A Low-CD Weakly-coupled FMF for Short-reach IM/DD MDM Transmission

Ruiting Cheng(1), Qichen He(1), Mingqing Zuo(3), Jiarui zhang(1), Chuyu Peng(4), Yuyang Gao(1), Zhangyuan Chen(1)(2), Yongqi He(1) and Juhao Li(1)(2)

(1) State Key Laboratory of Advanced Optical Communication Systems and Networks, Peking University, Beijing 100871, China, juhao_li@pku.edu.cn
(2) Peng Cheng Laboratory, Shenzhen 518055, China
(3) Department of Fundamental Network Technology, China Mobile Research Institute, Beijing 100053, China
(4) Fiberhome Fujikura Optic Technology Co., Ltd, China

Abstract *Based on an accurate model for the relationship between refractive indices and wavelengths in germanium-doped fibers, a weakly-coupled low-chromatic dispersion (CD) FMF is designed and fabricated with CD values lying between -6 and +6 ps/km/nm ranging from 1280 to 1340 nm for all 4 modes.*

Introduction

Weakly-coupled mode-division multiplexing (MDM) technique is a promising candidate for capacity enhancement of short-reach optical interconnections [1], for which the multiple-ring-core few-mode fiber (MRC-FMF) has been proved to be an effective design method to suppress distributed modal crosstalk [2]. Similar to low-chromatic-dispersion (CD) O-band transmission based on single-mode fibers (SMF), all the mode channels in a weakly-coupled FMF for short-reach applications should achieve low CD to support intensity-modulation/direct-detection (IM/DD) transmission [3,4]. However, effective design methods for such FMFs have seldom been discussed in previous studies. The MRC-FMF may provide a possible approach [5], in which multiple ring-area index perturbations are applied to the core of a step-index (SI) FMF to adjust the effective index n_{eff} distribution of all supported linearly-polarized (LP) modes. Because the CD is the 2th-order derivative of n_{eff} versus wavelength, the ring-area index perturbations could also adjust the CD values of all the LP modes. But the design method may be a great challenge because we should accurately estimate the influence of ring-area index perturbation to the CD value of each mode in an MRC-FMF. Some evaluation models have been proposed for the relationship between refractive index and wavelength for germanium-doped SiO_2-based optical fibers [6,7], but their accuracy has never been verified.

In this paper, we firstly propose a model to accurately evaluate the relationship between refractive indices and wavelengths of optical fiber by analyzing the dispersion characteristics of 3 kinds of germanium-doped SMFs with the same fabrication processing. Then, a weakly-coupled low-CD MRC-FMF supporting 4 linearly-polarized (LP) modes is designed with the perturbation method and then fabricated. The measured minimum effective index difference min|Δn_{eff}| among all modes of the fabricated FMF is larger than 1.3×10^{-3}, and the CD values of all the modes lie between -6 and +6 ps/km/nm ranging from 1280 to 1340 nm, which agree well with the design. The 2-km transmission experiment indicates that the fabricated MRC-FMF could support stable digital-signal-processing (DSP)-free IM/DD transmission for all 4 LP modes.

Evaluation Model for CD versus Wavelength

We firstly propose an accurate evaluation model for the relationship between refractive index *n(λ)* and wavelength *λ* in a typical fused silica fiber doped with germanium (SiO_2-GeO_2). According to previous studies, the *n(λ)* could be described by the Sellmeier formula in pure medium such as SiO_2 and GeO_2 [8,9]. However, for current widely-used SiO_2-GeO_2 optical fibers, it's hard to establish a universal method to model the *n(λ)* because the relationship may vary with the fabrication processing in different fiber manufacturers. To solve this problem, we firstly analyze the dispersion characteristics of three kinds of SMFs (G652, G654 and G655) with the same fabrication processing by Fiberhome Fujikura company, and then we propose a *n(λ)* model as below:

$$n_{doping}^2(R,\lambda)=(1-R)n_{SiO_2}^2(\lambda)+Rn_{GeO_2}^2(\lambda) \quad (1)$$

where *R* denotes the dopant concentration of doped GeO_2; n_{doping}, n_{SiO2} and n_{GeO2} denote the refractive indices of SiO_2-GeO_2, pure SiO_2 and GeO_2, respectively.

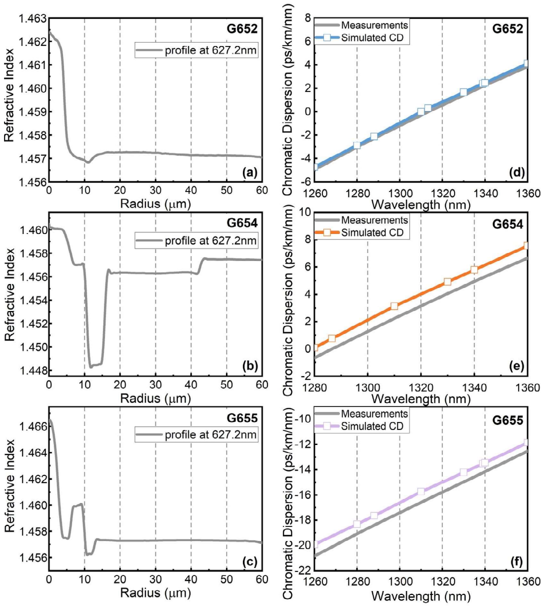

Fig. 1: Refractive index profiles of (a) G652, (b) G654 and (c) G655 fibers at 627.2 nm; measured and simulated CD of (d) G652, (e) G654 and (f) G655 fibers at O-band.

Figure. 1 (a)-(c) show the refractive index profiles of three fibers measured at 627.2 nm, while Fig. 1(d)-(f) depict the measured CD values by commercial fiber analysis system (PK-2800) and simulated CD values utilizing the proposed model. The simulations based on full-vectorial finite element method (FEM) are conducted to calculate corresponding CD of fundamental mode in the SMFs. Compared to other models in Ref. [6,7], the proposed model could more accurately evaluate the CD values. Therefore, the proposed modeling is suitable for the perturbation method to design MRC-FMF with both low modal crosstalk and low CD for all the LP modes.

4-mode FMF Design and Characteristics

A 4-mode low-CD weakly-coupled MRC-FMF is designed and fabricated, as shown in Fig. 2. An initial SI-FMF with the index profile of grey dash line in Fig. 2 is firstly designed. The value of normalized frequency V is set to 5.33 according to the number of accommodated LP modes. The values of relative core/cladding index difference Δ and core radius are set to be 0.64% and 6.75 μm, respectively, which are optimized to enlarge the minimum relative index difference among all the 4 modes as much as possible at the wavelength of 1310 nm. The perturbation method is adopted for the MRC-FMF design. The index profile of the designed MRC-FMF is shown in Fig. 2 as the orange solid line, which has the minimum effective index difference $\min|\Delta n_{eff}|\geq 1.3\times 10^{-3}$ and CD coefficient |CD|<6 ps/km/nm ranging from 1280 to 1340 nm. The maximum core refractive index $n_{core,max}$ is 1.45887 and the maximum relative refractive index Δ_{core} = 0.82%. The fiber is fabricated using the plasma chemical vapor deposition (PCVD) technique. The measured index profile is shown in Fig. 2 as the blue solid line. The n_{eff} distribution of all the 4 modes for the wavelengths from 1280 to 1340 nm in the fabricate FMF and corresponding SI-FMF are compare in Fig. 3. The $\min|\Delta n_{eff}|$ is increased from 0.76×10^{-3} to 1.321×10^{-3}, so the fabricated FMF could support weakly-coupled MDM transmission compared with previous study [10]. Fig. 4 (a) and (b) show the CD values of the SI-FMF and the fabricated FMF, respectively. We can see that the CD values are greatly reduced for the fabricated fiber, which lie between -6 and 6 ps/km/nm for the wavelengths ranging from 1280 to 1340 nm.

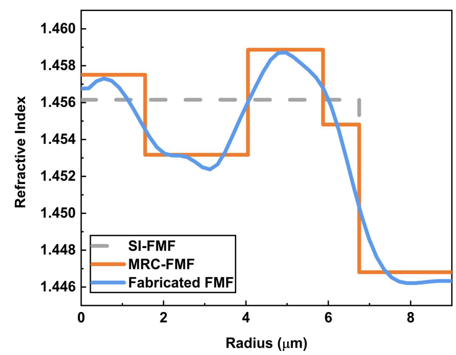

Fig. 2: Index profiles of the SI-FMF, the designed MRC-FMF and the fabricated FMF.

Then the CD values for all the 4 LP modes in the fabricated FMF are measured. We fabricate all-fiber mode-selective couplers (MSCs) to excite each LP mode one by one [11], which are realized by heating and tapering SMF with the fabricated FMF. Each MSC converts signal between fundamental mode of SMF and a specific LP mode of the fabricated FMF according to phase-matching conditions, which could be adjusted by different kinds of SMFs or different pre-tapering. So, the CD values of each LP mode still could be measured utilizing the PK-2800 by utilizing a pair of MSCs for each mode. The CD characteristics for the designed MRC-FMF and fabricated FMF are compared, as shown in Fig. 5. We can see that the deviation is less than 1 ps/km/nm across 1280~1340 nm for the LP_{01}, LP_{11}, LP_{21} modes, while a large deviation for the highest-order LP_{02} mode could be observed.

Transmission Experiment and Results

DSP-free IM/DD Transmission experiment is carried out to verify the transmission performance for the fabricated fiber. The experimental setup

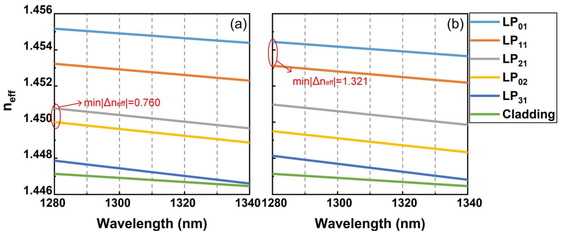

Fig. 3 n_{eff} distributions for (a) SI-FMF (b) fabricated FMF.

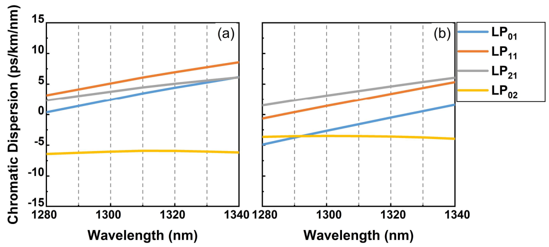

Fig. 4 CD values of (a) SI-FMF (b) fabricated FMF.

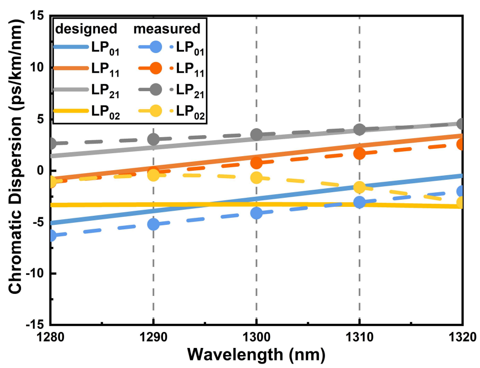

Fig. 5 measured CD for designed and fabricated fiber.

is shown in Fig. 6 (a). A bit error rate tester (BERT, eBERT-15G) is used for generating data patterns and error detection. 10-Gbps electric signal of pseudo-random binary sequence (PRBS) data is modulated using commercial 10-Gbps SFP+ optical modules at 1310 nm (AFASP13, 10G-CWDM-1310-40km-DDM) driven by an SFP+ evaluation boards (Youthton, YXTSFP+ TEST BOARD). The output optical power of the SFP+ module transmitter (Tx) is about 1.5 dBm. The output signal of the Tx is converted to LP_{01}, LP_{11}, LP_{21}, and LP_{02} modes of fabricated 4-mode fiber one-by-one using corresponding MSC. After transmission of 2-km fabricated FMF, the signal is converted to SMF utilizing another MSC and then is detected. The eye-diagrams at the Tx and after 2-km transmission are measured by digital serial analyzer (DSA, Tektronix DSA8300) and are shown in Fig. 6 (b)-(f). The received optical power is adjusted utilizing a variable optical attenuator (VOA, EXFO FVA 600) and the bit error rates (BER) are measured by the BERT. Forward error correction (FEC) is not used in the SFP+ modules.

Figure. 6 (g) shows the measured BER versus received optical power after transmission over 2-km fabricated FMF. As a reference, back-to-back (BTB) transmission by directly connecting the Tx and Rx is also performed. We can see that the receiver sensitivity penalties at the BER threshold of $1e^{-3}$ are about 1.4 dB, 2.4 dB, 4 dB and 7 dB for the LP_{01}, LP_{11}, LP_{21}, and LP_{02} modes, respectively compared to the BTB case. The large penalties for LP_{11} and LP_{21} modes may come from the influence of differential mode delays (DMD) in degenerate modes [11], while it is due to power leakage for the LP_{02} mode for the lack of trench outside the core.

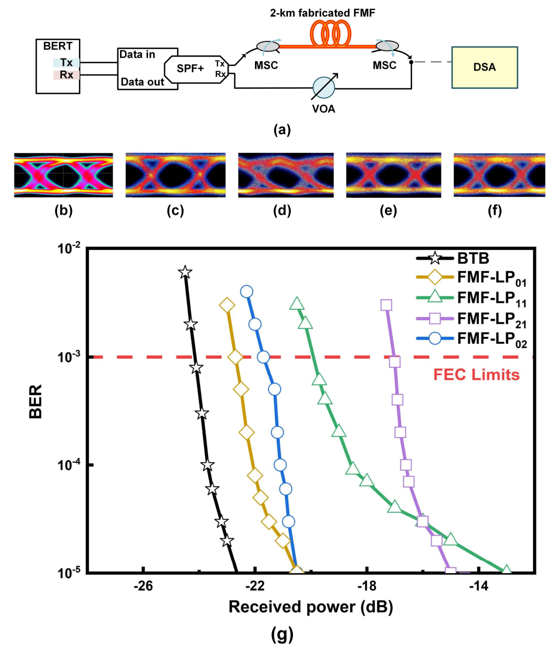

Fig. 6 (a) Experimental setup for BER performance over the fabricated fiber; (b)-(f) measured eye diagrams for BTB, LP_{01}, LP_{11}, LP_{21}, and LP_{02} modes after 2-km transmission; (g) measured BER versus received power for BTB and 2-km transmission.

Conclusions

Based on an accurate model for the relationship between refractive indices and wavelengths in germanium-doped fibers, a weakly-coupled low-CD FMF is designed and fabricated, which has a min|Δn_{eff}| larger than 1.3×10^{-3} among all modes and CD values lying between -6 and +6 ps/km/nm ranging from 1280 to 1340 nm for all 4 modes. The 2-km transmission experiment indicates that the fabricated MRC-FMF could support stable DSP-free IM/DD transmission for all 4 LP modes. This work is beneficial to the application of short-reach weakly-coupled MDM systems. *This work is supported in part by NSFC (U20A20160 and 62101009), and National Key Research and Development Program of China (2020YFB1806400).*

References

[1] D. J. Richardson, J. M. Fini, and L. E. Nelson, "Space-division multiplexing in optical fibres," *Nat. Photonics,* vol. 7, pp. 354-362, 2013,10.1038/NPHOTON.2013.94: https://doi.org/10.1038/NPHOTON.2013.94.

[2] S. Jiang, L. Ma, Z. Zhang, X. Xu, S. Wang, J. Du, C. Yang, W. Tong, and Z. He, "Design and Characterization of Ring-Assisted Few-Mode Fibers for Weakly Coupled Mode-Division Multiplexing Transmission," *Journal of Lightwave Technology,* vol. 36, no. 23, pp. 5547-5555, 2018,10.1109/jlt.2018.2874526: https://doi.org/10.1109/jlt.2018.2874526.

[3] W. Wang, P. Zhao, Z. Zhang, H. Li, D. Zang, N. Zhu, and Y. Lu, "First Demonstration of 112 Gb/s PAM-4 Amplifier-free Transmission over a Record Reach of 40 km Using 1.3 μm Directly Modulated Laser," presented at the Optical Fiber Communication Conference, San Diego, California United States, 2018.

[4] E. Forestieri, M. Secondini, F. Fresi, G. Meloni, L. Poti, and F. Cavaliere, "Extending the Reach of Short-Reach Optical Interconnects With DSP-Free Direct Detection," *Journal of Lightwave Technology,* vol. 35, no. 15, pp. 3174-3181, 2017,10.1109/jlt.2016.2647243: https://doi.org/10.1109/jlt.2016.2647243.

[5] D. Ge, Y. Gao, Y. Yang, L. Shen, Z. Li, Z. Chen, Y. He, and J. Li, "A 6-LP-mode ultralow-modal-crosstalk double-ring-core FMF for weakly-coupled MDM transmission," *Optics Communications,* vol. 451, pp. 97-103, 2019,10.1016/j.optcom.2019.06.015: https://doi.org/10.1016/j.optcom.2019.06.015.

[6] V. Brückner, "To the use of Sellmeier formula," p. 8, 2014,researchgate.net/publication/262294649: https://doi.org/researchgate.net/publication/262294649.

[7] Z. Su, F. Tian, Y. Zhang, B. Wang, L. Li, X. Yang, and J. Zhang, "A modified large mode-field area fiber with managing chromatic dispersion," *Optik,* vol. 208, p. 9, 2020,10.1016/j.ijleo.2019.164104: https://doi.org/10.1016/j.ijleo.2019.164104.

[8] I. H. MALITSON, "Interspecimen Comparison of the Refractive Index of Fused Silica," *J. Opt. Soc. Am.,* vol. 55, p. 5, 1965,10.1364/JOSA.55.001205: https://doi.org/10.1364/JOSA.55.001205.

[9] C. Z. Tan, "Determination of refractive index of silica glass for infrared wavelengths by IR spectroscopy," *J. Non·Cryst. Solids,* vol. 223, p. 6, 1998,10.1016/S0022-3093(97)00438-9: https://doi.org/10.1016/S0022-3093(97)00438-9.

[10] D. Soma, S. Beppu, Y. Wakayama, K. Igarashi, T. Tsuritani, I. Morita, and M. Suzuki, "257-Tbit/s Weakly Coupled 10-Mode C + L-Band WDM Transmission," *Journal of Lightwave Technology,* vol. 36, no. 6, pp. 1375-1381, 2018,10.1109/jlt.2018.2792484: https://doi.org/10.1109/jlt.2018.2792484.

[11] K. Y. Song, I. K. Hwang, S. H. Yun, and B. Y. Kim, "High Performance Fused-Type Mode-Selective Coupler Using Elliptical Core Two-Mode Fiber at 1550 nm," *IEEE Photonics Technology Letters,* vol. 14, no. 4, p. 3, 2002,10.1109/68.992591: https://doi.org/10.1109/68.992591.