Few-Mode Fiber for Uncoupled Mode-Division Multiplexing Transmissions

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Abstract: We report the design and fabrication of a few-mode fiber that supports 4 robust modes with low mode couplings, large differential group delays, large effective areas of similar values, and low losses.

OCIS codes: 060.2280 Fiber design and fabrication, 060.2270 Fiber characterization

1. Introduction

Space-division multiplexing is currently subject to intense researches [1-8] in order to increase the capacity of single-core, single-mode transmissions and thus avoid the foreseen “capacity crunch” [9].

Mode-division multiplexing transmissions are of particular interest because of the potential high number of modes that can be used in one fiber. One important issue in such transmissions, however, is the mode-coupling phenomenon. Multiple-input multiple-output signal processing helps to combat this deleterious effect [3,4]. Another (complementary) approach consists of designing uncoupled transmissions [5-7]. Fibers play a central role here, and new design tradeoffs have to be considered to limit mode couplings while still providing small non-linear effects.

In this paper, we report the fabrication of a Few-Mode Fiber (FMF) designed for uncoupled mode-division multiplexing transmissions. This FMF supports 4 low-loss and robust modes with large effective index differences to ensure low mode couplings. In addition, large Differential Group Delays (*DGD*s) and large effective areas (A_{eff}) ensure small inter-mode and small intra-mode non-linear effects [8]. This FMF was successfully used to demonstrate the transmission of 2 modes at 100Gbps over 40km [7].

2. Fiber Design

For our study, we have considered Step-index profiles that offer simplicity in term of design (required when studying the characteristics of more than 1 mode) and of fabrication (standard deposition and drawing processes allow for large-scale production) and that also offer good compatibility with Standard Step-index Single-Mode Fibers (S-SMFs). Fig.1 shows the well-known dependence of the normalized propagation constant, $B=\left(n_{eff,lm}^2-n_{cl}^2\right)/\left(n_{co}^2-n_{cl}^2\right)$, on the normalized frequency, $V=2\pi a/\lambda\sqrt{n_{co}^2-n_{cl}^2}$, where $n_{eff,lm}$, is the effective index of the LP_{lm} mode, n_{co} and n_{cl} are the refractive indexes of the core and of the cladding, respectively, a is the core radius, and λ is the wavelength. We have chosen V=5.1 to ensure robustness and good separation, i.e. high, different B values, for the first 4 modes (the fundamental LP_{01} mode and the higher-order LP_{11}, LP_{21} and LP_{02} modes) while cutting off the next higher-order LP_{31} and LP_{12} modes, thereby obtaining a 4-mode fiber. For a 2-mode fiber and a 6-mode fiber, V would be 3.8 and 7, respectively, to cut off the higher-order modes; and so forth.

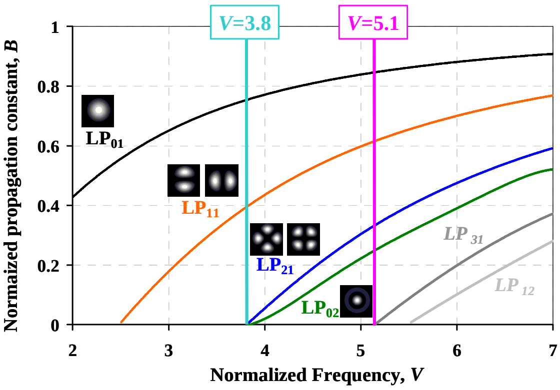

Fig.1: Normalized propagation constant, B, as a function of the normalized frequency, V, for Step-index profiles

There is a number of [a,(n_{co}-n_{cl})] pairs that give V=5.1 at 1550nm (see Fig.2 & 3) and the corresponding B values shown in Fig.1. On the one hand, one wants to have high ($n_{eff,lm}$-n_{cl}) to ensure low macro-bend losses for the 4 LP_{lm} modes, and large $|n_{eff,lm}-n_{eff,l'm'}|$ between any two LP_{lm} and $LP_{l'm'}$ modes to limit mode coupling [10]. At a constant V value, this can be achieved by increasing (n_{co}-n_{cl}), as deduced from the B formula and as shown in Fig.2. At V=5.1 at

1550nm, the LP_{02} mode, that is the most bend sensitive mode and that is the closest mode to the LP_{21} mode, has bend losses <10dB/turn at 10mm bend radius at 1550nm for $(n_{co}\text{-}n_{cl})>7.9\times10^{-3}$ and $|n_{eff,02}\text{-}n_{eff,21}|>0.5\times10^{-3}$ at 1550nm for $(n_{co}\text{-}n_{cl})>6.7\times10^{-3}$. And on the other hand, one wants to have large A_{eff} (>110µm²) to ensure small intra-mode non-linear effects and low losses. At a constant V value, this can be achieved by decreasing $(n_{co}\text{-}n_{cl})$, as typically done when designing large-A_{eff} SMFs [11] and as shown in Fig.3. At V=5.1 at 1550nm, the fundamental LP_{01} mode, that is the most confined mode, has A_{eff}>110µm² for $(n_{co}\text{-}n_{cl})<11.1\times10^{-3}$. A good tradeoff is obtained for $(n_{co}\text{-}n_{cl})=9.7\times10^{-3}$, yielding a=7.5µm for V=5.1 at 1550nm (see circle in Fig.2 & 3). Note that, for this design, A_{eff} have similar values (between 118 and 133µm²) for the 4 modes.

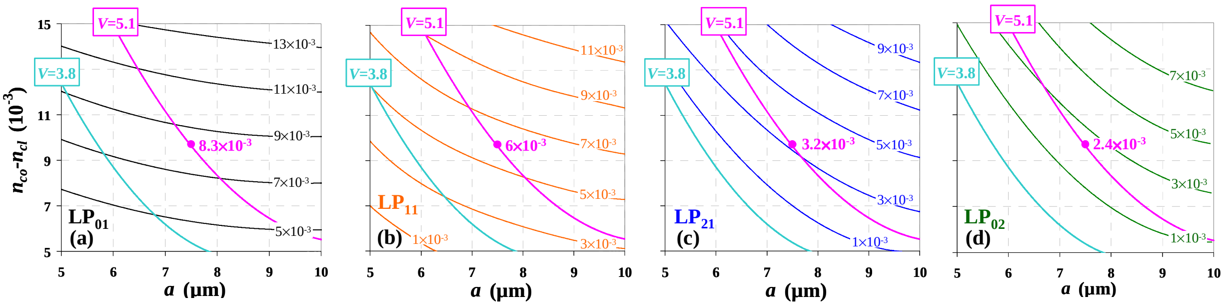

Fig.2: $(n_{eff}\text{-}n_{cl})$ at 1550nm of the LP_{01} (a), LP_{11} (b), LP_{21} (c), and LP_{02} (d) modes for different Step core radii, a, and indexes, $(n_{co}\text{-}n_{cl})$; the circle corresponds to a=7.5µm and $(n_{co}\text{-}n_{cl})=9.7\times10^{-3}$ yielding V=5.1 at 1550nm

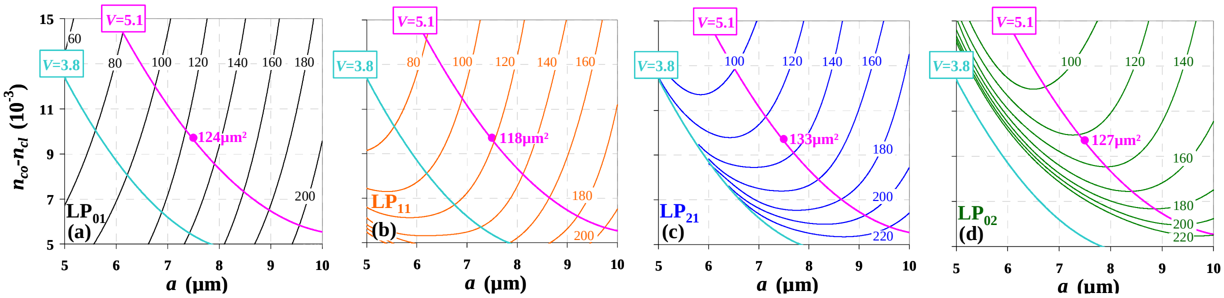

Fig.3: A_{eff} (µm²) at 1550nm of the LP_{01} (a), LP_{11} (b), LP_{21} (c), and LP_{02} (d) modes for different Step core radii, a, and indexes, $(n_{co}\text{-}n_{cl})$; the circle corresponds to a=7.5µm and $(n_{co}\text{-}n_{cl})=9.7\times10^{-3}$ yielding V=5.1 at 1550nm

There is one more property that is desirable for FMFs, to wit:

$$DGD=\left(\frac{n_{eff,lm}-n_{eff,l'm'}}{c}\right)-\frac{\lambda}{c}\left(\frac{\partial n_{eff,lm}}{\partial\lambda}-\frac{\partial n_{eff,l'm'}}{\partial\lambda}\right)>>0.1\text{ps/m}$$

between any two LP_{lm} and $LP_{l'm'}$ modes in order to ensure small inter-mode non-linear effects [8]. For our design, because the modes are well separated, the *DGD*s are large, between 1.3 and 8.5ps/m, at 1550nm.

3. Fiber Fabrication and Characterization

We have fabricated this FMF using standard manufacturing processes. Main characteristics are given in Table 1.

Table 1. Characteristics of the 4 modes of the FMF

		LP_{01}		LP_{11}		LP_{21}		LP_{02}	
		Calc.	**Meas.**	**Calc.**	**Meas.**	**Calc.**	**Meas.**	**Calc.**	**Meas.**
$(n_{eff}$ - $n_{cl})$ at 1550nm	$\times10^{-3}$	8.3	/	6.0	/	3.2	/	2.4	/
***DGD* vs. LP_{01}**	ps/m	/	/	**4.4**	**4.4**	**8.5**	**8.9**	**7.2**	**7.9**
Chromatic Dispersion	ps/nm-km	**21.9**	**21**	**24.9**	**26**	**20.9**	**19**	**7.8**	**8**
A_{eff}	µm²	**124**	**124**	**118**		**133**		**127**	
Loss	dB/km	**<0.22**	**0.218**	***0.215***		***0.21***		***0.21***	
Cable Cutoff Wavelength	nm	/	/	**2980**	**>1700**	**1950**	**>1700**	**1800**	**>1700**
Macro-Bend Loss (10mm bend radius)	dB/turn	**<0.005**	**0.002**	**<0.01**		**0.01**		**1.9**	
Polarisation Mode Dispersion	$\text{ps/km}^{0.5}$	**<0.10**	**0.04**						

The fundamental LP$_{01}$ mode has been characterized with standard measurements procedures. For the higher-order LP$_{11}$, LP$_{21}$ and LP$_{02}$ modes, the *DGD* and dispersion spectra have been measured on a 5m sample following the method described in [12] (see Fig.4). Despite some measurements inaccuracy, especially for the highest-order LP$_{02}$ mode, good agreement between calculations and measurements has been obtained at 1550nm. Note that *DGD*s measured at 1550nm with the standard multimode differential mode delay setup (see solid symbols in Fig.4(a)) are also in good agreement. Losses have been estimated based on the LP$_{01}$ measurements and the power distributions of the different higher-order modes, and were found to be <0.22dB/km at 1550nm for all the modes. No cable cutoff wavelengths could be characterized up to 1700nm for the LP$_{11}$, LP$_{21}$ or LP$_{02}$ modes, which confirmed their full guidance in the C band, while the LP$_{31}$ and LP$_{12}$ modes were effectively cut off.

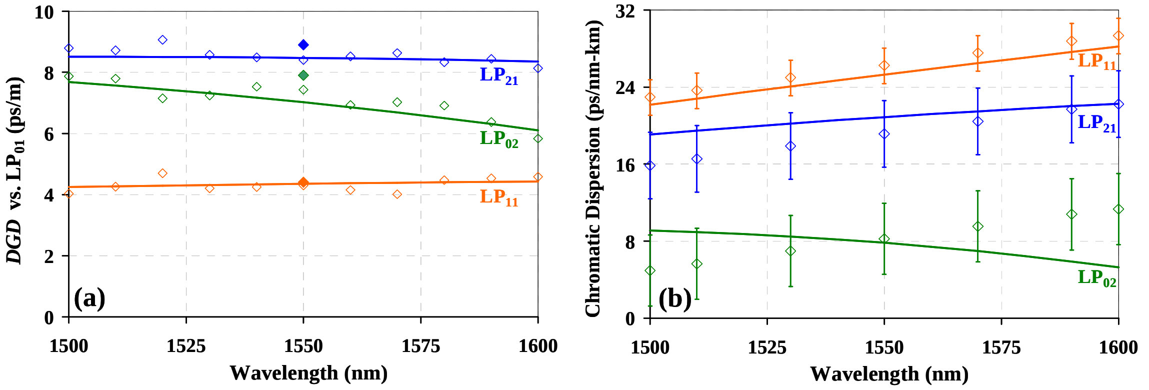

Fig.4: Experimental (symbols) and theoretical (lines) spectra of the *DGD*s versus the fundamental LP$_{01}$ mode (a) and of the chromatic dispersion (b) of the higher-order LP$_{11}$, LP$_{21}$, and LP$_{02}$ modes

Finally, we have measured multi-path interference of -38.7dB for the fundamental LP$_{01}$ mode on a 40km sample spliced to S-SMFs at both ends (~0.20dB/splice) [13]. This value confirmed the very low mode couplings in our FMF on such a length. We have also performed micro-bend-loss measurements (IEC-62221, Method B) and obtained a loss increase <0.20dB/km at 1550nm when that of a SSMF is ~1.6dB/km, which again demonstrated very low mode couplings.

4. Conclusion

We have set out the design tradeoffs of a FMF suitable for uncoupled mode-division multiplexing transmissions. Optimizing these tradeoffs, we have designed and fabricated a FMF that supports 4 robust modes with large n_{eff} differences ($\geq 0.8\times10^{-3}$) that ensure low mode coupling, large *DGD*s (between 1 and 9ps/m) and large A$_{\text{eff}}$ (between 118 and 133µm²) that ensure small inter- and intra-mode non-linear effects, and low losses (<0.22dB/km). This FMF was successfully used to demonstrate the transmission of the 2 degenerate LP$_{11}$ modes at 100Gbps over 40km.

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