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PHOTONIC CRYSTAL AND PHOTONIC CRYSTAL FIBERS COMMUNICATIONS

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Abstract

The development of all optical communications could benefit from the index guiding photonic crystal fibers. In communication the photonic crystal fibers could provide many new solutions. Conventional optical fibers have within the last decades revolutionized the communications industry and it is today a mature technology being pushed to its limit with respect to properties such as losses, single mode operation and dispersion. The spectra have been used by others to develop optical frequency standards. The process can potentially be used for frequency conversion in fiber optic network. In this system the dispersive properties can be controlled by the optical lattice making it possible to achieve phase-matched four wave mixing, like look the process taking place in the photonic crystal fibers. In this paper we will discuss the use of photonic crystal fibers in communications.

Keywords: photonic crystal, communications, propagation, dispersion, photonic crystal fibers.

1. Introduction

A new class of microstructured optical fiber containing a fine array of air holes running longitudinally down the fiber cladding [1] has been developed. Since the microstructure within the fiber is often highly periodic due to the fabrication process, these fibers are usually referred to as photonic crystal fibers (PCFs), or sometimes just as holey fibers [2]. Whereas in conventional optical fibers electromagnetic modes are guided by total internal reflection in the core region, which has a slightly raised refractive index, in PCFs two distinct guidance mechanisms arise. Furthermore, the existence of two different guidance mechanisms makes PCFs versatile in their range of potential applications. For example, PCFs have been used to realize various optical components and devices including long period gratings [3], multimode interference power splitters [4], tunable coupled cavity fiber lasers [5], fiber amplifiers [6], multichannel add/ drop filters [7], wavelength converters [8] and wavelength demultiplexers [9]. As with conventional optical fibers, however, a crucial issue with PCFs has been the reduction in overall transmission losses which were initially several hundred decibels per kilometer even with the most straightforward designs. Increased control over the homogeneity of the fiber structures together with the use of highly purified silicon as the base material has now lowered these losses to a level of a very few decibels per kilometer for most PCF types, with a loss of just 0.3 dB km1 at 1.55m for a 100 km span being recently reported [10]. Before 1970, optical fibers were used mainly for medical imaging over short distances [11]. Their use for communication purposes was considered impractical because of high losses (1000 dB/km). However, the situation changed drastically in 1970 when, following an earlier suggestion [12], the loss of optical fibers was reduced to below 20 dB/km [13]. Further progress resulted by 1979 in a loss of only 0.2 dB/km near the 1.55-μm spectral region [14]. The availability of low-loss fibers led to a revolution in the field of lightwave technology and started the era of fiber-optic communications. Several books devoted entirely to optical fibers cover numerous advances made in their design and understanding [15].In 1987, Yablonovitch and John - by using the tools of classical electromagnetism and solid-state physics - introduced the concepts of omnidirectional photonic bandgaps in two and three dimensions [16]. From then, the name "photonic crystal" was created and led to many subsequent developments in their fabrication, theory, and application. A few years later in 1991, Yablonovitch and co-workers produced the first photonic crystal by mechanically drilling holes a millimeter in diameter into a block of material with a refractive index of 3.6 [17].

2. The objective of the paper

The photonic crystal fibers offer the possibility of low losses and dispersion, a possible competitor to conventional fibers. These fibers are based on a new and very promising technology and could provide solutions to many optical problems in communications, light source manufacturing and has already revolutionized the field of frequency metrology. The propagation of light in a Photonic crystal fibers provides an opportunity to reduce the Kerer effect and thus worry attenuation of the signal. Photonic crystal fibers present special properties that lead to an outstanding potential for sensing applications according to these features we can elimination a lot of the problems that exist in the conventional fiber optic communications and getting better and more accurate results in the same conditions when using this Fibers.

3. Optical fiber communication system

An optical fiber communication system is similar in basic concept to any type of communication system. A block schematic of a general communication system is shown in **Fig. 1,** the function of which is to convey the signal from the information over the transmission medium (photonic crystal fiber) to the destination. The communication system is consists of a transmitter, the transmission medium, and a receiver or demodulator at the destination point. For optical fiber communications the information source provides an electrical signal to a transmitter comprising an electrical stage which drives an optical source to give modulation of the light wave carrier. The optical source which provides the electrical–optical conversion may be either a semiconductor IR. The transmission medium consists of an photonic crystal fiber and the receiver consists of an optical detector which drives a further electrical stage and hence provides demodulation of the optical carrier. Photodiodes in some instances, phototransistors and photoconductors are utilized for the detection of the optical signal and the optical–electrical conversion. Thus there is a requirement for electrical interfacing at either end of the optical link and at present the signal processing is usually performed electrically.

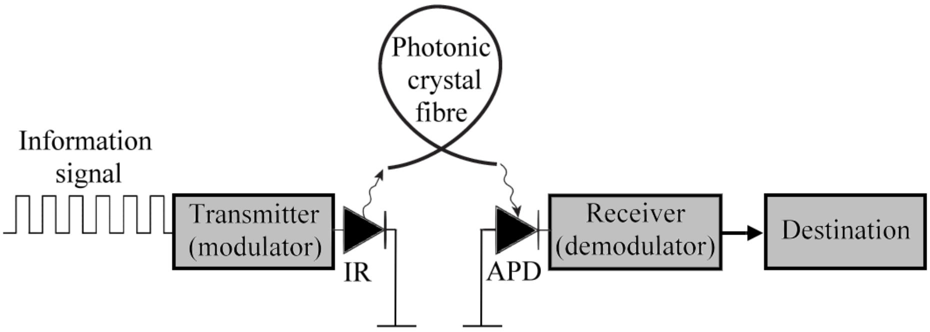

Fig. 1. General communication system

4. Photonic crystal (PhCs)

Photonic crystals (PhCs) are inhomogeneous dielectric media with periodic variation of the refractive index. In general, (PhCs) have a photonic band gap. That is the range of frequencies in which light cannot propagate through the structure. (PhCs) are optical media with spatially periodic properties. This definition is too general to be useful in all contexts, and there has been some debate about the conditions under which it is legitimate to use the term [18]. Photonic crystals are periodic structures of dielectric materials and can today be produced with almost any imaginable structure. It is only a decade ago that Bose-Einstein condensation was first achieved in alkali gases [19, 20] and it has certainly turned into a very rich field since the condensates are very flexible model systems for solid state physics and statistical physics in general. The dynamics of the wave propagation in both systems is mainly determined by the interplay between dispersive and nonlinear effects. In the Bose-Einstein condensates (BECs) the nonlinear response originates in the s-wave scattering between atom pairs, whereas the nonlinearity in the PCFs stems from saturation and optical pumping accounted for through a nonlinear susceptibility. The micro-structuring of the PCFs leads to unique and tailorable dispersive properties. In the Bose-Einstein condensed system the optical lattice does the job of tuning the dispersion.

5. Photonic crystal fibres

Photonic-crystal fibres (PCFs) [21, 22], also referred to as microstructure, or holey, fibres, are optical waveguides of a new type. In PCFs, radiation can be transmitted through hollow core see **Fig. 2,** surrounded with a microstructured cladding, consisting of an array of cylindrical air holes running along the fibre axis. Such a microstructure is usually fabricated by drawing a perform composed of capillary tubes and solid silica rods.

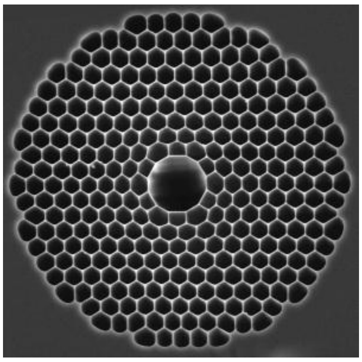

Fig. 2. Cross-section of photonic-crystal fibres

Along with conventional waveguide regimes, provided by total internal reflection, PCFs under certain conditions can support guided modes of electromagnetic radiation due to the high reflectivity of their cladding within photonic band-gaps (PBGs) or regions of low densities of photonic states [23, 24], as well as by the antiresonance mechanism of waveguiding [22, 25]. Such regimes can be supported by fibres with a hollow [24, 26, 27] core and a two-dimensionally periodic (photonic crystal) cladding. A high reflectivity provided by the PBGs in the transmission of such a cladding confines radiation in a hollow core, substantially reducing the loss, which is typical of hollow-core-guided modes in conventional, capillary-type hollow waveguides and which rapidly grow with a decrease in the diameter of the hollow core [28, 29]. Unique properties of PCFs open up new routes for a long-distance transmission of electromagnetic radiation [21, 22], as well as for nonlinear-optical transformation of laser pulses [30]. Photonic-crystal fibres offer new solutions for laser physics, nonlinear optics, and optical technologies, as they combine dispersion tuneability and a high degree of light-field confinement in the fibre core. The maximum laser fluence in an optical system is limited by the laser damage of material of optical components. An increase in a fibre cross section is a standard strategy for increasing the energy of laser pulses delivered by fibre lasers. Standard large-core-area fibres are, however, multimode, making it difficult to achieve a high quality of the transverse beam profile. This difficulty can be resolved by using PCFs with small-diameter air holes in the cladding, which filter out high-order waveguide modes [31, 32]. Hollow PCF compressors in fibre-laser systems [33, 34] allow the generation of output light pulses with a pulse width on the order of 100 fs in the megawatt range of peak powers. Thus, PCFs play the key role in the development of novel fibre-laser sources of ultrashort light pulses and creation of fibre-format components for the control of such pulses. In what follows, we examine the physical mechanisms behind supercontinuum generation in such fibres, analyze various scenarios of spectral broadening and wavelength conversion, and discuss applications of PCF white-light sources and frequency converters in nonlinear spectroscopy and microscopy, as well as in optical metrology.

6. Attenuation of photonic crystal fibres

If the transverse scale of a photonic crystal fibres changes without otherwise changing the fibre's structure, the wavelength λ_c of minimum attenuation must scale in proportion [35]. Without recourse to the approximations of the previous section, the mean square amplitude of the roughness component that couples light into modes with effective indices between n and $n+\delta n$ is:

$$u^2 = \frac{k_B T}{4\pi\gamma(n-n_0)} \coth\left(\frac{(n-n_0)kW}{2}\right)\delta n, \qquad (1)$$

where

γ – the surface tension;

k_B – Boltzmann's constant;

T – the temperature.

The attenuation to these modes is proportional to u^2 [36] but the only other independent length scale it can vary with is λ_c. As attenuation has units of inverse length, it must therefore by dimensional analysis be inversely proportional to the cube of λ_c. If this is true for every set of destination modes, it must be true for the net attenuation α to all destination modes, so:

$$\alpha(\lambda_c) \approx \frac{1}{\lambda_c^3}. \tag{2}$$

This equation [35], predicts the attenuation of a given fibre drawn to operate at different wavelengths. The result differs from the familiar 1/ λ^4 dependence of Rayleigh scattering in bulk media [37], and importantly applies to inhomogeneities at all length scales not just those small compared to λ. The fibres had 7-cell cores but were drawn to different scales, giving them different λ_c but otherwise comparable properties [35]. The minimum attenuation is plotted in **Fig. 3** against λ_c on a log-log scale. A straight-line fit is shown and has a slope of 3.07, supporting the predicted inverse cubic dependence in Eq. (2).

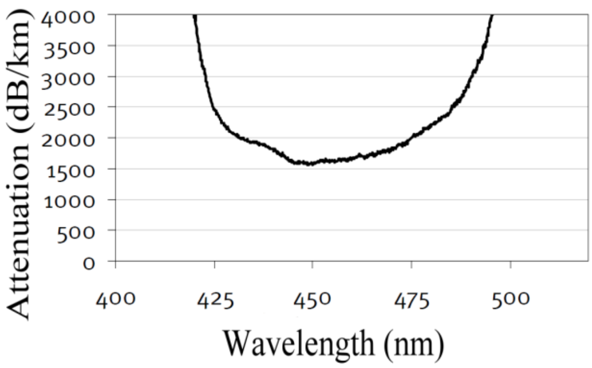

Fig. 3. Attenuation spectrum of a photonic crystal fibre

The minimum optical attenuation of ~0.15 dB/km in conventional fibres is determined by fundamental scattering and absorption processes in the high-purity glass [37], leaving little prospect of much improvement. Over 99 % of the light in (PCFs) can propagate in air [35] and avoid these loss mechanisms, making (PCFs) promising candidates as future ultra-low loss communication fibres. The lowest loss reported in photonic crystal fibres is 1.7 dB/km [35], though we have since reduced this to 1.2dB/km. Since only a small fraction of the light propagates in silica, the effect of material nonlinearities is insignificant and the fibers do not suffer from the same limitations on loss as conventional fibers made from solid material alone.

7. Dispersion of photonic crystal fibres

In a homogeneous medium the dispersion relation between wave vector *k* and frequency ω of the propagating light is given through the refractive index of the material $\omega=c|k|/n$. In a PCF it is the combined effect of the material dispersion and the band structure arising from the 2D photonic crystal that determines the dispersion characteristics of the fiber. For propagation in fibers it is the dispersion for the wave vector component along the z-direction *kz* that is the interesting parameter. In the fiber optics literature *kz* is referred to as the propagation constant β. It is then reasonable to define an effective refractive index as

$$n_{eff} = \frac{\beta c}{\omega_{fund}}, \tag{3}$$

where ω_{fund}. denotes the frequencies of the lowest lying mode in the fiber. The higher derivatives of the propagation constant are given as

$$\beta_n(\omega) = \frac{\partial^n \beta}{\partial \omega^n}, \quad (4)$$

and the second order dispersion $D = -\frac{2\pi c}{\lambda^2}\beta_2$ is just another way of expressing β_2. The zero-dispersion wavelength (λ_{ZD}) is defined as the free space wavelength $\lambda = \frac{2\pi c}{\omega}$ where $\beta_2 = 0$.

A cross-section of an index guiding PCF is shown in Fig.(4) a calculation of the dispersion properties and effective area of this fiber will be sketched. The dispersion given by $\beta_2(\lambda)$ is shown in **Fig. 4** and the fiber has λ_{ZD} = 721 nm, whereas the zero dispersion wavelength for bulk silica is found around 1300 nm.

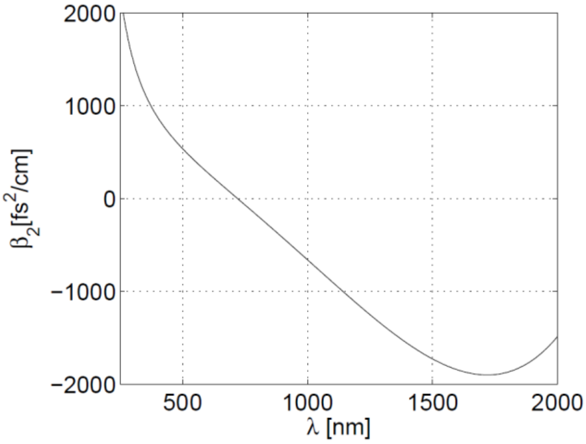

Fig. 4. Dispersion characteristics for the fundamental frequency mode of the 1.7μm core diameter PCF

The zero dispersion wavelength for this fiber has consequently been shifted into the visible regime due to the micro-structuring. This widely tunable group velocity dispersion is an extremely valuable property of the PCFs. The dispersion can be tuned by a proper choice of the size of the air holes, the distance between the holes (pitch) and the size of the central defect. A general tendency is that the zero dispersion wavelength is found at a shorter wavelength when the fraction of air filling is increased and the central defect is decreased [38]. It is possible to manufacture fibers with zero dispersion wavelengths between 500 and 1500 nm. Another general trend is that decreasing either the pitch or the hole-size leads to a higher curvature of the dispersion profile, eventually leading to two closely lying zero dispersion wavelengths. The fibers can be made with cores down to 1μm in diameter. Due to the small core areas huge intensities can be obtained in the cores of the fibers. Consequently, such fibers will exhibit a highly nonlinear response. Another very useful property of the fibers is that they can be made endlessly single mode. Only one mode should have a propagation constant between the effective propagation constants for the cladding and the core i.e. $n_{core}k > \beta > n_{clad}k$, where k is the free space propagation constant. The restriction corresponds to only one solution to Maxwell's equations propagating in the core and evanescent in the cladding. The effective frequency parameter is given by [39]

$$V_{eff} = \left(\frac{2\pi\rho}{\lambda}\right)\sqrt{n_{core}^2 - n_{clad}^2}, \quad (5)$$

where ρ is the core radius. For the fiber to be single mode Veff should be below 2.405. As λ decreases, the effective index of the cladding n_{clad} increases, because more intensity of the light will be confined to the silica part of the cladding. Consequently, Veff can be kept below 2.405 for a

wide range of wavelengths and the fiber is said to be endlessly single mode. In this way fibers, even with a very large core, can be made endlessly single mode [40]. As the mode area of the fiber increases the relative intensity in the core will decrease. Hence the fibers can be used for linear propagation, where a lot of power can be delivered without going into a nonlinear propagation regime.

8. Nonlinear effects

As mentioned, Eq. (6)

$$\frac{d}{dz}\tilde{A}(\omega_1) = i(\beta(\omega)-\beta_1\omega)\tilde{A}(\omega_1)+i\gamma(\omega\int_{-\infty}^{\infty} dte^{i\omega_1 t}A(t)\times\int_{-\infty}^{\infty} dt_1\ \ g(t-t_1)\,|\,A(t_1)\,|^2, \quad (6)$$

can be implemented directly as it is including both full frequency dependency of the propagation constant and the effective area as well as self-steepening and Raman effects.

8. 1. Raman response

For the Raman response function the expression $g(t) = (1- fR)\delta(t) + f_R g_R(t)$ has been used, where the delta function term originates from the electronic response i.e. the Kerr interaction and the last term takes the Raman scattering into account. The function $g_R(t)$ can be chosen on the form

$$g_R(t) = \frac{\tau_1^2+\tau_2^2}{\tau_1\tau_2^2}e^{\frac{-t}{\tau_2}}\sin(\frac{t}{\tau_1}); t>0, \quad (7)$$

$$g_R(t) = 0; t<0, \quad (8)$$

as given by [41]. Raman scattering can be explained as scattering of light on the optical phonons and $1/\tau1$ gives the optical phonon frequency. $1/\tau2$ gives the bandwidth of the Lorentzian line (**Fig. 5**). The same values as in [42] have been applied for the constants: $\tau1$ = 12.2*fs*, $\tau2$ = 32*fs*, f_R = 0.18.

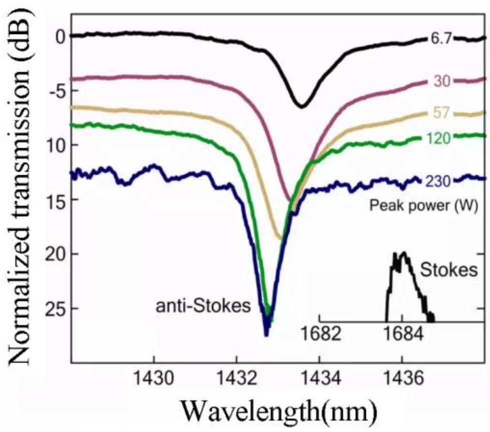

Fig. 5. Inverse Raman scattering are corollary processes arising in Raman scattering.

8. 2. Kerr nonlinearity

The Kerr effect is the effect of an instantaneously occurring nonlinear response, which can be described as modifying the refractive index. In particular, the refractive index for the high intensity light beam itself is modified according to

$$\Delta n = n_2| \ , \quad (9)$$

with the nonlinear index n_2 and the optical intensity *I*. The n_2 value of a medium can be measured e.g. with the z-scan technique. Note that in addition to the Kerr effect, electrostriction can significantly contribute to the value of the nonlinear index [43, 44]. A Kerr nonlinearity can be assumed

by ignoring the Raman response in the fibers corresponding to setting $g(t) = \delta(t)$. If the nonlinearity factor is assumed constant $\gamma = \gamma_0$ the following equation arises

$$\frac{d}{dz}\tilde{A}(\omega_1) = i(\beta(\omega) - \beta_1)\tilde{A}(\omega_1) + i\gamma_0 \int_{-\infty}^{\infty} dte^{i\omega_1 t} A(t)\left|A(t)\right|^2 . \quad (10)$$

If all terms are transformed to the time domain and only up to second order dispersion is taken into account the following equation appears

$$\frac{d}{dz}A(t) = -i\frac{\beta_2}{2}\frac{\partial^2}{\partial t^2}A(t) + i\gamma\left|A\right|^2 A(t) . \quad (11)$$

8. 3. Nonlinearity factor γ

For the nonlinearity factor the convention suggested in [42] has been followed

$$\gamma(\omega) = \frac{n_2\omega}{cA_{eff}(\omega)} . \quad (12)$$

The frequency dependent nonlinearity factor $\gamma(\omega)$ in Eq. (12). Since the effective area $A_{\text{eff}}(\omega)$ often does not vary too drastically with frequency seen on **Fig. 4** a valuable approximation is to assume the effective area to be constant A_{eff},0. With this approximation the nonlinearity factor can be written as

$$\gamma(\omega) = \frac{n_2\omega}{cA_{eff,0}} = \gamma_0(1 + \frac{\omega_1}{\omega_0}) , \quad (13)$$

where $\omega_0 = \omega - \omega 1$ is the frequency of the input pulse and $\gamma_0 = \frac{n_2\omega_0}{cA_{eff,0}}$. With this nonlinearity factor the nonlinear Schrödinger equation is given by

$$\frac{d}{dz}\tilde{A}(\omega_1) = i(\beta(\omega) - \beta_1\omega)\tilde{A}(\omega_1) + i\gamma_0\left(1 + \frac{\omega_1}{\omega_0}\right) \times \int_{-\infty}^{\infty} dte^{i\omega_1 t} A(t) \int_{-\infty}^{\infty} dt_1 g(t - t_1)\left|A(t_1)\right|^2 . \quad (14)$$

In the time domain the nonlinearity factor above is given by $\gamma_0(1 + i\frac{1}{\omega_0}\frac{\partial}{\partial t})$, where the time derivative takes self-steepening and shock formation into account. Consequently, for very long pulses this time derivative can be omitted corresponding to assuming a constant nonlinearity factor

$$\gamma(\omega) = \gamma_0 . \quad (15)$$

If the computational grid is centered at a frequency ωc different from the central frequency of the pulse ω_0 the nonlinearity factor has to be changed accordingly $\gamma_0 = \frac{n_2\omega_c}{cA_{eff,0}}$.

9. Calculation of the propagation

The spacing between the air holes in a photonic crystal structure with air holes embedded in dielectric material is given roughly by the wavelength of the light divided by the refractive index of the dielectric material. The problem in making these small structures is enhanced because it is more favorable for a photonic band gap to form in dielectrics with a high refractive index, which reduces the size of the lattice spacing even further. The linear part is

$$\frac{d^2}{dz^2}\tilde{G}(z,\omega)+\beta(\omega)^2\tilde{G}(z,\omega)=-\frac{\omega^2}{c^2}\frac{x^{(3)}}{A_{eff}(\omega)}\tilde{p}(z,\omega), \quad (16)$$

$$\frac{d^2}{dz^2}\widehat{G}(z,\omega)=-\beta(\omega)^2\widehat{G}(z,\omega). \quad (17)$$

Decoupling Maxwells equations with no free charges and currents, assuming linear response of the medium and no losses leads to a wave equation for the $H\omega(r)$ field

$$\nabla\times\left[\frac{1}{\varepsilon(r)}\nabla\times H_\omega(r)\right]=\left(\frac{\omega}{c}\right)^2 H_\omega(r), \quad (18)$$

where ε is the dielectric function.

$$H_\omega(r)=\sum_m \alpha_m h_m(x,y)e^{-i\beta^{(m)}(\omega)z}, \quad (19)$$

where m denotes the mth eigenmode with transverse part $\boldsymbol{h}m(x, y)$ and propagation constant $\beta^{(m)}(\omega)$.

And Eq. (18) both originate from Maxwell's linear equations. By considering the magnetic field $\mathbf{H}\omega(\mathbf{r})$ as given by Eq. (19) and taking the second derivative with respect to z the following equation arises

$$\frac{d^2}{dz^2}H_\omega(r)=-\beta(\omega)^2 H_\omega(r). \quad (20)$$

The magnetic and electric fields are related by

$$E_\omega(r)=-\frac{ic}{\omega\varepsilon(x,y)}\nabla\times H_\omega(r), \quad (21)$$

where with translational symmetry $\varepsilon(x, y)$ is independent of z. Consequently, $\mathbf{E}\omega(\mathbf{r})$ also fulfills Eq. (17). The emitting power of the light (IR) from the transmitter may take many reflected and refracted paths before arriving at the receiver. The receiver in a optical communication system is the light detector (photodiode) . The large size of the photodiode with respect to the wavelength of the light provides a degree of inherent spatial diversity in the receiver which mitigates the impact of multipath fading. Multipath fading is not a major impediment to optical communication, temporal dispersion of the received signal due to multipath propagation remains a problem. This dispersion is often modelled as a linear time invariant system since the channel properties change slowly over many symbol periods [45]. The impact of multipath dispersion is most noticeable in diffuse infrared communication systems. Unlike conventional fiber optical systems, multipath fading is not a major impairment in photonic crystal fiber transmission. The multipath propagation of light produces fades in the amplitude of the received electromagnetic signal at spacings on the order of half a wavelength apart. The **Fig .6** shows distribution and of photonic crystal fibers.

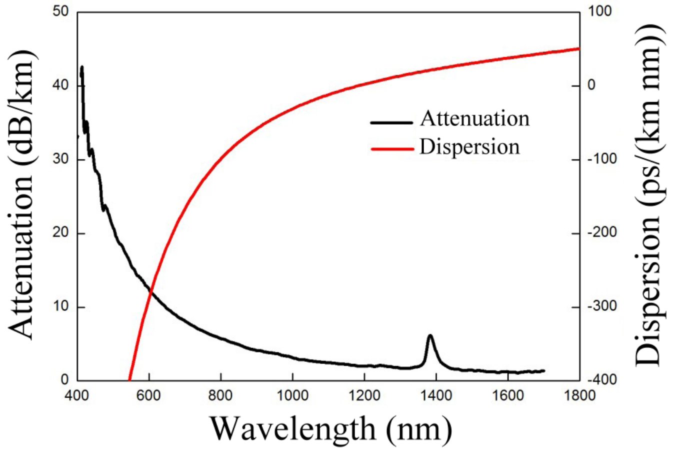

Fig. 6. Distribution and attenuation of the output power with a hollow core photonic crystal fibers

10. Conclusion

The transverse micro-structuring makes the dispersion of the fibers highly tunable and together with the high index contrast it leads to the small effective area, cade of nonlinear effects can take place in the fibers. The interplay between the special dispersion of the fibers and these nonlinear effects makes the phenomenon of supercontinuum generation possible. The full frequency dependency of the propagation constant as well as the effective transverse area serve as input for the model and these parameters can either be calculated as measured. Low loss per unit length, to satisfy the optical power budget allocation for fiber loss and low backscatter, to prevent noise and associated measurement error. The low nonlinearities, such as the Kerr effect, whereby refractive index dependencies in the light-guiding material due to electric field can cause a non-reciprocal effect in the fiber loop leading to measurement error.

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SCHRÖDINGER EQUATION FOR PROPAGATION IN PHOTONIC CRYSTAL FIBERS

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Abstract

The propagation of light in a guided medium is generally described by the Maxwell's equations. For long lengths of fiber, the Nonlinear Schrödinger (NLS) wave equation is typically derived under a few approximations on the waveguide properties of the guiding medium. In theoretical physics, the nonlinear Schrödinger equation is a nonlinear variation of the Schrödinger equation. The propagation of the wave is a fundamental phenomenon occurring in several physical systems. It is a classical field equation whose principal applications are to the propagation of light in nonlinear planar waveguides and optical fibers to the Bose-Einstein condensates confined to highly anisotropic cigar-shaped traps in the mean-field regime. We will focus on the Schrödinger equation for signal propagation in photonic crystal fibers.

Keywords: Schrödinger, nonlinear optics, propagation, photonic crystal, Maxwell's

1. Introduction

The Schrödinger equation is a partial differential equation that describes how the quantum state of a quantum system changes with time. It was formulated in 1926 by the physicist Schrödinger. The nonlinear Schrödinger wave equation has a closed-form solution for no linear dispersion, no Raman effect, and no higher-order fiber nonlinearities, [1]. When the dispersion is present, the Nonlinear Schrödinger equation is generally solved using recursive numerical methods such as the split-step Fourier method or finite-difference methods [1]. The fiber is divided into small segments and the output of each segment is found numerically. Very small segment lengths are required to get accurate results; therefore, the computational cost becomes prohibitively high for long lengths of fibers and short pulse-widths, which are important for future systems. If the segment lengths are increased to reduce these effects, the accuracy. There is no true derivation of this equation, but its form can be motivated by physical and mathematical arguments at a wide