Dispersion Compensating Fibers

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Abstract: In this paper we briefly review the work on dispersion compensating fibers (DCFs) in the last few years. Starting with the basic principle behind DCF, its need for upgrading the 1310 nm optical fiber links is discussed. The experimental and theoretical results of some researchers have been cited. The latest trend in optical communication has been to use dense wavelength division multiplexed (DWDM) systems in the gain window of an optical fiber amplifier. However, nonlinear effects like four wave mixing (FWM) impose serious limitations. To overcome this difficulty use of fibers with non-zero dispersion has been suggested. For long distance repeater less transmission this dispersion will go on accumulating and will limit the number of bits one can send at each wavelength. Properly designed dispersion compensating fibers can overcome this difficulty. Already there has been some work in this direction by various researchers.

More than 70 million km of conventional single mode fiber (CSF) with zero dispersion wavelength (λz) ~ 1300 nm had already been laid underground operating around this wavelength. It is known that fiber has lowest loss at 1550 nm and also that efficient amplifiers operate around this wavelength. So it is desirable to operate around 1550 nm. Dispersion shifted fibers (DSF) having zero dispersion wavelength at 1550 nm were developed for this purpose. If we use the existing CSFs at 1550 nm, they will have dispersion coefficient D ~16 ps/km·nm which will limit the bit rate one can transmit. The solution of this problem is through dispersion compensation [1].

In order to understand dispersion compensation let us consider a Gaussian input pulse

$$E(x=0,t) = E_0 e^{-t^2/T_0^2} e^{i\omega t}$$

It can be shown [2] that due to group velocity dispersion in an optical fiber; the pulse at a distance x along the fiber will be given by

$$E(x,t) = \frac{E_0}{[T(x)/T_0]^{1/2}} \exp\left[-\frac{(t-\frac{x}{v_g})^2}{T^2(x)} \right] e^{i\Phi(x,t)}$$

where

$$\Phi(x,t) = \omega_0 t + \kappa(t-\frac{x}{v_g})^2 - \frac{1}{2}\tan^{-1}\left(\frac{2\alpha x}{T_0^2}\right) - \beta x \ ;$$

$$\kappa = \frac{2\alpha x}{T^2(x)} \ ; \ \alpha = \frac{d^2\beta}{d\omega^2}\Big|_{\omega=\omega_0} \ ; \ T(x) = T_0\left[1+\frac{4\alpha^2 x^2}{T_0^4}\right]^{1/2}$$ and β is the propagation constant.

So the pulse remains Gaussian, moves with a velocity $v_g = \left(\frac{d\beta}{d\omega}\right)^{-1}$ and its width *T(x)* goes on increasing with x. From the phase term it can be seen that the instantaneous frequency within the pulse envelope i.e.

$$\omega(t) = \frac{\partial\Phi}{\partial t} = \omega_0 + 2\kappa\left(t - \frac{x}{v_g}\right)$$

changes with time. This is called a *chirped* pulse. It may be mentioned here that since we are considering a linear system, the frequency spectrum of the input and output pulses will be the same.

If α is +ve, then $\omega(t)$ will increase with time and the leading edge ($t < \frac{x}{v_g}$) will be red shifted ($\omega(t) < \omega_0$). Similarly the trailing edge will be blue shifted.

The broadening of the pulse and *chirping* can be understood yet another way. Every pulse has a finite spectral width say $\Delta\lambda_0$. Fig.1 shows the typical variation of the group velocity v_g for a CSF with wavelength λ. It attains a maximum at λ_z and then monotonically decreases with λ. If we are sending pulses with central wavelength λ_0 ~ 1550 nm, then higher wavelengths within the pulse will move slower than the lower wavelengths. As a result the pulse will be broadened, the leading edge will be blue shifted and the trailing edge will be red shifted (see Fig. 2).

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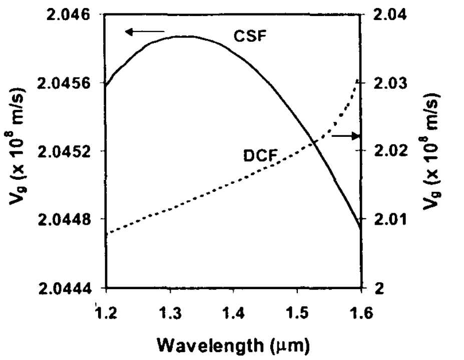


Fig. 1. Typical variation of v_g with wavelength.

Figure 1 also shows the typical variation of v_g in a DCF. In this case the group velocity monotonically increases with λ. So in a DCF higher wavelengths move faster than lower wavelengths. If a pulse with $\lambda_0 > \lambda z$ is first propagated through a CSF, it will get broadened and the leading edge will be blue shifted and now if we propagate it through a DCF where the longer wavelengths move faster, the pulse will tend to regain its original shape. Total dispersion D_t (measured in ps/km.nm) of a single mode fiber is given by

$$D_t = -\frac{2\pi c}{\lambda_0^2}\frac{d^2\beta}{d\omega^2}$$

If the dispersion coefficients and lengths of CSF (D_1, l_1) and DCF (D_2, l_2) satisfy the relation:

$$D_1 l_1 + D_2 l_2 = 0$$

Then the pulse will regain its original shape (see Fig.2).

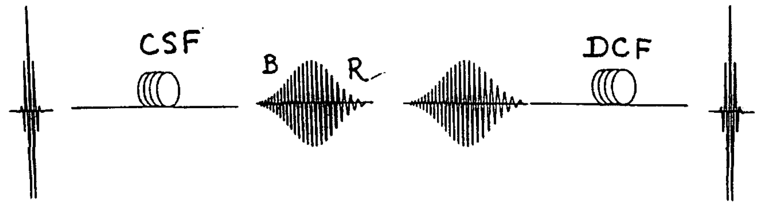


Fig. 2. A Gaussian pulse passes a CSF and the output chirped pulse then passes through a DCF.

In order to achieve dispersion compensation, proper length of a DCF has to be added to the existing CSF links. It will increase the loss of the link; even otherwise it would be economical that a smaller length of the DCF serve the purpose. The length of the DCF can be reduced if its dispersion coefficient at 1550 nm has a large –ve value. The dispersion compensation efficiency of a DCF is measured in terms of the figure of merit (FOM), which is defined as the ratio of the dispersion coefficient D to the total loss α. Thus

$$FOM(ps/(dB\cdot nm)) = |D|/\alpha$$

Figure 3 shows the results of Poole et al. (1994) [3]. One can see that it is impossible to get any information from the output of a 50 km long CSF. However, almost original pulses are obtained after passing this output through a DCF.

A lot of work has been reported on the design of dispersion compensating fibers [4-9]. Thyagarajan et. al. [6] gave a design of DCF, consisting of two highly asymmetric concentric cores, which can provide a very high value of D (see Fig.4b). In Fig. 4a, the variation of the effective index (β/k_0) with λ has been shown. The solid curve is for the dual core DCF; dashed and dotted curves correspond to the two separate fibers, one having only the inner core and the other only the outer core respectively. It can be noticed that at wavelengths far from 1550 nm, the effective index of the DCF is near to the effective indices of the modes of the individual fibers with only inner or the outer core. But close to 1550 nm, there is a phase matching and the effective index of the composite fiber (dual core DCF) changes rapidly because of strong coupling between the two individual modes of the inner and the outer core. Due to a large asymmetry between the two cores, the slope of the curve changes very fast. This is the reason for a large numerical value of D in the vicinity of 1550 nm (see fig. 4b).

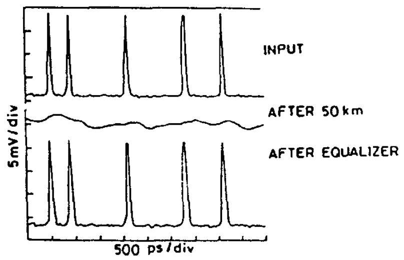
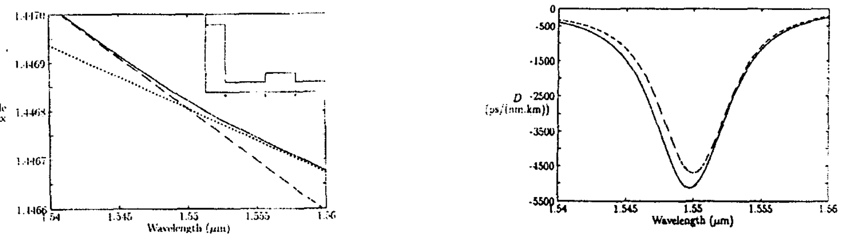


Fig. 3. Typical results showing the performance of a DCF. [Adapted from Poole et. al. (1994)]



(a) (b)

Fig. 4. (a) Variation of βk_0 with wavelength. Refractive index profile of the DCF is shown in the inset. (b) Variation of D with wavelength. Solid and dashed curves correspond to the step and parabolic index profiles respectively. [Adapted from Thyagarajan et. al.].

The latest trend in optical communication has been to use a DWDM system in the gain window of fiber amplifiers. Due to simultaneous transmission at very close wavelengths ($\Delta\lambda \sim 0.6$ nm) and high optical gain of optical fiber amplifiers, nonlinear effects like four wave mixing (FWM) impose serious limitations. If three signal frequencies (ω_1, ω_2 and ω_3) are propagating through a fiber then due to FWM new frequecies ω_4 are generated: $\omega_4 = \omega_1 \pm \omega_2 \pm \omega_3$

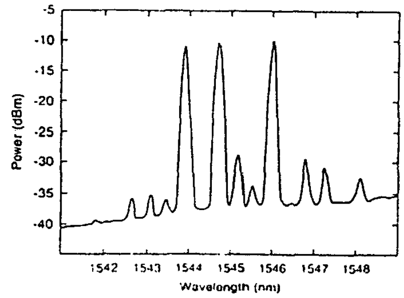


Fig. 5. Three input wavelengths producing new wavelengths by FWM. [After Tkach et. al. (1995).]

.Fig.5 illustrates this effect [10]. If any of the above frequencies i.e. $\omega_1 + \omega_2 - \omega_3$, coincides with one of the signal frequencies of the DWDM system, it will cause cross talk. The efficiency of FWM is maximum if the phase matching condition is satisfied: $\Delta\beta = \beta_4 + \beta_3 - \beta_2 - \beta_1 \cong 0$, i.e. if one operates at the zero dispersion wavelength λ_z of the fiber. To avoid FWM, one operates the DWDM system in the wavelength range slightly away from λ_z.

So one can use a CSF or a NDSF (nonzero dispersion shifted fiber) so that the λ_z is away from the transmission window and there is chromatic dispersion at wavelengths of transmission. This chromatic dispersion goes on accumulating with distance which can be compensated [11-12] by using a DCF. Ideally the dispersion slopes of the DCF and the transmission fiber should be so matched as to compensate the accumulated dispersion at all the wavelengths simultaneously. It requires a very careful design of the refractive index profile of the DCF. Some designs have already been proposed [13-16]. In Fig.6 we show the results of Palai et.al. [13], where the effective dispersion at all wavelengths between 1530 – 1560 nm remains between ± 1 ps/km. Lot of work is going on in various groups in this direction and better designs of DCF will evolve.

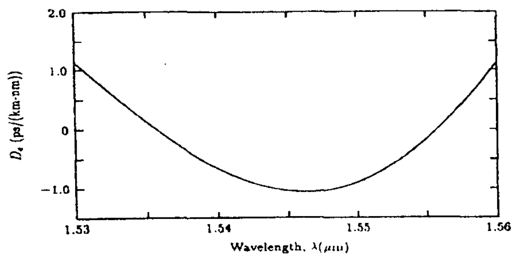


Fig. 6. Variation of the effective dispersion coefficeint of the link consisting of a 40 km of NDSF and 1.525 km of DCF. [Adapted from Palai et. al. (2001)].

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References

[1] H. Izadpanah, C. Lin, J.L. Gimlett, A.J. Antos, D.W. Hall and D.K. Smith,'Dispersion Compensation in 1330 nm optimized SMF using optical equalizer fiber, EDFA and 1310/1550 nm WDM', *Electron. Lett.* **28**, 1469, 1992.

[2] Ajoy Ghatak, K. Thyagarajan,'*Introduction to fiber optics*', Published by Cambridge University Press, U.K., 1998.

[3] C.D. Poole, J.M. Wlesenffold, D.J. Digiovanni and A.M. Vengsarkar,'Optical fiber based dispersion compensation using higher order modes near cut off', *J. Lightwave Tech.* **12**, 1746,1994.

[4] A.J. Antos and D.K. Smith,'Design and characterization of dispersion compensating fiber based on the LP01 mode', *J. Lightwave Tech.* **12**, 1739, 1994.

[5] D.W. Hawtof, G.E. Berkley and A.J. Antos,'High figure of merit dispersion compensating fiber', presented at the *Optical Fiber Commun. Conf.*, Washington, DC, paper PD-6, 1996.

[6] K. Thyagarajan, R.K. Varshney, P. Palai, A.K. Ghatak and I.C. Goyal,' A novel design for a dispersion compensating fiber', *IEEE Photon. Technol. Lett.* **8**, 1510, 1996.

[7] U. Peschel, T. Peschel and F. Lederer,'A compact device for highly efficient dispersion compensation in fiber transmission', *Appl. Phys. Lett.* **67**, 2111, 1995.

[8] A.M. Vengsarkar and W.A. Reed,'Dispersion compensating single-mode fiber: efficient designs for first and second order compensation', *Opt. Lett* **18**, 924, 1993.

[9] D.W. Howtoff,'High figure of merit dispersion compensating fiber', *Proc. OSA Conf. Optical Fiber Communication*, PD-6, 1996.

[10] R.W. Tkach, A.R. Chraplyvy, F. Forghieri, A.H. Gnauck and R.M. Deosier,'Four wave mixing and high speed WDM systems', *J. Lightwave Tech.* **13**, 841, 1995.

[11] H. Onaka, H. Miyata, G. Ishikawa, K. Otsuka, H. Ooi, S. Kinoshita, M. Seino, H. Nishimota and T. Chikama,'1.1 Tb/s WDM transmission over 150 km in 13 m zero dispersion single mode fiber', *Proc. OSA Conf. Optical Fiber Communication*, PD-19, 1996.

[12] N.S. Bergano and C.R. Davidson,'Wavelength division multiplexing in long-haul transmission systems',
J. Lightwave Tech. **14**, 1996.

[13] P. Palai, R.K. Varshney and K. Thyagarajan,'A dispersion flattening Dispersion Compensating Fiber Design for broadband dispersion compensation', *Fiber and Integrated Optics* **20**, 21, 2001.

[14] C.D. Poole, J.M. Wlesenffold, A.R. McDomick and K.T. Nelson,'Broadband dispersion compensation by using higher order spatial mode in two-core fiber', *Opt. Lett.* **17**, 985, 1992.

[15] T. Tsuda, Y. Akasaka, S. Sentsui, K. Aiso, Y. Suzuki and T. Kamiya, 'Broadband Dispersion slope compensation of dispersion shifted fiber using negative slope fiber', *ECOC'98*, 233.

[16] A. H. Gnauck, L.D. Garrett, Y. Danziger, U. Levy and M. Tur,'Dispersion and dispersion slope compensation of NZDSF for 40 Gb/s operation over the entire C band', *ECOC'96*, PD8, 191.