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Dispersion Management in Photonic Crystal Fibers

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Abstract: Optical fibers have low losses, enormous bandwidth, and capability to realize high speed transmission networks As the photonic crystal fibers offer high flexibility in its design they have attracted great interest in many research areas Recent studies and analysis showed that dispersion properties of PCF are expected to exhibit some unusual features and these will decide whether the PCF is potentially capable to be used in telecommunication and other related applications. In this paper we look upon these properties and its management.

1.Introduction

The optical fiber has been an ideal medium for transmitting large amount of data over very long distances for the last several decades because of their low losses, enormous bandwidth hand capability to realize high speed transmission networks After the evolution of PCF, it has shown its prospective as a high data rate, large information carrying capacity and suitable for long distance transmission medium[1]. Photonic crystal fibers are the periodic structures of air holes running along the fiber around a solid or hollow core and because of the design flexibility they have shown an enormous potential over conventional fibers in many application areas From the practical point of view, several feasibility studies need to be undertaken which include investigating its transmission characteristics and reliability over wide wavelength regions and comparing it with the existing technology of conventional fibers regarding applications and specifications matters required to replace the existing fibers revolutionary impact to the progress of the optical communications in the future.[4,5]

Polarization effects can have a huge impact on the operation of fiber-baseddevices and communication systems. In particular, polarization-mode dispersion can limit long distance high bit-rate data transmission.[4]

Hollow-core PCFs are well geometrically organized fibers with glass cladding incorporating arrays of air holes throughout its length. The core is formed by removing several unit cells of material from the cladding. In this structure cladding with holes is having a two dimensional photonic bandgap that can restrict and guide light to the core for wavelengths having a minimum-loss λ_c, even when the core is hollow and filled with air . In contrast, a conventional fiber light is propagated by TIR so its core must have a higher refractive index as compared with the cladding. Particularly soft glasses and polymers (plastics) can also be used in the fabrication of performs for photonic crystal fibers by extrusion . There is a great flexibility in designing and arranging the holes leading to PCFs with very unique and important properties. All these tailored fibers can be considered as specialty fibers.[1,2]

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2.Dispersion and Attenuation in PCF

The attenuation as low as about 0.15 dB/km in conventional fibers is observed by basic scattering and absorption processes in the high-purityglass which means that there are very less possibilities to further reduce it.But in case of HC-PCFsover 99 % of the light is propagated in air and avoid these loss mechanisms, making Hollow-core photonic crystal fibers bright and suitable nominee as future ultra-low loss telecommunication fibers. Although, the lowest loss determined in Hollow-core photonic crystal fibers is 1.7 dB/km, though we have since reduced this to 1.2 dB/km[1,4].So it is of utmost important to understand and analyze the primary limitations of this loss. As already mentioned that only a little fraction of the light propagates in silica, so the effect of material non-linearities is insignificant and the PCF do not suffer from the same limitations on loss as conventional fibers does.

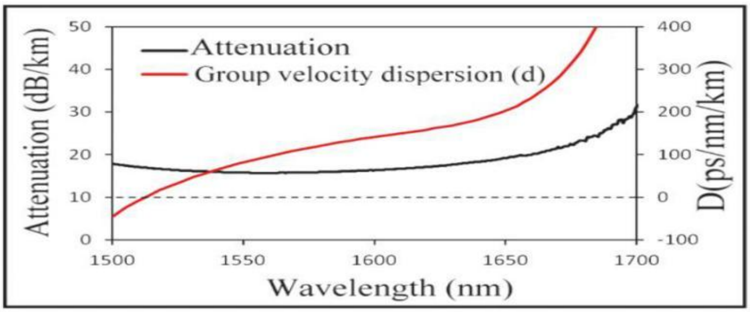

Figure 1 Attenuation and Dispersion curve as a function of wavelength

In the above figure 1 we have shown typical variation in attenuation and the dispersion as a function of wavelength.On the left vertical axis attenuation in db/km and on right vertical axis dispersion in ps/nm/km are shown.From this we can see that at a wavelength 1500 nm dispersion effect is minimum and it keep on increasing as we move towards right hand side and shows abrupt increase in dispersion at about 1665nm ,as can be seen by red curve.On the other hand attenuation factor is almost constant from 1500nm to1650nm but after that it shows slight increase, as can be seen by black curve. At around 1540nm wavelength, the attenuation and dispersion curve are intersecting. {4,5]

3.Dispersion Management

In a fiber-optic communication system, information is transmitted over a fiber by using a coded sequence of optical pulses whose width is determined by the bit rate B of the system. Dispersion-induced broadening of pulses is undesirable as it interferes with the detection process and leads to errors if the pulse spreads outside its allocated bit slot (T_B=1/B). Clearly, GVD limits the bit rate B for a fixed transmission distance L. The dispersion problem becomes quite critical when optical amplifiers are used to compensate for fiber losses because L can exceed thousands of kilometers for long-haul systems.[2,4]

A helpful measure of the information-transmission capacity is the bit rate–distance product BL. This section discusses how the BL product is controlled by fiber dispersion and how it can be improved by using the technique of dispersion management.

3.1 Dispersion-Induced Pulse Broadening

The effect of GVD on optical pulses transmitting in a linear dispersive medium are studied by setting γ□ = 0 in Eq1

$$\frac{i\,\partial A}{\partial Z} = -\frac{i\alpha A}{2} + \frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2} - \gamma|A|^2 A=0 \qquad (1)$$

If we define the normalized amplitude U((z;,T)) and U(((z;,T)) satisfies the following linear partial differential equation:

$$i\frac{\partial U}{\partial Z}=\frac{\beta_2}{2}\frac{\partial^2}{\partial T^2}U \qquad (2)$$

This equation is identical to the paraxial wave equation that administer diffraction of CW light and becomes one and the same when diffraction appears in only one transverse direction and β2 is replaced by $-\lambda/(2x3.14)$), where λ is the wavelength of light. For this cause, the dispersion-induced temporal effects have a close equivalence with the diffraction-induced spatial effects.

Equation (2) is readily solved by using the Fourier-transform method.

If Û((z;,T)) is the Fourier transform of U((z,T) such that

$$U((z,T)=\frac{1}{2\pi}\int_{-\infty}^{+\infty} \hat{U}(z,T)\exp(-i\omega T)\, d\omega \qquad (3)$$

then it satisfies an ordinary differential equation

$$i\,\frac{\partial \hat{U}}{\partial z}= -\frac{1}{2}\,\beta_2\,\omega^2\,\hat{U} \qquad (4)$$

Whose solution is given by

$$\hat{U}(z,\omega)= \hat{U}(0,\omega)\ \exp\left(\frac{i}{2}\ \beta_2\omega^2 z\right) \qquad (5)$$

Equation (5) shows that GVD modifies the phase of every spectral component of the pulse by an amount that bank on both the frequency and the propagated distance. Although such phase changes do not change the pulse spectrum, they can modify the pulse shape.By putting Eq. (5) in Eq.(3), the solution of Eq. (2) is given by

$$U((z,T) =\frac{1}{2\pi}\int_{-\infty}^{+\infty} \hat{U}(0,\omega)\ \exp\left(\frac{i}{2}\ \beta_2\omega^2 z-i\omega T\right) d\omega \qquad (6)$$

Where $\hat{U}(0,\omega)= \int_{-\infty}^{+\infty} \hat{U}(0,T)\exp(i\omega T)\, dT$ (7)

Equations (6) and (7) can be used for input pulses of arbitrary shapes

3.2 GVDInduced Limitations

Consider first the case in which pulse broadening is dominated by the large spectral width σ_ω of the source. For a Gaussian pulse, the broadening factor can be obtained). Assuming that the contribution of the β3 term is negligible together with C=0 and $V_\omega \gg 1$, the RMS pulse width σ is given by

$$\sigma = \left[\sigma_0{}^2 + \left(\beta_{2L\sigma_w}\right)^{\wedge}2\right]^{1/2} = \left[\sigma_0{}^2 + (DL\sigma_\lambda)^{\wedge}2\right]^{1/2} \quad (8)$$

where L is the fiber-link length and σ_λ is the RMS spectral width of the source in wavelength units.

One can relate σ to the bit rate B by using the criterion that the broadened pulse should remain confined to its own bit slot (TB=1/B)commonly used criterion is 4Bσ<TB ; for a Gaussian pulse, notably about 95% of the pulse energy remains within the bit slot when this condition is satisfied. The limiting bit rate is obtained using 4Bσ<1. Assuming, σ_0 « σ this condition becomes

$$BL|D|\sigma_\lambda<1/4 \quad (9)$$

As an illustration, consider the case of multimode semiconductor lasers for which σ_λ ≈2 nm. If the system is operating near λ =1.55μm using standard fibers, D≈16 ps/(km-nm). For a 100-km-long fiber, GVD reduce the bit rate to relatively low values of only 80 Mb/s. on the other hand, if the system is designed to operate near the zero-dispersion wavelength (occurring near 1.3 μm) such that |D|<j < 1 ps/(km-nm), the BL product increases to beyond 100 (Gb/s)-km[4].

3.3 Dispersion Compensation

Although operation at the zero-dispersion wavelength is most desirable from the standpoint of pulse widening, other examination may preclude such a design. For example, at most one channel can be located at the zero dispersion wavelength in a wavelength-division-multiplexed (WDM) system. Moreover, strong four-wave mixing occurring when GVD is relatively low forces WDM systems to operate away from the zero-dispersion wavelength so that each channel has a finite value of β_2. Of course, GVDinduced pulse broadening then becomes of serious concern. The technique of dispersion management provides a solution to this context. It comprise of combining fibers with different traits such that the average GVD of the entire fiber link is quite low while the GVD of each fiber section is chosen to be large enough to make the four-wave-mixing effects negligible[6,7]. As a general rule, a periodic dispersion map is used with a period equal to the amplifier spacing (typically 50–100 km). Amplifiers compensate for accumulated fiber losses in each section. Between each pair of amplifiers, just two kinds of fibers, with opposite signs of β_2, are combined to reduce the average dispersion to a small value. When the average GVD is set to zero, dispersion is totally compensated. Such a dispersion-compensation technique takes benefit of the linear nature of eq.2

The basic idea can be understood from Eq. (6) representing the general solution of Eq. (2). For a dispersion map consisting of two fiber segments, eq.(6) becomes the condition for dispersion compensation can be written as

$$D1L1 + +D2\ L2=0 \qquad (10)$$

Equation (10) can be satisfied in numerous different ways. If two segments are of equal lengths (L1=L2), the two fibers ought to have D1= -D2. Fibers with equal and opposite values of GVD can be made by shifting the zero dispersion wavelength appropriately at some stage in the manufacturing process. [8,9] However, a large quantity of standard fiber is already installed in existing lightwave systems. Because this fiber has anomalous GVD with D=16 ps/(km-nm), its dispersion can be compensated by the help of a relatively short segment of dispersion-compensating fiber (DCF), designed to have 'normal' GVD with values of D> -100 ps/(km-nm).

3.4 Compensation of Third-Order Dispersion

When the bit rate of a single channel exceeds 100 Gb/s, one must use ultra short pulses (width ∼1 ps) in each bit slot. For such short optical pulses, the pulse spectrum becomes broad enough that it is not easy to compensate GVD over the entire bandwidth of the pulse (because of the frequency dependence of β_2).

The simplest solution to this problem is provided by fibers, or other devices, designed such that both β_2 and β_3 are compensated simultaneously [2]. The necessary conditions for designing such fibers can be obtained. For a fiber link containing two different fibers of lengths L1 and L2,

the conditions for broadband dispersion compensation are given by

$$\beta_{21}L_1++\beta_{22}L_2=0 \quad \text{and} \quad \beta_{31}\ L_1++\beta_{32}\ L_2=0 \qquad (11)$$

where β_{2j} and β_{3j} are the GVD and TOD parameters for fiber of length Li((i=1;,2)). It is generally difficult to satisfy both conditions simultaneously over a wide wavelength range. However, for a 1-ps pulse, it is sufficient to satisfy Eq. (11) over a 4–5 nm bandwidth. This requirement is easily met for DCFs , especially designed with negative values of β_3 (sometimes called reverse-dispersion fibers). Fiber gratings, liquid-crystal modulators, and other devices can also be used for this purpose

$$\frac{\partial A}{\partial Z} + \beta_1 \frac{\partial A}{\partial Z} + \frac{i\beta 2}{2}\frac{\partial^2 A}{\partial t^2} = i\,\gamma |A|^2 A \qquad (12)$$

The parameters β_1 and β_2 include the effect of dispersion to first and second orders, respectively.

Equation (12) can be normalized in the form

$$i\frac{\partial u}{\partial z} - \frac{s}{2}\frac{\partial^2 u}{\partial \tau^2} \pm |u^2|\,u = 0 \qquad (13)$$

By using simple conversion

$$\tau = (t - \beta_1 Z) / T_0, \quad z = Z / L_D, \quad u = \sqrt{|\gamma| L_D} A \tag{14}$$

Where T_0 is pulse width and $L_D = T_0^2 / |\beta_2|$ is the dispersion length.

Using inverse scattering method reveals the solution of above mentioned equation has a form:-

$$u (z , \tau) = N * 2 / (e^{\tau} + e^{-\tau}) * \; e^{iz/2} = N \operatorname{sech}(\tau) \, e^{iz/2} \tag{15}$$

If N is integer, it represent the order of the soliton pulse.Very interesting situation comes when N=1.

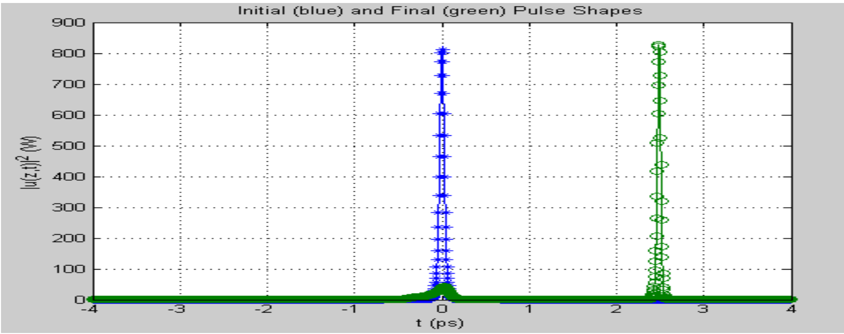

Figure 2 Pulse intensity versus propagation time

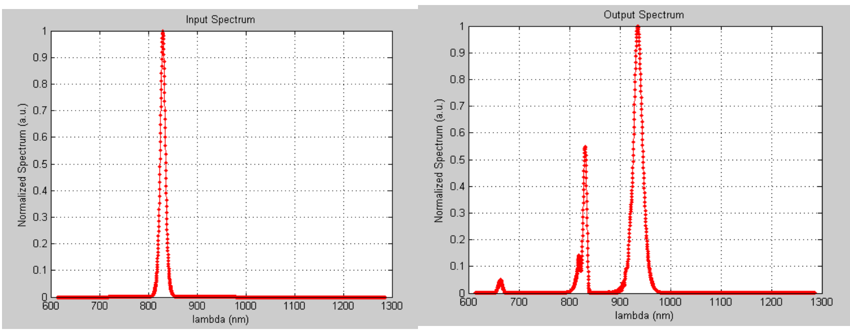

Figure: 3 Input Spectrum Vs. Output Spectrum

From figure 2 we see that pulse shape remains almost constant as it is propagated through the fiber This is how this light pulse maintain its shape and manage the ill effects of dispersion and non linearity in PCF.Same thing can be seen in figure 3,where we compare input and output spectrum as a function of wavelength .By seeing the solitonic behavior there is a fascinating expectation of using the PCFs as dispersion compensating or dispersion managed fibers for optical communication systems.

Result and conclusions

From the above discussion it is clear that the dispersion effects can be managed by the solitonic behaviour of these fibers for the light pulse and these fibers have a strong character and possibility to behave as dispersion compensating elements in various applications in optical fiber communication

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