DISPERSION MODELLING OF MICRO STRUCTURED OPTICAL FIBRES FOR TELECOMMUNICATIONS DEPLOYMENT

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ABSTRACT

Chromatic dispersion is a critical issue in the design of optical fibers due to pulse spreading. It is related to the variation in group velocity of optical signals in a fiber. The term "chromatic" emphasizes its wavelength dependent nature. Chromatic dispersion limits the maximum distance, to which a pulse can be transmitted without the necessity of regeneration of its shape, timing, and amplitude. Pulse broadening can deteriorate performance of a high bit rate systems. Hence it is essential to either prevent the occurrence of dispersion or provide adequate compensation for it. In this regard Micro structured optical fibers [MOFs] or Photonic Crystal Fibers (PCF) or Holy Fibers [HFs] display tailor able unique dispersion properties in comparison to conventional silica optical fibers. This paper presents a systematic study of dispersion properties of PCFs along with its dependence on structure and material used. An overview of current innovations on this issue also is mentioned.

Keywords**:** *PCF,MOF, Group velocity, dispersion, chromatic*

I. INTRODUCTION

PCFs are characterized by the refractive index periodicity, with the arrangement of air holes around the core. The core acting as a defect and guiding and confining light can be either solid or another hole. Many rings around the core help to trap light well inside the core minimizing the confinement loss.

Based on structure PCFs can be either a] solid core high-index guiding fibres or b] hollow core low-index guiding fibers. The Index Guiding PCF guides light in a solid core by Modified Total Internal Reflection (M-TIR) similar to the conventional optical fibers. The solid core can be silica and the lower effective index material is provided by air holes in the cladding.

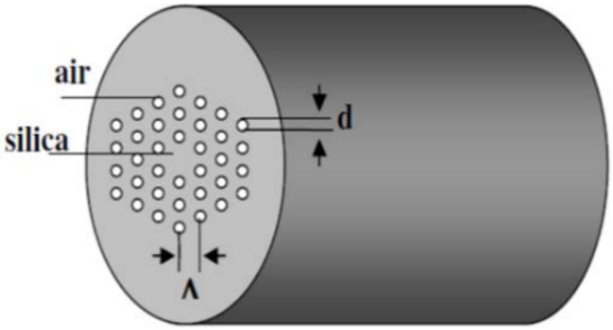

Fig.1 PCF cross section d- dia of hole & - pitch

Hollow Core Photonic Crystal Fiber guides light by the Photonic Band Gap (PBG) effect. Light is confined in the low-index core, as the distribution of energy levels in the structure makes the propagation in the cladding region impossible.

II. NOVEL PROPERTIES ACHIEVABLE IN PHOTONIC CRYSTAL FIBERS

For a simplified analysis the effective index of a PCF fiber can be modeled as that of a standard step-index fiber, with a high-index core and a low-index cladding. However it is to be noted that the refractive index of a micro structured cladding in PCFs is wavelength dependent. Hence PCFs can be designed with a new set of remarkable features like a] endlessly single mode [ESM] PCF and b] unusual spectral characteristics.

III. ENGINEERING OF CHROMATIC DISPERSION IN PCFS

Chromatic dispersion consists of two components. The first one comes from bulk material dispersion Dmat. The second one comes from waveguide dispersion Dw. The material and the waveguide dispersion are expressed as given below.

$$D_{\mathrm{mat}} = -\frac{\lambda}{c}\frac{d^2 n_m}{d\lambda^2} \tag{1}$$

$$D_w = -\frac{\lambda}{c}\frac{d^2\left[\mathrm{Re}\, n_{eff}\left|n_{m[\lambda]=const}\right|\right]}{d\lambda^2} \tag{2}$$

The dispersion slope is expressed as

$$S_0[\lambda] = \frac{dD}{d\lambda} \tag{3}$$

Where c is the speed of light, Re (n_{eff}) is the real part of the effective index and n_m is dependent on λ in dispersive media. In the case when $n_{m[\lambda]}$ = const., material dispersion is neglected.

Fig2 shows the dispersion components of conventional silica fibres in the wavelengths range of interest. When the chromatic dispersion coefficient is less than zero, the dispersion regime is said to be anomalous. The shorter wavelengths propagate faster than longer wavelengths. The pulse is said to be negatively chirped. When dispersion coefficient is greater than zero, the dispersion regime is said to be normal. Long waves are guided faster than the short ones.

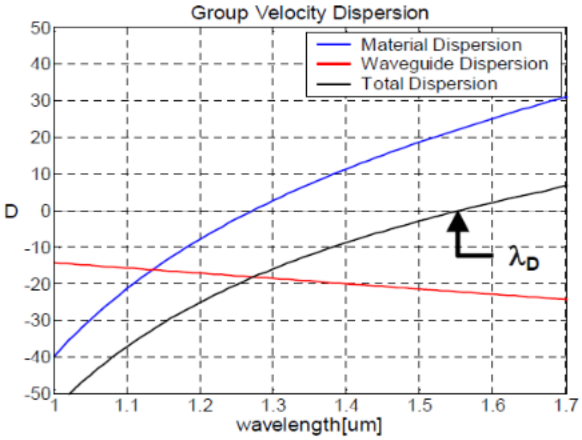

Fig 2. Total dispersion and dispersion shifting in conventional silica fibres

As the waveguide dispersion can be anomalous and material dispersion normal, optimal dispersion design can be achieved balancing dispersion components. Hence with a proper design it is possible to have a zero dispersion wavelength [ZDW]. Beyond this, the fiber exhibits a region of anomalous dispersion.

In order to obtain a specific value of total dispersion, one must compensate material dispersion D_{mat} with waveguide dispersion D_w. The slope of D_w should be adjusted by optimizing the fiber's geometry in order to make it parallel to –Dmat. To obtain a flattened dispersion over a desired wavelength interval, one must control D_w to make it follow a path parallel to that of –Dmat.

PCFs are highly flexible for engineering and/or tailoring dispersion. This mainly arises from the highly controllable waveguide dispersion. In conventional fibres the parameters to be adjusted are limited. For PCFs, however, there are many degrees of freedom. By adjusting the size of the hole-to-hole pitch, Λ , and the hole diameter, *d*, one can control the air filling ratio easily to change the core-cladding index difference and the core size so that desired dispersion is achieved. In addition the option of infiltrating the holes with suitable liquids also is available.

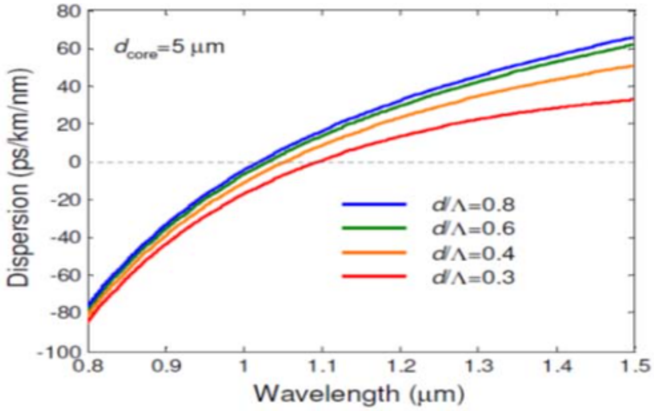

Fig 3. Calculated GVD for fixed core dia D and different d/Λ ratio

The Fig 3 shows that the zero-dispersion wavelength (ZDW) of a PCF can be shifted to shorter than 1.27μm, the ZDW of bulk silica. When the holes get bigger, the ZDW gets shifted to further shorter wavelengths. The ZDW shift is due to the large waveguide dispersion contribution to the total group velocity dispersion [GVD]. Large air holes increase the core-cladding index step resulting in a large anomalous waveguide dispersion, which can cancel the normal material dispersion at $\lambda <$ 1:27μm or even overcome it to yield anomalous net dispersion there. However, the ZDW shift becomes slower with the increasing of *d/λ*. If we want to shift the ZDW of PCFs to even

shorter wavelengths, we need to consider altering the fibre core diameter.

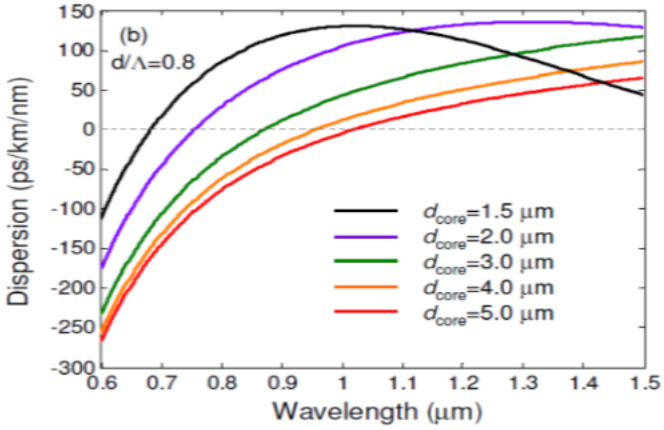

Fig 4. Calculated GVD for fixed d/Λ and different core dia

In order to study how the GVD of PCFs varies with the fibre core diameter *d*core, the GVD curves of the fundamental mode are calculated for PCFs with different core diameters but having a fixed *d/Λ* and plotted in Fig.4. It can be seen that when *d/Λ* is fixed, decreasing *d*core can also shift the ZDW to shorter wavelengths. This is because when fibre core becomes smaller whilst core-cladding index difference keeps constant, the V_{eff} [normalized frequency] will be smaller. As a result, the fibre mode will expand more into the cladding. This will lead to large anomalous waveguide dispersion at $\lambda <$ 1:27 μm as well. However, when *d/Λ* is not very big, d/Λ =0.4, for example, simply decreasing *d*core cannot shift the ZDW further once *d*core < 3μm. Instead, a second ZDW appears at a longer wavelength. If we want to achieve an even shorter ZDW, we need to increase d/Λ when decreasing *d*core. Figure also shows that the ZDW can be as short as 680 nm when $d/\Lambda = 0{:}8$ and *d*core =1.5μm. Such PCFs with high d/Λ and small *d*core are normally used for nonlinear applications.

III. DISPERSION COMPENSATING FIBERS

Zero dispersion is useful for low-speed systems, but undesirable in high data rate communications systems, as the phase match of all the frequency components can result in certain nonlinear effects. Another method of keeping a constant pulse width is to retain small normal dispersion in optical fibers and compensate it by using Dispersion Compensation Fiber (DCF) with strong anomalous dispersion, added at signal repeater.

Dispersion compensating fiber is used to nullify the dispersion caused by that fiber. The terms of broadband dispersion compensation,

$$DSMF.LSMF + DDCF.LDCF = DT \qquad (4)$$

Where *DSMF*, *DDCF*, *LSMF*, and *LDCF* are, respectively, the dispersion coefficients and the lengths of the single-mode and the dispersion compensating fibers. If the total compensation of the dispersion is required, the length of the DCFs *LDCF* is chosen so that total residual dispersion *DT =0*. However, due to nonlinear effects and possible chirp in transmitter, full compensation is not always optimum.

For multichannel high-speed WDM systems, dispersion compensation over a broad wavelength range is necessary. This means that besides the dispersion, it is also necessary to compensate for the dispersion slope. The total dispersion slope is

$$S_{slope} = SSMF.LSMF + SDMF.LDCF \qquad (5)$$

Where *SSMF*, *SDCF* are the dispersion slopes of the SMFs and the DCFs respectively. As seen from Eq. (5), a negative dispersion slope of the DCFs is necessary in order to achieve slope compensation (Sslope = 0). If the length of the DCFs is chosen to give full compensation (*Dres* =0), then the condition for full slope compensation is that the relative dispersion slope (RDS) of the DCFs shall be equal to the relative dispersion slope of the standard SMFs

$$RDSDCF = RDSSMF \qquad (6)$$

The relative dispersion slope is defined as the ratio of dispersion slope to dispersion

$$RDS = S/D \qquad (7)$$

Again from Eq. (6) and Eq. (7), we can write

$$SSMF / DSMF = SDCF / DDCF \qquad (8)$$

It is noticed that RDS value of standard SMFs is about 0.0036 nm^{-1} at 1.55 μm.

Various techniques have been reported for dispersion compensation like[a] Dual core fibres [b] Ge doped core [c] Erbium doped fibre [d] central defected core etc. PCFs can offer solutions without doping as well.

Fig 5 depicts the transverse cross-section of typical DC-PCFs which contains six air-hole rings. The material of the studied PCF is taken to be silica. The cladding is formed by a triangular-lattice of air holes. It has a pitch Λ, two types of air hole diameters d_1 and d_2. In the proposed structure, the diameter of the first air-hole ring d_{1i} *is less* ($d_2 > d1$) to obtain large negative dispersion. The diameter of other air hole rings d_2 is selected large for keeping low confinement loss level in the targeted region. The total number of air-hole rings is chosen to be six in order to simplify as much as possible the structural composition of the PCF.

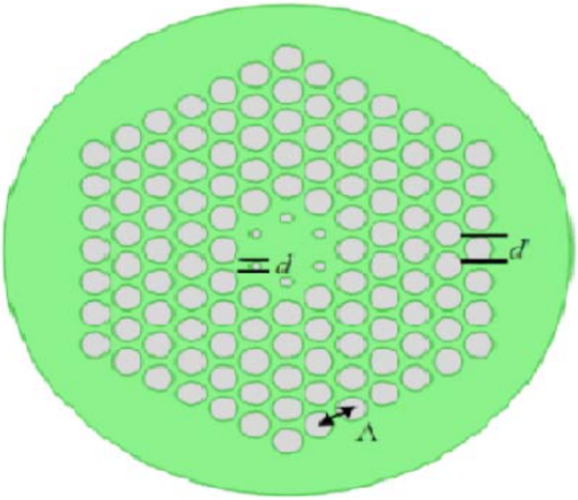

Fig 5. Cross section of a typical DC PCF

IV. DISPERSION FLATTENED PHOTONIC CRYSTAL FIBERS

The narrow bandwidth of operating wavelengths is a limitation, in particular for WDM systems. Broadband telecommunications systems demand same minimum dispersion over a large range. Dispersion flattened PCFs meet this condition. It is established now that an ultra-flattened dispersion curve could be achieved by a] modifying the form of the hole into ellipse, or b] gradually increasing the diameter of the hole from inner ring to the outer, c] selectively filling the PCF with liquids d] application of double cladding , etc. Combinations of one or more of these techniques also provide desired variation. These techniques besides reducing or flattening the dispersion help to reduce confinement loss also.

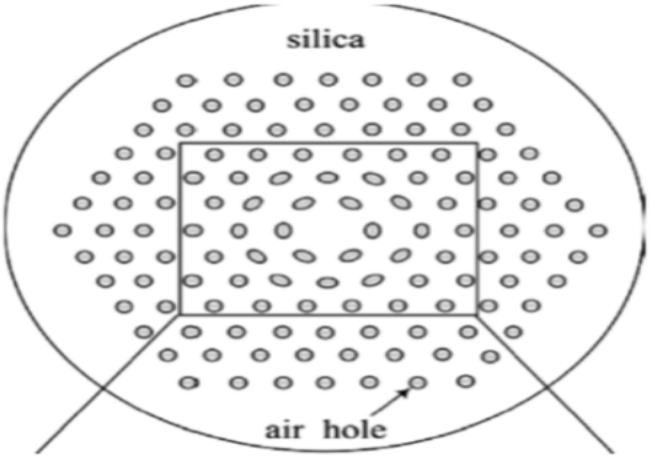

Fig.6. Cross section of PCF with elliptical holes

A typical optimized design of a PCF for example can be made over ultra-wide band by replacing two rings of inner circular air holes with elliptical air holes. In index guiding PCF, the holes closer to the core have a stronger impact on dispersion. However their effect on confinement loss is quite negligible.

A lower ratio of d/Λ in the cladding reduces the dispersion and its slope, therefore in this design the holes of the inner rings are chosen to be smaller. On the other hand, increasing the d/Λ results in reduction of the confinement loss, hence the choice of larger diameter for the holes in outer rings.

The permitted dispersion fluctuation is 0.6–1.0 ps/nm/km within a broad band from 1000 nm to 1900 nm, covering S, C, and L bands. The design process requires high attention to all important parameters such as flattened chromatic dispersion curve, effective mode area, confinement loss over broad bandwidth. In addition, designers should keep in mind the complexity of fabricating new structure.

V. ENHANCING THE DISPERSION PROPERTIES

(a) Doped cores can be used to enhance dispersion properties of IGPCF. The technique isbased on doping of the central part of the SiO2 core by the GeO2 material. The germanium dioxide raises the refractive index of the doped region and hence modifies the waveguide properties of the PCF.

(b) Fibers can be filled with appropriate liquids also for tailoring and tuning dispersion. For example fibres can be filled with CCl4 or toluene, or nitrobenzene, or CS2 etc. The guiding mechanism is the modified total internal reflection because the refractive index of CCl4 (n = 1.4503 at a wavelength of 1.03μm] and of toluene, nitrobenzene, or CS2 is slightly higher than that of fused silica (n = 1.4497 at a wavelength of 1.03μm). The filled liquid strand acts as the core and the surrounding photonic structure as the cladding. Even for chloroform with a refractive index marginally below the refractive index of fused silica (n = 1.4365 at a wavelength of 1.03μm] guiding is preserved in this structure because of the high air filling fraction in the cladding. This reduces the effective refractive index of the holey region to close to one. Guiding is therefore possible due to modified internal reflection for all kinds of liquids.

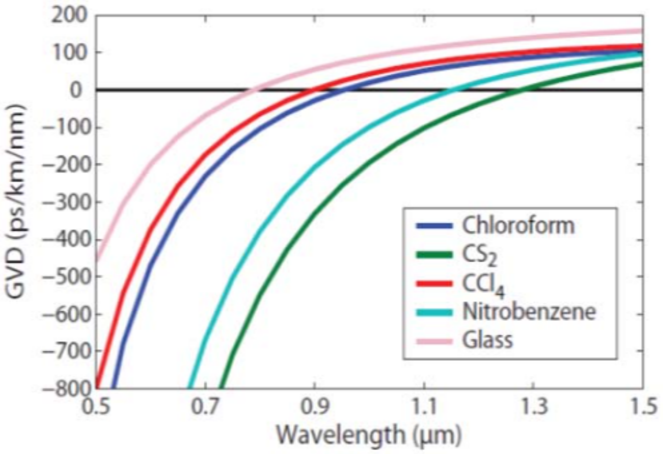

Fig 7. GVD of fibre filled with different liquids

By changing the filled strand medium or the geometry of the fiber, the dispersion properties of the fiber device can be tailored. If an additional temperature change or mixtures of different liquids are allowed, another degree of freedom is added to engineer the dispersion properties almost continuously. Just by replacing the liquid in a single filled strand of a typical PCF one can shift the ZDW from 900nm for CCl4 to 1300nm for CS2 over almost 400 nm. The dispersion curves for different liquids inside the PCF chosen are plotted in Fig 7

(c) Despite excellent physical and optical properties silica has [a] low nonlinearity and [b] strong absorption features in mid IR region [beyond 2 μm].

Hence there is a need to develop alternate materials to overcome these shortcomings.

Chalcogenide glasses [As_2S_3] based on Sulphur, Selenium, Tellurium and the addition of other elements such as Arsenic, Germanium, Antimony, and Gallium. They are well known for their large infrared transmission window as well as for their large non linearity besides relatively higher refractive index. It has been demonstrated that As_2S_3 glass PCF provides much higher negative dispersion compared to silica PCF of the same structure, in wavelength range 1.25 –1.6μm and hence such PCFs have high potential to be used as a dispersion compensating fiber in optical communication systems.

Similarly tellurium dioxide [TiO_2] based family of glasses collectively known as tellurites also have high non linearity and optical transmission up to as high as 5μm. However, the dispersion of tellurite holey fiber is difficult to tailor because of the difficulties in fabrication. Tellurite glass shows a low viscosity at the fiber drawing temperature. Moreover the viscosity decreases sharply with increasing temperature. Tellurite holey fiber with a complex microstructure could be subject to heavy deformation during fabrication process. So far most tellurite highly nonlinear holey fibers just have a simple structure with just one ring, which results in an unflattened dispersion.

Since the holey structure is simple, to improve the flexibility in tailoring dispersion, two [or more at times] kinds of composite tellurite glasses which have different refractive-indices are used. By using such structure the dispersion is engineered to be the most flattened for the highly nonlinear soft glass fibre within 1.5-1.6μm.

The Chalcogenide and tellurite fibres have a] high linear and nonlinear refractive index b] high transparency from near to mid infrared region c] low photon energy and d] higher rare earth solubility. Hence these materials are very attractive for short active new fibre devices, for mid infrared transmission and many non linear applications involving all futuristic optical signal processing. Low Interaction length, low power levels and low dispersion are the key requirements in all optical signal processing. Tailoring tellurites to zero dispersion is an issue. Hence current trend is to use the combination of Chalcogenide and tellurites with the former making the core and the later the cladding.

VI. CONCLUSION

Various design and methods to tailor dispersion in the telecommunication window for PCFs were discussed in this paper. The effects of core and pitch sizes and liquid infiltration are mentioned. The current developments of using materials other than silica also detailed. PCF structure thus we see is very suitable to achieve suitable zero dispersion, flattened dispersion and even to provide negative dispersion for compensation.

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