Broadband dispersion compensation using microstructure fibers

Xia Zhang (张 霞), Xiaomin Ren (任晓敏), Yongzhao Xu (徐永钊),
Zinan Wang (王子南), Yongqing Huang (黄永清), and Xue Chen (陈 雪)

Key Laboratory of Optical Communication and Lightwave Technologies, Ministry of Education,
Beijing University of Posts and Telecommunications, Beijing 100876

Received August 14, 2006

Dispersion and dispersion slope compensation of 10-Gb/s pulses using microstructure fibers (MFs) is demonstrated experimentally. A 26-m MF is used to compensate the dispersion of 2-km standard singe mode fiber in a 20-nm range in C band. The experimental results show that a significant improvement can be achieved in the quality of the observed pulses with the dispersion compensation. Moreover, the further research shows that the MF can compensate the anomalous dispersion of a single mode fiber within ±0.27 ps/(nm·km) over a 50-nm wavelength range from 1520 to 1570 nm.

OCIS codes: 060.2330, 060.2310.

The capacity of optical fiber transmission systems has experienced explosive growth over the past few years due, in part, to the management of the fiber's chromatic dispersion[1]. A popular technique for dispersion management along a link is to alternate between two types of fiber, one having positive and the other having negative dispersion. With this method, many wavelength division multiplexing (WDM) channels can be compensated simultaneously. Unfortunately, because of the dispersion slope of optical fibers, ideal compensation can only be achieved at a single wavelength, with WDM channels located far from this singular wavelength accumulating progressively more dispersion. For broadband, high-speed, and long-distance systems, the issue of dispersion slope compensation remains a crucial problem.

Dispersion compensating fiber (DCF) is routinely used for this purpose. Because of the small index variation over the transverse cross section, modal characteristics of conventional DCF cannot be changed significantly to realize effective broadband dispersion compensation. A typical DCF compensates for approximately 60% of the conventional single-mode fiber (CSF) dispersion slope so that a residual dispersion slope of 0.023 ps/(nm^2·km) remains after the compensation[2]. This shortcoming may be overcome for the design of microstructure fibers (MFs)[3−5], whose transverse cross sections consist of a central region of pure silica surrounded by a lattice of air-holes in the cladding running along their length. By manipulating the air-hole radius or the lattice period of the cladding, it is possible to control the dispersion properties of MFs, such as the zero-dispersion wavelength that can be tuned over a very wide range[6], or the dispersion characteristics that can be engineered to be ultra-fattened[7]. The idea to use MF for dispersion compensation was first proposed in Ref. [8], in which a simplified model consisting of a silica core in air was used for the proof of concept. In order to control dispersion and dispersion slope simultaneously, several improved theoretical design models of chromatic dispersion in MF were reported[9,10]. In this paper, the experiment on dispersion and dispersion slope compensation of 10-Gb/s pulses using microstructure fibers is demonstrated. The efficiency of broadband compensation in a range of 50 nm is assessed by further research.

Because of the positive dispersion and dispersion slope of CSF, the basic requirement of MF for dense wavelength-division-multiplexing (DWDM) operation is a large negative dispersion and dispersion slope over a wide range of wavelength. Here, we assume that a fiber link consists of a CSF of length L_1 with dispersion $D_1(\lambda)$ and a MF of length L_2 with dispersion $D_2(\lambda)$, the effective compensated dispersion $D_{\mathrm{e}}(\lambda)$ on the fiber link in series can be written as[10]

$$D_{\mathrm{e}}(\lambda)=\frac{D_1(\lambda)L_1+D_2(\lambda)L_2}{L_1+L_2}, \tag{1}$$

which only considers the effective dispersion. In order to compensate the accumulated dispersion at $\lambda=\lambda_0$ of CSF by MF, the following condition has to be satisfied

$$R=\frac{L_1}{L_2}=-\frac{D_2(\lambda_0)}{D_1(\lambda_0)}, \tag{2}$$

where R is the fiber dispersion ratio and λ_0 is the center of the operating wavelength range. Furthermore, the accumulated dispersion of CSF should be compensated over a wavelength range. For simplicity, we assume that both fibers have slowly varying dispersion slopes $S_1(\lambda)$ and $S_2(\lambda)$, which is reasonable for a fiber link due to its linear nature, so that

$$D_1(\lambda)=D_1(\lambda_0)+(\lambda-\lambda_0)S_1(\lambda_0), \tag{3}$$

$$D_2(\lambda)=D_2(\lambda_0)+(\lambda-\lambda_0)S_2(\lambda_0). \tag{4}$$

In order to compensate the accumulated dispersion over a range of wavelength, the following conditions ($D_{\mathrm{e}}(\lambda)=0$, $\lambda\neq\lambda_0$) has to be satisfied

$$R=\frac{L_1}{L_2}=-\frac{S_2(\lambda_0)}{S_1(\lambda_0)}. \tag{5}$$

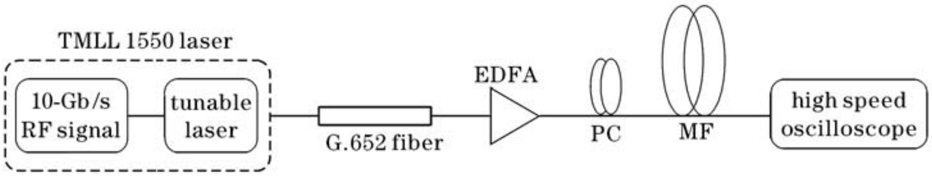

Fig. 1. Experimental setup for dispersion compensation.

By combining Eqs. (2) and (5), a new parameter K is introduced

$$K = \frac{D_1(\lambda_0)}{S_1(\lambda_0)} = \frac{D_2(\lambda_0)}{S_2(\lambda_0)}. \tag{6}$$

The parameter K is usually used to judge the dispersion compensation satisfaction over a range of wavelength.

Figure 1 shows a schematic of the setup used for dispersion compensation. The Hyperbolic-Secant shaped pulses generated by mode-locked laser (TMLL 1550) are ~ 2 ps in width with the repetition rate of 10 GHz. After propagating through a 2-km standard SMF, the pulse signals are broadened, and then amplified by an erbium-doped fiber amplifier (EDFA). A polarization controller (PC) is used to control the input state of polarization of 26-m MF, which is used for dispersion compensation. The scanning electron micrograph (SEM) of MF is shown in Fig. 2. The measured size of the pitch is 1.026 μm, and the normalized air-hole diameters are within 1.065 ± 0.064 μm in the first ring, 0.552 ± 0.047 μm in the second ring, 0.820 ± 0.054 μm in the outer rings, respectively. The measured chromatic dispersion at the wavelength of 1550 nm is of -1023.9 ps/(nm·km), which is about 10 times higher than that of the standard DCF, and the dispersion slope is of -4.07 ps/(nm^2·km). We assume that the referenced standard fiber is made of silica with 16.24 ps/(nm·km) dispersion and 0.058 ps/(nm^2·km) dispersion slope at wavelength of 1550 nm, respectively. If the dispersion ratio and the dispersion slope ration between MF and the standard fiber is the same, the broadband compensation efficiency will be best, but since the dispersion parameters of the actual fabricated MF should be deviated from the designed ones, so the perfect condition can never be realized and in this experiment we use a 2-km standard fiber.

A high-resolution oscilloscope with bandwidth of 40 GHz is used to observe the pulses shape. The initial pulses shape generated by mode-locked laser operating at the wavelength of $\lambda = 1550$ nm are shown in Fig. 3(a). The broadened pulses after passing through the 2-km standard SMF are shown in Fig. 3(b). As can be seen clearly, the pulses were severely broadened. The pulses after dispersion compensation using a 26-m MF are shown in Fig. 3(c). Experimental results show that the broadened pulses have nearly recovered their initial shapes after propagating through the MF.

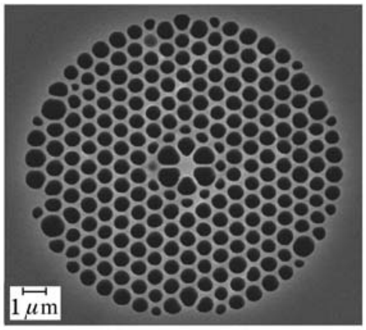

Fig. 2. Scanning electron micrograph of MF.

To demonstrate the effectiveness of the broadband dispersion compensation, we change the central wavelength in a range of wavelength from 1540 to 1560 nm. It is found that the pulses shape changes little when the central wavelength is tuned in the 20-nm range. The pulses after dispersion compensation using the 26-m MF at the wavelength of $\lambda = 1540$ and 1560 nm are shown in Figs. 3(d) and (e), respectively. The results show that a significant improvement can be achieved in the quality of the observed pulses shape with the dispersion compensation at $\lambda = 1540$ nm. The pulses have even been compressed at the wavelength of $\lambda = 1560$ nm. So the effect of broadband dispersion compensation is favorable. In order to obtain more accurate results, it is necessary to use an autocorrelator to observe such narrow pulses.

To investigate the specific satisfaction on each wavelength, we plot the calculated dispersion of the standard fiber as a function of wavelength. The compensation ratio R is defined as the fraction of the dispersion of standard fiber that is compensated by MF, the lengths of both are chosen so that compensation is perfect at the single wavelength of 1550 nm.

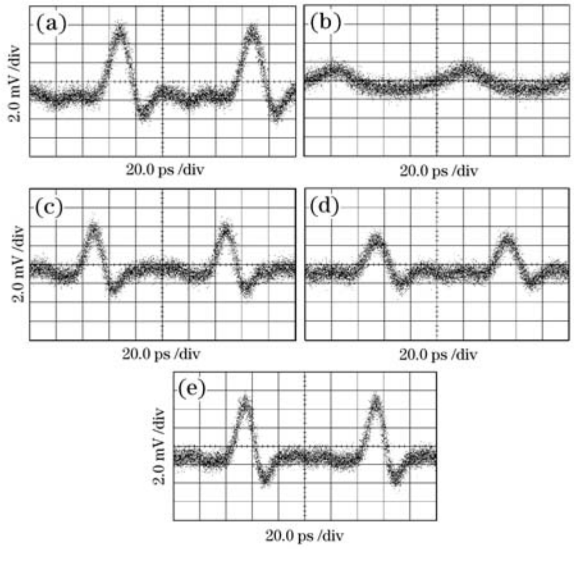

Fig. 3. Pulse shapes. (a) Initial pulses; (b) broadened pulses; (c) after dispersion compensation at 1550 nm; (d) at 1540 nm; (e) at 1560 nm.

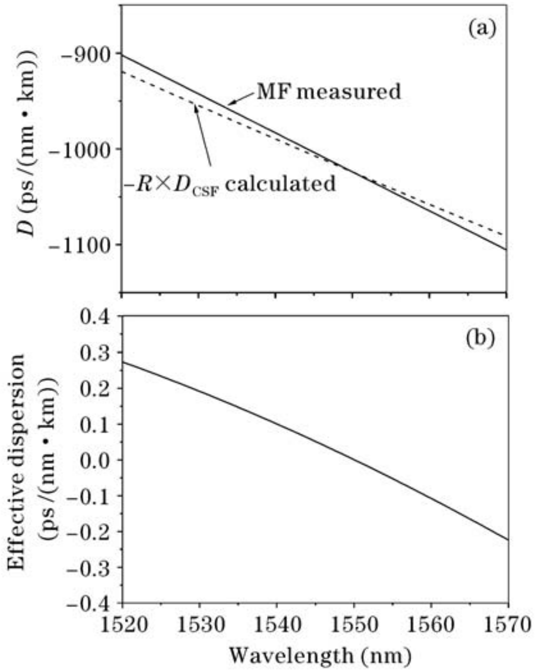

Fig. 4. (a) MF measured dispersion (solid line) and standard fiber calculated dispersion (dotted line), in which the dotted line represents the product of dispersion of standard fiber and the dispersion ratio $R = 63.05$; (b) effective dispersion of the fiber link after being compensated by MF.

Figure 4(a) shows the dispersion of MF (solid line) measured by using phase-shift method and the dispersion of the referenced standard fiber. The length of the referenced standard fiber is selected to acquire the best compensation efficiency at 1550 nm. This result shows that if we use the MF to compensate the dispersion of 63.05 times of length of standard fiber, the best compensation effect is achieved at 1550 nm while the effective dispersion is zero. Since the mismatch of dispersion slope, the absolute value of effective dispersion increases when the operating wavelength is deviating from 1550 nm. In Fig. 4(a), the dotted line represents the product of the calculated dispersion of standard fiber and compensation ratio $R = 63.05$. Figure 4(b) is the effective dispersion of the fiber link after being compensated by MF. It is seen from Fig. 4 that MF can compensate standard fiber within ±0.27 ps/(nm·km) over 50-nm wavelength range from 1520 to 1570 nm.

MFs can be fabricated to have unusual dispersion characteristics by altering the size and arrangement of the surrounding air holes. The experiment on dispersion and dispersion slope compensation of 10-Gb/s pulses using MFs is demonstrated. The results show that the effect of dispersion and dispersion slope compensation is favorable. MF will play an important role in optical fiber communication, especially in broadband dispersion compensation.

This work was supported by the National Basic Research Program of China (No. 2003CB314900), and the Key Grant Project of Chinese Ministry of Education (No. 104046). X. Zhang's e-mail address is xzhang@bupt.edu.cn.

References

1. Y. Xie, S. Lee, Z. Pan, J.-X. Cai, A. E. Willner, V. Grubsky, D. Starodubov', E. Salik, and J. Feinberg, in *Proceedings of OFC'2000* **ThS2-1,** 271 (2000).
2. L. Grüner-Nielsen, B. Edvold, D. Magnussen, D. Peckham, A. Vengsarkar, D. Jacobsen, T. Veng, C. C. Larsen, and H. Damsgaard, in *Proceedings of OFC'1998* **TuD5,** 24 (1998).
3. J. C. Knight, T. A. Birks, P. S. J. Russell, and D. M. Atkin, Opt. Lett. **21,** 1547 (1996).
4. J. Broeng, D. Mogilevstev, S. E. Barkou, and A. Bjarklev, Opt. Fiber Technol. **5,** 305 (1999).
5. Y. Ni, L. Zhang, and J. Peng, Chin. Opt. Lett. **1,** 385 (2003).
6. J. C. Knight, J. Arriaga, T. A. Birks, A. Ortigosa-Blanch, W. J. Wadsworth, and P. St. J. Russell, IEEE Photon. Technol. Lett. **12,** 807 (2000).
7. A. Ferrando, E. Silvestre, P. Andrés, J. J. Miret, and M. V. Andrés, Opt. Express **9,** 687 (2001).
8. T. A. Birks, D. Mogilevtsev, J. C. Knight, and P. St. J. Russell, IEEE Photon. Technol. Lett. **11,** 674 (1999).
9. K. Saitoh, M. Koshiba, T. Hasegawa, and E. Sasaoka, Opt. Express **11,** 843 (2003).
10. L. P. Shen, W.-P. Huang, G. X. Chen, and S. S. Jian, IEEE Photon. Technol. Lett. **15,** 540 (2003).