles (inset).

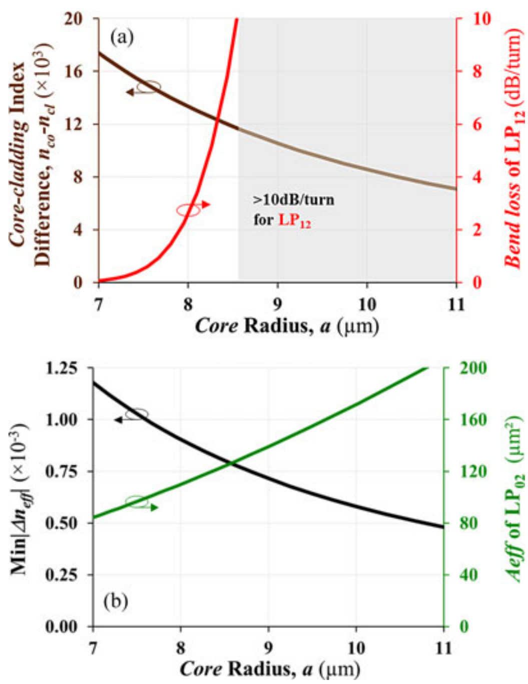

Fig. 7. Step-index-core 6-LP-mode fibers with $V = 6.4$: core-cladding index difference & *Bend Losses* of the most bend sensitive LP_{12} mode at 10 mm bend radius (a), and Min$|\Delta n_{\mathrm{eff}}|$ and A_{eff} of the most confined LP_{02} mode (b) as a function of the core radius a.

possible (Min$|\Delta n_{\mathrm{eff}}|$ $>0.8 \times 10^{-3}$, preferably $>1.0 \times 10^{-3}$, between any 2 LP modes) to limit mode coupling [27], [28], and A_{eff}, that have to be as large as possible ($>80\ \mu\mathrm{m}^2$, preferably $>100\ \mu\mathrm{m}^2$) to limit intra-mode non-linearity. This is illustrated below for 6-LP-mode fibers but, again, this can be applied to any p-LP-mode fiber ($p \geq 6$).

B. Optimizing 6-LP-Mode Fiber

For 6-LP-mode fibers, V is thus set at 6.4. Again, increasing the core radius at constant V decreases the core-cladding index difference and increases the bend losses of the LP modes. The core radius has to be kept $<8.6\ \mu$m so that the bend losses of the most bend-sensitive LP_{12} mode remain <10 dB/turn at 10 mm

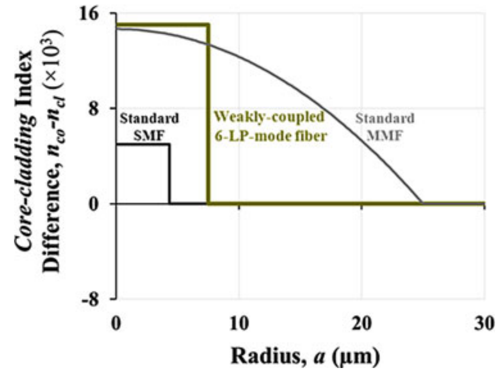

Fig. 8. Index profile of the optimized weakly-coupled 6-LP-mode fiber. The index profiles of standard single-mode and 50 μm-diameter-core multi-mode fibers are added for sake of comparison.

TABLE II
CHARACTERISTICS OF THE OPTIMIZED STEP-INDEX-CORE WEAKLY-COUPLED 6-LP-MODE FIBER AT 1550 nm

		LP_{01}	LP_{11}	LP_{21}	LP_{02}	LP_{31}	LP_{12}
n_{eff} - n_{cl}	($\times 10^{-3}$)	13.48	11.12	8.01	6.99	4.28	2.43
Bend Loss	(dB/turn)	<<1	<<1	<<1	<<1	<<1	<1
Min$|\Delta n_{eff}|$	($\times 10^{-3}$)			**1.02 (LP_{21} vs. LP_{02})**			
A_{eff}	(μm²)	115	107	113	98	117	112
DMGD vs. LP_{01}	(ns/km)	/	5.56	1.45	1.35	1.89	1.59
Dispersion	(ps/nm/km)	22.4	26.9	29.9	27.1	28.2	-9.6

bend radius (see Fig. 7(a)). Then, one has to find the optimum trade-off between Min$|\Delta n_{\mathrm{eff}}|$ that increases when the core radius decreases and the A_{eff} of the most confined LP_{02} mode that increases when the core radius increases (see Fig. 7(b)).

An optimized profile is obtained for a core radius $a = 7.5\ \mu$m (yielding core-cladding index difference $(n_{co}–n_{cl}) = 15 \times 10^{-3}$ for $V = 6.4$ at 1550 nm, see Fig. 8). It is worth noting that adding a trench in the cladding does not help here because it does not change the behavior of Min$|\Delta n_{\mathrm{eff}}|$ as a function of the core radius and because Min$|\Delta n_{\mathrm{eff}}|$ is $>0.75 \times 10^{-3}$ when the bend losses of the LP_{12} mode are already <10 dB/turn. The main characteristics of the optimized step-index-core 6-LP-mode fiber are given in Table II at 1550 nm. We note that all LP modes have similar A_{eff} (between 98 and 117 μm²) due to similar confinements ensured by the step-index-core structure. Using attenuation measurements of standard single-mode and multi-mode fibers, and calculations of the different mode power distributions and attenuation contributions, we find the attenuation of the fundamental LP_{01} mode to be at 0.24 dB/km at 1550 nm, for a Germanium-doped structure, and the differences between all LP modes to be <0.01 dB/km. This, combined with similar A_{eff}, ensures similar propagation characteristics for all LP modes.

This strategy has been successfully applied to a 4-LP-mode fiber [15], whose measurements confirmed low mode coupling (Min$|\Delta n_{\mathrm{eff}}|$ of 0.8×10^{-3} led to an integrated crosstalk between all the 4 LP modes of -23 dB on 10 km) and large A_{eff} together with low bending sensitivity. This fiber was successfully used to transmit the 3 LP modes at 100 Gbps over 40 km [14]. Further experimental investigations, however, are needed to fully assess the low mode-coupling feature of 6-(or more [16]) LP-mode fibers.

Finally, it is worth noting that such weakly-coupled FMFs are much less sensitive to process variability than low-DMGD FMFs. Their main characteristics do not significantly change when variations are within the manufacturing tolerances.

IV. Conclusion

FMFs offer promising properties for mode-division-multiplexed systems but, to give their full potential, the number of their LP modes has to be increased. From a design point of view, we have shown that the complex task that consists of optimizing a high number ($\geq$6) of LP modes can be simplified when choosing the adapted type of index profile and when applying the correct design strategy.

For low-DMGD FMFs adapted to strongly-coupled mode-division-multiplexed systems, trench-assisted graded-index-core profiles appear to be the most suited type of index profile. We have shown that there is an optimum core radius for which DMGDs are minimized and undesired leaky LP modes are appropriately cut off, while all guided LP modes have low bend losses. For a 6-LP-mode fiber with $V = 9.65$ at 1550 nm, this optimum is obtained for a core radius of 14 μm that gives Max|DMGD| <10 ps/km. Such low-DMGD FMFs being sensitive to process variability, we have shown how fiber concatenations can efficiently compensate for this issue and that values <25 ps/km can realistically be reached.

For weakly-coupled FMFs adapted to weakly-coupled mode-division-multiplexed systems, step-index-core profiles are very well suited. Here, there is also an optimum core radius for which both Min$|\Delta n_{\mathrm{eff}}|$ and A_{eff} are maximized, while all LP modes have low bend losses. For a 6-LP-mode fiber with $V = 6.4$ at 1550 nm, this optimum is obtained for a core radius of 7.5 μm that gives Min$|\Delta n_{\mathrm{eff}}| > 1.0 \times 10^{-3}$ and $A_{\mathrm{eff}} > \sim 100\ \mu\mathrm{m}^2$. For such weakly-coupled FMFs, sensitivity to process variability is small and main characteristics do not significantly change when variations are within the manufacturing tolerances.

One last important point is that these FMFs can be made with standard manufacturing processes, which allows for good compatibility with standard single-mode and multi-mode fibers and for large-scale production.

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