Front. Optoelectron. China 2010, 3(4): 333–338
DOI 10.1007/s12200-010-0117-6

RESEARCH ARTICLE

Dispersion compensation optical fiber modules for 40 Gbps WDM communication systems

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Abstract Dispersion compensation was originally proposed to equalize pulse distortion. With the development of wavelength division multiplexing (WDM) techniques for large capacity optical communication systems, dispersion compensation technologies have been applied into the field. Fiber-based dispersion compensation is an attractive technology for upgrading WDM communication systems because of its dispersion characteristics and good compatibility with transmission optical fibers. Dispersion compensation fibers and the modules are promising technologies, so they have been receiving more and more attention in recent years.

In this work, high performance dispersion compensation fiber modules (DCFMs) were developed and applied for the 40 Giga bit-rate systems. First, the design optimization of the dispersion optical fibers was carried out. In theory, the better the refractive index profile is, the larger the negative dispersion we could obtain and the higher the figure of merit (FOM) for the dispersion optical fiber is. Then we manufactured the fiber by using the plasma chemical vapor deposition (PCVD) process of independent intellectual property rights, and a high performance dispersion optical fiber was fabricated. Dispersion compensation fiber modules are made with the dispersion compensating fibers (DCFs) and pigtail fibers at both ends of the DCFs to connect with the transmission fibers. The DCFMs present the following superior characteristics: low insertion loss (IL), low polarization mode dispersion, good matched dispersion for transmission fibers, low nonlinearity, and good stability for environmental variation.

The DCFMs have the functions of dispersion compensation and slope compensation in the wavelength range of 1525 to 1625 nm. The experiments showed that the dispersion compensation modules (DCMs) met the requirements of the GR-1221-CORE, GR-2854-CORE, and GR-63-CORE standards. The residual dispersions of the G.652 transmission lines compensated for by the DCM in the C-band are less than 3.0 ps/nm, and the dispersion slopes are also compensated for by 100%. With the DCFMs, the 8×80 km unidirectional transmission experiments in the 48-channel 40 Gbps WDM communication system was successfully made, and the results showed that the channel cost was smaller than 1.20 dB, without any bit error.

Keywords dispersion compensation module (DCM), fiber communication, optical fiber, wavelength division multiplexing (WDM)

1 Introduction

With the development of wavelength division multiplexing (WDM) techniques for large capacity optical communication systems [1–5], dispersion is becoming an important factor that affects transmission performance, therefore dispersion compensation technologies are now applied into this field. Dispersion compensation is to counteract the accumulated dispersion of the communication transmission fibers by using opposite dispersion optical fibers.

Fiber-based dispersion compensation is an attractive technology for upgrading WDM communication systems because of its dispersion characteristics and good compatibility with transmission optical fibers [6–10]. Dispersion compensation fibers and their modules are promising technologies, so they have been receiving more and more attention in recent years.

Received July 12, 2010; accepted August 16, 2010

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2 Design of dispersion compensation fibers

Dispersion compensation fiber (DCF) is a kind of optical fiber which has dispersion characteristics opposite to that of transmission link fibers. In most conditions for the present communication system, the transmission link is the common single mode optical fiber (CSMF), which is named G.652 according to the ITU.T standard. The fiber has positive dispersion in the C-band operation window, and has about 18 ps/(nm·km) dispersion at 1550 nm wavelength. After a long transmission distance, the accumulated positive dispersion becomes big, which results in the reduction of the signal to noise ratio (SNR), an increase in bit error rate, and deterioration in the system performance. Therefore, we must design a kind of DCF that can compensate for the accumulated positive dispersion, which has negative dispersion and a negative dispersion slope in the operation wavelength range [11–16].

DCFs to compensate for the dispersion slope of the CSMF as well as the dispersion are required. In order to have a large negative dispersion or low optical nonlinearity, a DCF based on the higher-order mode like LP_{11} or LP_{02} could be developed. Having an extremely large negative dispersion, the DCF must have the optical properties that can deliver broadband dispersion compensation with low added loss and non-linearity to the communication system.

The dispersion is related to the second derivative of the propagation constant (β):

$$D=\frac{-2\pi c}{\lambda^2}\frac{\mathrm{d}^2\beta}{\mathrm{d}\omega^2}=\frac{1}{c}\left(2\frac{\mathrm{d}n_\mathrm{e}}{\mathrm{d}\omega}+\omega\frac{\mathrm{d}^2n_\mathrm{e}}{\mathrm{d}\omega^2}\right), \tag{1}$$

where c is the light velocity in the vacuum, λ is the wavelength, ω is the frequency, and n_e is the effective index.

The propagation constant can be written in terms of the free space wave number and the effective index:

$$\beta=k_0n_\mathrm{e}=\frac{\omega}{c}n_\mathrm{e}=\frac{2\pi}{\lambda}n_\mathrm{e}, \tag{2}$$

and the effective index as

$$n_\mathrm{e}=\Delta n_\mathrm{e}+n_0, \tag{3}$$

where Δn_e is the effective index difference, and n_0 is the refractive index of the cladding.

Therefore, the dispersion can be written as

$$\begin{aligned}D&=\frac{-2\pi c}{\lambda^2}\frac{\mathrm{d}^2k_0\Delta n_\mathrm{e}}{\mathrm{d}\omega^2}+\frac{-2\pi c}{\lambda^2}\frac{\mathrm{d}^2k_0n_0}{\mathrm{d}\omega^2}\\&=D_\mathrm{waveguide}+D_\mathrm{material}.\end{aligned} \tag{4}$$

Therefore, we designed this kind of waveguide structure, which is shown in Fig. 1. The DCF has triple-clad index profiles with a core surrounded by a region with a depressed index (the trench) followed by a raised ring.

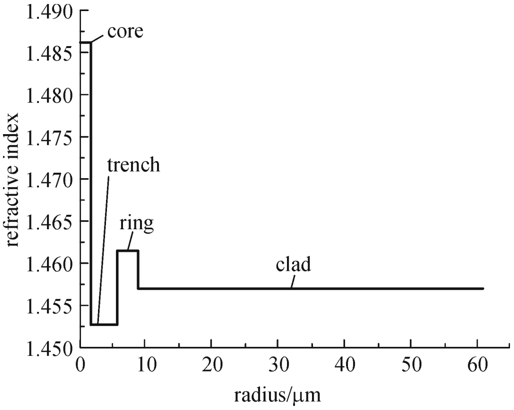

Fig. 1 Refractive index profile of DCF

With the specific triple-clad index profile, the effective index of the combined modes can be described by n_e.

$$n_\mathrm{e}=\frac{n_{\mathrm{e(core)}}+n_{\mathrm{e(ring)}}}{2}\pm\sqrt{l^2+\frac{(n_{\mathrm{e(core)}}-n_{\mathrm{e(ring)}})^2}{4}}, \tag{5}$$

where $n_{\mathrm{e(core)}}$ is the effective index of the core mode, $n_{\mathrm{e(ring)}}$ is the effective index of the ring mode, and l is the coupling strength between the two modes.

For most dispersion compensating fibers, the material dispersion around 1550 nm is at the order of 18 ps/(nm·km). According to Eq. (4), the total dispersion can be optimized by adjusting the waveguide dispersion. In other words, we can change the $n_{\mathrm{e(core)}}$ or the $n_{\mathrm{e(ring)}}$ and the coupling length, so that the dispersion could be changed.

In order to cancel out the accumulated dispersion of the link road, the following principle will be obeyed:

$$D_\mathrm{TF}L_\mathrm{TF}+D_\mathrm{DCF}L_\mathrm{DCF}=0, \tag{6}$$

where D_TF is the dispersion coefficient of the transmission fiber, L_TF is the length of the transmission optical fiber, D_DCF is the dispersion coefficient of the DCF , and L_DCF is the length of the DCF.

Besides considering the high negative dispersion, we must consider the wideband compensating performances. Generally, WDM systems operate in the wide wavelength range from 1525 to 1565 nm. Therefore, we must compensate for all the accumulative positive dispersion of the operation waveband, and the following formula will be met:

$$S_\mathrm{TF}L_\mathrm{TF}+S_\mathrm{DCF}L_\mathrm{DCF}=0, \tag{7}$$

where S_TF is the slope coefficient of the transmission fiber, and S_DCF is the slope coefficient of the DCF.

According to Eqs. (6) and (7), it can be concluded that the DCF can compensate for the dispersion at wideband and at the slope, at the same time using the same DCF that is seen in Eq. (8).

$$\text{Kappa} = \frac{D_{\text{DCF}}}{S_{\text{DCF}}} = \frac{D_{\text{TF}}}{S_{\text{TF}}}. \tag{8}$$

The CSMF has a dispersion of 16.8 ps/(nm·km) and a slope of 0.06 ps/(nm^2·km) at 1545 nm wavelength; its Kappa is 280 nm. Therefore, the Kappa of DCF will be designed to be around 280 nm, and the link dispersion and slope can be compensated at the same time.

As a typical profile in Fig. 1, at short wavelengths the effective index of the LP$_{01}$ mode approaches that of the core mode, indicating that the LP$_{01}$ mode is confined mainly to the core. At longer wavelengths the effective index of the LP$_{01}$ mode approaches that of the ring, indicating that the mode is confined to the ring.

The dispersion curve of the DCF in Fig. 2 was achieved. The DCF has a negative dispersion of – 144.6 ps/(nm·km) and a slope of – 0.58 ps/(nm^2·km) at 1550 nm wavelength.

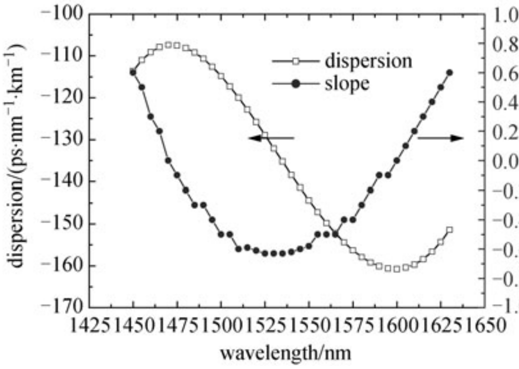

Fig. 2 Dispersion and slope curves of DCF

As another key characteristic, bending-loss, will affect the DCF in fabricating dispersion compensation module (DCM), because the DCF will be wound on a metallic mandrel with a small diameter. Therefore, when we design the waveguide structure of the DCF, the anti-bending performances must be considered. Raising the core-index or the trench-index or the ring-index can decrease the bending loss. Figure 3 shows the relation curve between the relative refractive index difference of the core and macro-bending loss. We can see that the macro-bending loss was reduced with an increase in the core refractive index difference.

Finally, the DCF we fabricated successfully is demonstrated to have superior dispersion and good bending performance. Its specifications are shown in Table 1.

The nonlinear characteristics of the DCF are shown in Table 2.

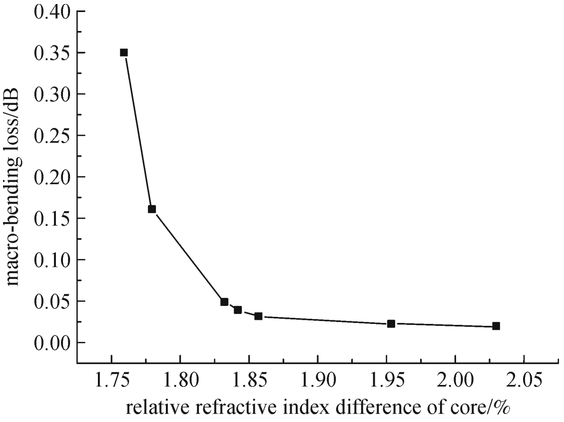

Fig. 3 Relation curve between macro-bending loss and core index difference (bending loss: 10 nm; turns: 1)

Table 1 Specifications of DCF for CSMF (PMD: polarization mode dispersion; MFD: mode field diameter)

item		unit	value
PMD		ps·km$^{-1/2}$	0.06
dispersion	1525 nm	ps/(nm·km)	– 129
	1545 nm	ps/(nm·km)	– 141
	1550 nm	ps/(nm·km)	– 144
	1565 nm	ps/(nm·km)	– 152
slope	1525 nm	ps/(nm^2·km)	– 0.63
	1545 nm	ps/(nm^2·km)	– 0.60
	1550 nm	ps/(nm^2·km)	– 0.58
	1565 nm	ps/(nm^2·km)	– 0.46
attenuation 1550 nm		dB/km	0.42
MFD1550 nm		μm	5.40
L-cutoff		nm	1160–1460
figure of merit (FOM)		ps/(nm·dB)	343
macro-bending loss at 1550 nm (bending radius: 10 mm × 1 turn)		dB	0.05

Table 2 Nonlinear parameters of DCF (SBS: stimulated Brillouin scattering)

parameters	unit	min	max
SBS threshold	dBm	4	—
nonlinear coefficient	W^{-1}	—	1.40×10^{-9}
effective area	μm^2	20	—

3 Dispersion compensation modules and experiments

DCMs have become essential devices in dense wavelength-division multiplexing optical transmission networks. They greatly improve the performance of communication systems. Dispersion compensation fiber modules consist of DCFs and pigtail fibers at both ends of the DCFs to connect with the transmission fibers, such as standard single mode fibers or non-zero dispersion shifted fibers. The lengths of the DCFs are determined to cancel out the accumulated dispersion of the transmission fibers within the proper amount of residual dispersion. Various characteristics of the DCFs in addition to the dispersion must be considered to realize high performance DCMs. The general requirements for the DCMs are given below.

a) Exactly matched dispersion with the transmission fibers;

b) Comparatively low insertion loss (IL): in order to maintain the high SNR, the IL of the DCM is expected to be as small as possible;

c) Low polarization mode dispersion;

d) Low nonlinearity: the lower the nonlinear impairments of DCM on the system are, the better;

e) Stability for environmental variation: the optical properties have to be stable in changing operating conditions with respect to temperature, humidity, and vibration;

f) Lastly, dispersion compensation fiber modules with reduced physical dimensions are the tendency.

With the DCFs which were manufactured by the process of plasma chemical vapor deposition, we fabricated high performance dispersion compensation modules. Their specifications are shown in Table 3.

According to the standard of the GR-1221-CORE, the GR-2854-CORE, and the GR-63-CORE standards, we made reliable experiments. The testing results are shown in Table 4, and proved that the DCMs met with the requirements of the passive devices.

In Fig. 4, the 8×80 km unidirectional transmission experiments in the 48-channel 40 Gbps WDM communication system were successfully done by using the DCMs to compensate for the accumulated positive dispersion. The results proved that the channel cost was smaller than 1.20 dB, and there was no bit error. The residual dispersions of the G.652 transmission link compensated for by the DCMs in the C-band were less than 3.0 ps/nm, and the dispersion slopes were also compensated for by 100%, as shown in Fig. 5.

4 Conclusion

The DCFs were manufactured by using the plasma chemical vapor deposition (PCVD) process of independent intellectual property rights, and high performance dispersion optical fibers were fabricated successfully. Dispersion

Table 3 Specifications of DCMs for CSMF (WDL: wavelength dependence loss; PDL: polarization dependence loss; TDL: temperature dependence loss)

parameters	unit	DCM-20	DCM-40	DCM-60	DCM-80	DCM-100	DCM-120
compensated distance	km	20	40	60	80	100	120
dispersion at 1545 nm	ps/nm	−340±10	−670±20	−1000±30	−1340±40	−1680±50	−2010±60
Kappa	nm	280×(1±10%)					
max IL (C-band)	dB	⩽3.0	⩽4.7	⩽6.4	⩽8.0	⩽9.5	⩽11.0
typical IL (C-band)	dB	2.6	4.1	5.2	6.5	8.1	9.0
WDL (C-band)	dB	⩽0.5, type 0.3					
max PMD	ps	⩽0.50	⩽0.6	⩽0.7	⩽0.8	⩽0.95	⩽1.1
typical PMD	ps	0.35	0.46	0.56	0.72	0.80	0.90
PDL	dB	⩽0.10	⩽0.10	⩽0.10	⩽0.10	⩽0.10	⩽0.10
TDL	dB	⩽0.25	⩽0.25	⩽0.25	⩽0.25	⩽0.25	⩽0.25

Table 4 Reliable testing data of DCMs for CSMF

No.	item	ΔIL/dB	ΔPMD/ps	Δdispersion at 1545 nm/%
1	mechanical shock test	⩽ ± 0.15	⩽ ± 0.10	⩽ ± 0.32
2	viable frequency vibration test	⩽ ± 0.19	⩽ ± 0.12	⩽ ± 0.35
3	high temperature storage test (dry heat)	⩽ ± 0.11	⩽ ± 0.10	⩽ ± 0.34
4	high temperature storage test (damp heat)	⩽ ± 0.16	⩽ ± 0.11	⩽ ± 0.36
5	low temperature storage	⩽ ± 0.15	⩽ ± 0.10	⩽ ± 0.32
6	temperature cycling test	⩽ ± 0.19	⩽ ± 0.14	⩽ ± 0.43
7	cycling moisture resistance test	⩽ ± 0.18	⩽ ± 0.13	⩽ ± 0.32
8	packaged drop test	⩽ ± 0.19	⩽ ± 0.12	⩽ ± 0.31
9	unpackaged drop test	⩽ ± 0.22	⩽ ± 0.15	⩽ ± 0.39
10	operation environmental vibration test	⩽ ± 0.23	⩽ ± 0.09	⩽ ± 0.09
11	transportation vibration test	⩽ ± 0.17	⩽ ± 0.05	⩽ ± 0.08
12	operation environmental temperature test	⩽ ± 0.28	⩽ ± 0.22	⩽ ± 0.16

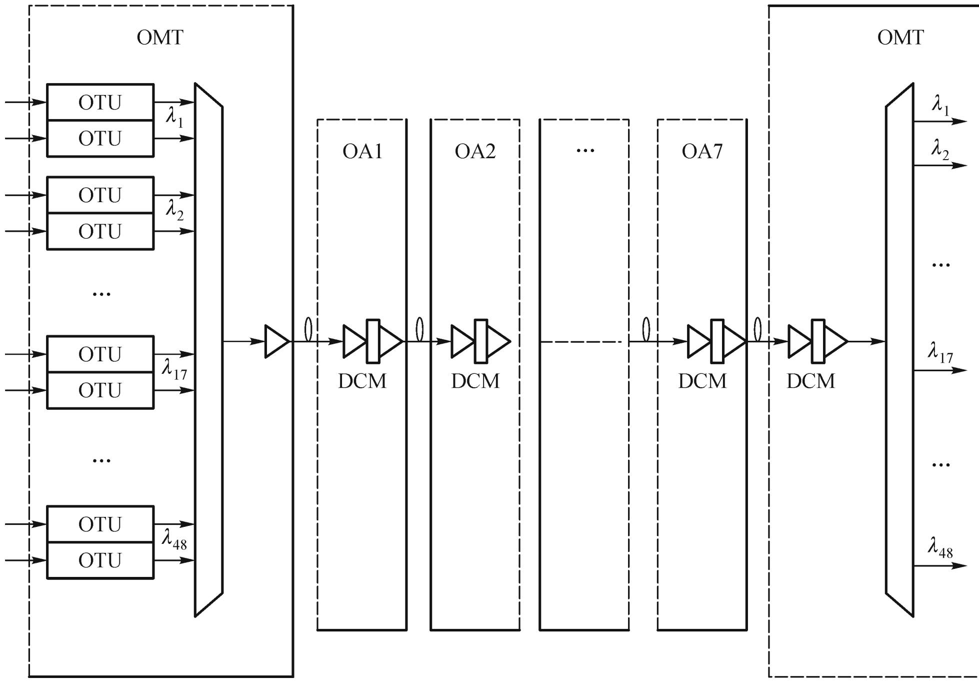

Fig. 4 48×40 Gbps dispersion compensation setup (OMT: optical multiplexing terminal; OA: optical amplifier; OTU: optical transmission unit)

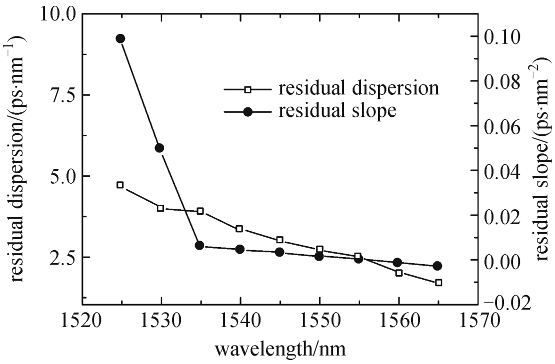

Fig. 5 Residual dispersion and slope after compensation for 80 km link

compensation fiber modules are made with dispersion compensating fibers (DCFs) and pigtail fibers at both ends of the DCFs to connect with the transmission fibers. The DCFMs present the following superior characteristics: low IL, low polarization mode dispersion, good matched dispersion for transmission fibers, low nonlinearity and good stability for environmental variation.

The transmission experiments of the 48×40 Gbps communication system proved that the DCFMs have superior functions of dispersion compensation and slope compensation in the wavelength range of 1525 to 1625 nm. The experiments showed that the DCMs met with the requirements of the GR-1221-CORE, GR-2854-CORE, and GR-63-CORE standards.

Acknowledgements This work was supported by the National Basic Research Program of China (Grant No. 2010CB327606).

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