International Journal of Current Engineering and Technology
ISSN 2277 – 4106

Research Article

Photonic Crystal Fiber based Network Components: The Future Trend in Optical Network Design

Uma R. Rao[a*] and B. K. Lande[a]

[a]Shah & Anchor Kutchchi Engg College,Mumbai 400088

Abstract

Optical networks have improved the global connectivity with very high data rates. The need for higher data rates is perpetually increasing with increased number of internet users. The fabrication technique of conventional optical fibers is refined to a great extent ever since the first fiber was fabricated. There has been very little scope left in the future in this regard. A special class of optical fibers known as Photonic Crystal Fibers(PCF) have been recently developed. They exhibit peculiar propagation characteristics and hence prove to have potential application in the design of advanced optical network components. PCFs are the major focus of current research in the field of optical networks. A brief account of these amazing optical structures and the possibilities of designing optical network components using PCFs have been presented in this paper.

***Keywords**: Photonic crystal fibers, index guiding, photonic band gap, dispersion compensator, erbium doped fiber amplifiers, fiber nonlinearities.*

---

1. Introduction

The revolution in the field of communications may be treated as one of the major breakthroughs in technological growth of the last century. Inventions of the optical fiber and the laser in the mid sixties were the major contributors to this spectacular growth. Optical fibers are thin dielectric tubes that can carry huge amount of data at astonishing rates and hence interconnect the world. Lasers provide the focused coherent light pulses that carry information and travel within the optical fiber.The fabrication technology of optical fibers has at present refined greatly so as to make possible attenuations of the order of 0.2 to 0.3 dB/km. The improvement that could be achieved with the performance of optical fibers in terms of their attenuation and data rate is almost saturated. However, the demand for higher data rates and longer repeater less transmission spans is ever increasing. The desire to control the optical properties of materials to further advance the telecommunication facilities has resulted in the invention of a special optical material known as photonic crystal. Photonic crystal fiber (PCF) is a very important application of photonic crystals (J. D. Joannopoulos et al, 1995). PCFs exhibit wave guiding properties that are very different from those of the conventional optical fibers (J. C. Knight et al 1998). These unusual propagation characteristics cannot be achieved with step index single mode telecommunication fibers. These properties have made PCFs enjoy the attention of researchers in the past decade. The very special propagation characteristics of PCFs are being explored in designing more efficient optical communication links.

2. Construction and mechanism of light propagation in PCFs

Photonic crystal fibers are very different in structure as compared to the conventional optical fibers. The basic building block of such a fiber is a photonic crystal. It is a dielectric material with a dielectric constant that varies periodically with distance within the crystal (P. St. J. Russell, 2006). The space periodicity has a dimension that is comparable to the wavelength of the propagating optical energy. The micro structured cladding has cylindrical air holes running through the length of the fiber in the silica background. The central portion has no air holes and it forms the core. The micro structured cladding exhibits a much lesser effective refractive index as compared to the solid silica core. Hence optical energy can propagate through the core by total internal reflection in a manner somewhat similar to conventional step index optical fibers. These are the index guiding PCFs.

PCFs are also fabricated to have a central air hole that forms the air core. Optical energy in such fibers cannot propagate through total internal reflection owing to the fact that the micro structured cladding possesses a higher refractive index than the air core. These fibers utilize photonic band gap effect to guide the light through them. The propagation of certain wavelengths in the cladding is inhibited by the destructive interference which is achieved

---

*Corresponding author: **Uma R. Rao**

by providing proper design geometry to the microstructure. All such wavelengths are said to form a photonic band gap (PBG) in the cladding. This nomenclature is in accordance with the energy band gaps exhibited by the electrons in a semiconductor crystal lattice. The wavelengths that form the PBG are forced to propagate in the core simply because they cannot enter the cladding. These are the photonic band gap PCFs. The structure of a silica core and an air core PCF is shown in Fig. 1 a) and b) respectively.

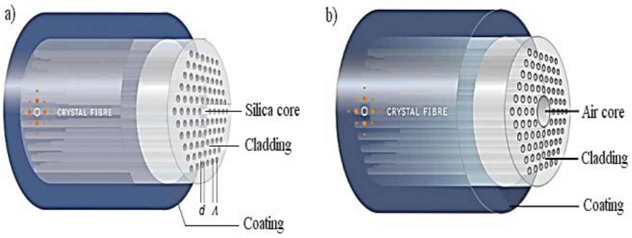

Fig. 1 Structure of PCFs: a) Index guiding type b) Photonic band gap type. Air hole diameter is indicated as d and the distance between the centres of the adjacent air holes by Λ. (reproduced with permission from http://www.nktphotonics.com/side5302.html)

A cross sectional view of an index guiding PCF is shown in Fig. 2. It shows the triangular lattice of air holes arranged in four concentric rings forming the cladding and a missing air hole at the centre resulting in a silica core. The two design parameters namely, diameter of the air holes, d and the distance between the centres of the adjacent air holes, Λ are marked. The dark circles in the figure represent air holes and the back ground material is silica. The transmission properties of PCFs depend largely on the shape and the position of the air holes and hence can be tailored over a wide range of operating wavelengths.

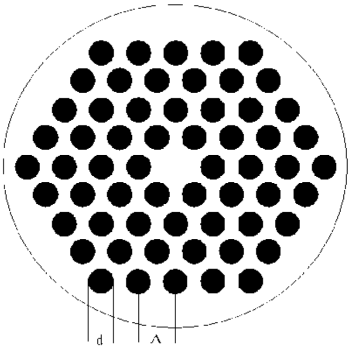

Fig. 2 Cross sectional view of an index guiding PCF showing the design parameters d and Λ. Dark circles correspond to air holes, the background material is silica

3. Fabrication of PCFs

Photonic crystal fibers are manufactured currently in different laboratories worldwide using different manufacturing techniques. The most widely used technique is to stack circular capillaries in a jig with large enough diameters to ensure stiffness while stacking and then to draw the fiber. The outer diameter of the capillaries is typically around 1mm. These capillaries are drawn from initial starting tubes with 20 mm diameter and an inner to outer diameter ratio in the range of 0.3 to 0.9. This parameter decides the d/Λ value of the final fiber where d is the diameter of the air hole and Λ is the pitch of the holes (P. St. J. Russell, 2001)

4. Modeling of PCFs

Photonic crystal fibers are complicated micro structures. It is essential to understand the light guiding mechanism through them in order to utilize their peculiar properties to our advantage. Techniques from traditional fiber theory are inadequate in analyzing light propagation through PCFs due to the complex geometry of the cladding structure. The full vectorial nature of the electromagnetic waves has to be taken into account in the analysis. Though the starting point for the analysis is the basic set of Maxwell's equations as applied to the propagation of electromagnetic waves, the space dependent refractive index term makes the equations highly complicated. This calls for a numerical solution rather than an analytical one. Hence need arises to properly model a PCF. Several approaches for the modeling of the PCFs are reported in the literature. The research in the field of developing simple, accurate and less computationally complex techniques to analyze PCFs is as intense as the research in exploring their utility. The light guidance in an index guiding PCF is somewhat similar to the total internal reflection in step index fibers (SIF). However, the effective refractive index of the cladding microstructure is dependent on the wavelength of propagating light. Due to this, unlike the conventional SIFs, PCFs can remain single mode for a very wide range of operating wavelengths if the air hole diameters are kept small. Thus they are described as *endlessly single mode fibers* (P. St. J. Russell, 2001). By properly modeling a PCF structure, all the propagation characteristics such as effective refractive index, dispersion, birefringence etc. can be evaluated. Methods to analyze photonic band gap fibers are also addressed in the literature. A brief account of modeling techniques for index guiding PCFs is presented here along with a comparison of their performance.

4.1 Effective Index Method

In order to establish a relatively simpler numerical tool that could provide qualitative mode-propagation properties of the high-index core triangular PCFs, J. C. Knight proposed a method in which sequential use of well-established fiber tools was applied (J. C. Knight et al, 1998). The fundamental idea behind this work was to first evaluate the periodically repeated hole-in-silica structure of the cladding and then based on the approximate wave guiding properties of this cladding structure, replace the cladding by a properly chosen effective index.

4.2 Plane Wave Expansion Method (PWE)

The effective index approach gives a qualitative analysis of mode properties of PCFs in a computationally less demanding way. But it cannot very accurately provide dispersion and birefringence properties. PWE method is an efficient and direct method to overcome this drawback (K. Saitoh, and M. Koshiba, 2005). The valid modes are directly solved by expanding the expression for the magnetic field, $H(r)$ in terms of basis functions such as sinusoidal functions. The position dependent refractive index is also expanded in terms of reciprocal lattice vector using Fourier series. An infinitely extending microstructure is assumed. In order to include the periodicity with respect to solid core region (which is termed as 'defect' in the lattice), a super cell is formed around this core region. If the super cell is assumed to be large enough such that the neighbouring defects do not influence the super cell, it can give accurate modeling of PCF.

4.3 Finite Element Method (FEM)

Finite element method is the most versatile method of PCF modeling. It is capable of modeling PCFs even with noncircular and asymmetrically arranged air holes. This advantage of FEM comes with a price of highly involved and computationally intense calculations. In this method, the fiber cross section is divided into very small portions known as finite elements. An equivalent descritized model of scalar wave equation is constructed for each element yielding matrices for these elements. Contributions of all the elements are integrated to get the total contribution for the complete cross section of the fiber. The effective refractive index is calculated by this method and using this value , other modal properties are computed (M. Szpulak et al, 2006)

5. Design of network components using PCFs

Unlike a telecommunication step index fiber, two of the design parameters namely the pitch Λ and the air hole diameter d of PCFs may be varied widely to tailor their propagation characteristics. The PCFs that are currently fabricated have a loss of about 0.3 dB/km. Though this figure is comparable to that of SIFs, we cannot expect the PCFs to replace the existing SIFs as there are millions of km of SIFs laid all over the world that are suitable for current needs and future expansions. However, the attractive propagation characteristics of PCFs may be well utilized in designing some of the optical network components.

In this paper, the possibility of using PCFs in four of the network components namely, Dispersion Compensators, Erbium Doped Fiber Amplifiers, Nonlinear Optical Loop Mirrors and Optical Sources for wave length division multiplexing (WDM) networks is explored. The large refractive index contrast between the core and the cladding of PCF, the tighter confinement of the modal field within the core region and the enhanced nonlinear effects in the PCFs are used in the design there by making this choice superior to that of the conventional SIFs.

5.1 Dispersion Compensators

PCFs can provide a large refractive index contrast between the core and the cladding. It is possible to get a very high negative dispersion co-efficient in PCFs by suitably designing the micro structured cladding. Such PCFs can be used as compact dispersion compensator units in long distance communication links (J. C. Knight et al 1998). The optical networks currently use Dispersion Compensating Fibers (DCFs) to fight the accumulated dispersion over the long spans of the fibers. A light pulse that has undergone a certain amount of positive dispersion can correct itself by traveling through a DCF which has a negative dispersion of an equivalent amount. Typically a 5:1 length ratio of single mode SIF to DCF is needed to compensate the group velocity dispersion (GVD) induced pulse broadening. The chromatic dispersion parameter D for a PCF is given by

$$D = -\frac{\lambda}{c}\frac{d^2 n_{eff}}{d\lambda^2} \qquad (1)$$

where λ is the operating wavelength, c is the velocity of light in a vacuum and n_{eff} is the effective refractive index of the cladding. The effective refractive index, n_{eff} depends on the geometry of the PCF structure. We have considered an index guiding PCF with five air hole rings arranged in a triangular array. The inset in Fig. 3 shows the cross sectional view of this fiber. The variation of refractive index with respect to the wavelength for fundamental mode is computed using plane wave expansion method by the commercial software RSoft. The chromatic dispersion parameter of the fiber is calculated using equation (1). The double derivative of n_{eff} with respect to λ is calculated by fitting a polynomial of order 5 into the data points of n_{eff} and λ.

The effect of PCF geometry on the dispersion parameter for various ratios of diameter to pitch of the second air hole ring is studied (U. R. Rao, and B. K. Lande, 2009). The pitch, Λ of the PCF is taken as 1.0 μm and the diameter, d of the air holes is taken as 0.98 μm. The dispersion curves are shown in Fig. 3. Very high negative dispersion of the order of −1650 ps/km/nm is seen at a wavelength of 1550 nm due to the anti crossing of the modes at this wavelength for a second ring diameter of 0.5 μm.

5.2 Erbium Doped Fiber Amplifiers with PCFs as Gain Media

Signal amplification at suitable transmission distances is essential to make the data decodable at the receiving end in a long distance optical link. Present day data links use Erbium Doped Fiber Amplifiers (EDFAs) to amplify the weak signals at the receiving end of a data link.

The EDFAs have undergone several design refinements to achieve better performance ever since they were first reported in 1987 (E. Desurvire, 1994). Their designs have been optimized with respect to choice of gain medium, erbium dopant concentration, host fiber geometry etc. The refinement process seems to have reached a saturation level. However, the possibility of using PCFs in EDFAs has opened a new door for further improving the performance of EDFAs.

In our work, the variation of EDFA gain with different *d/Λ* ratios of PCF is investigated. The modal profiles are approximated to a Gaussian envelope making the solution of rate equations much simpler (E. Desurvire , 1994 and A. Ghatak, and K. Thyagarajan , 2007). This approach gives a direct comparison with the performance of a step index fiber since the same rate equations are used to analyze SIF EDFA. A comparison of gain of a PCF EDFA and an SIF EDFA is made. The results show that the PCF amplifiers give higher gain for a given fiber length and pump power. A comparison of EDFA performance using PCFs of different *d/Λ* is shown in Fig.4 (U. R. Rao, and B. K. Lande , 2006).

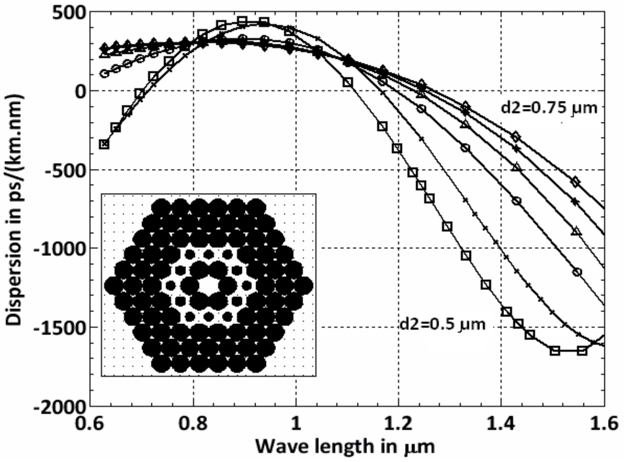

Fig. 3 Dispersion versus wavelength curves with varying d_2 from 0.5 μm to 0.75 μm in steps of 0.05 μm and fixed *d/Λ* ratio of 0.98. Inset shows the cross sectional view of the PCF geometry

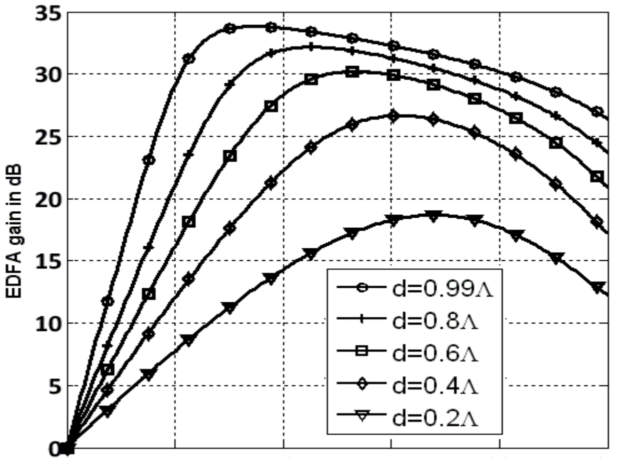

Fig. 4 Gain characteristics of EDFA with PCF

5.3 Nonlinear Optical Loop Mirror using PCFs

A non linear optical loop mirror (NOLM) is basically a two port optical coupler whose output terminals are connected with a short length of optical fiber. When input is given through one of the input terminals, clockwise (CW) propagating and counter clockwise (CCW) propagating light waves are set in the optical fiber loop. The interaction between these two waves under different operating conditions leads to a behaviour of the device that may result in interesting applications. The CW and the CCW beams in the loop traverse the same optical path before getting recombined at the coupler. If the device is operated in the nonlinear domain with a coupling factor α other than 0.5, phenomenon of self phase modulation (SPM) can make this device act as an optical switch. The non linear phase shift acquired by the beam under the influence of SPM is given by,

$$\phi_{NL} = \frac{2\pi n_2}{\lambda}\frac{P}{A_{eff}}L \qquad (2)$$

where n_2 is the nonlinear refractive index, P is the power level, λ is the operating wavelength, A_{eff} is the effective area of the fiber mode and L is the length of the loop. With $\alpha \neq 0.5$, the CW and CCW waves experience different phase changes. It may be shown that and the ratio of the output power at port 2 to the input power at port 1 of the optical loop mirror will be one under certain conditions and is very negligible under certain other conditions (N. J. Doran, and D. Wood, 1988).

Switching may be treated as an immediate application of an NOLM. Fiber lengths in excess of 6 km and power levels as high as 200 W are common in NOLM switching applications(N. J. Doran, and D. Wood, 1988). Reduction in power level or length is possible with an increase in the nonlinear coefficient. The nonlinear coefficient of telecommunication fiber is quite low and is in the range of 11 to 20 $(\mathrm{kmW})^{-1}$. It is inversely proportional to the effective area of the fiber mode. As the effective core area is fixed in a telecommunication fiber, it is not practically possible to increase the nonlinear coefficient and hence either the power level or the length cannot be reduced. PCFs tend to confine the modal profile to a greater extent due to the increased index contrast between the core and the micro structured cladding. Highly nonlinear PCFs are being designed exploring this improved modal confinement. We have investigated the advantages of using a PCF in an optical loop mirror switch.

5.3 Spectral Broadening in Highly Nonlinear PCFs due to SPM

The highly nonlinear PCFs designed for NOLM as explained in the previous section have a second application as well. The SPM due to nonlinearity results in the widening of the spectrum of the propagating optical pulse. Due to the dependence of the refractive index on the intensity of the optical pulse, the pulse undergoes frequency chirping without changing its temporal power distribution. As a result, new frequencies appear in the output pulse causing the initial spectrum to widen. The amount of frequency shift due to chirping is given by,

$$\nabla\omega = \frac{k_0 n_2 z}{A_{eff}} \frac{dP}{dt} \quad (3)$$

where k_0 is the free space wave number and z is the length of the fiber. The frequency shift and the subsequent spectral widening are directly proportional to the peak power and inversely proportional to the mode area. For a given length of the fiber, PCF offers wider spectrum due to the higher nonlinear coefficient.

The propagation of an optical pulse with Gaussian temporal variation in to a PCF is modeled with an expression having amplitude and a phase angle that depend on the nonlinear coefficient (A. Ghatak, and K. Thyagarajan , 2007). The spectrum of this pulse may be estimated by taking the Fourier Transform of this expression. We have numerically estimated the spectrum using periodogram function of Matlab©. The PCF used for simulation is same as the one used for NOLM. It has a mode diameter of 0.73 μm at 1550 nm. As expected, the spectrum gets wider with either increased power levels or increased fiber lengths for a given effective mode area (U. R. Rao, and B. K. Lande , 2010).

The spectral widening has application in optical sources for WDM networks. We have considered the spectral broadening only with respect to SPM. Other nonlinear factors such as Raman scattering may lead to further expansion of the spectrum and result in super continuum generation

Conclusion

The dispersion tailoring and tight modal confinement make the PCFs potential candidates for network components such as dispersion compensators, fiber amplifiers, demultiplexers, wavelength converters etc. Some of these network components have been designed and analyzed in our work. We have designed and analyzed dispersion compensators, erbium doped fiber amplifiers and nonlinear switches using PCFs. The phenomenon of spectral broadening in a highly nonlinear PCF is investigated with the intention of extending the same to super continuum generation.

References

J. D. Joannopoulos, R. D. Meade, and J. N. Winn (1995), Photonic crystals molding the flow of light, Princeton University Press

J. C. Knight, T. A. Birks, P. St. J. Russell, and J. P. de Sandro (1998), Properties of photonic crystal fiber and the effective index model, J. Optics Society, vol. 15, no. 3, pp. 748-752

P. St. J. Russell (2006), Photonic crystal fibers, J. Lightwave Tech., vol. 24, no. 12, pp. 4729-4749

P. St. J. Russell (2001), A neat idea, Excerpts from an interview in IEE review, pp 19-23.

K. Saitoh, and M. Koshiba (2005) , Numerical Modeling of photonic crystal fibers J. Light wave Tech., vol. 23, no. 11, pp. 3580-3590

M. Szpulak, W. Urbanczyk, E. Serebryannikov, A. Zheltikov, A. Hochman, Y. Leviatan, R. Kotynski, and K. Panajotov (2006), Comparison of different methods for rigorous modeling of photonic crystal fibers, Optics Express, vol. 14, no. 12, pp. 5699-5714

P. Urquhart, O. G. Lopez, G. Boyen, and A. Bruckmann (2007), Optical Amplifiers for Telecommunications, 1-4244-0830-X/07/2007 IEEE.

E. Desurvire (1994), Erbium doped fiber amplifiers, NY John Wiley & Sons,Inc.

Ghatak, and K. Thyagarajan (2007) , Introduction to Fiber Optics, Cambridge University press, pp. 296-302.

N. J. Doran, and D. Wood (1998), Nonlinear-optical loop mirror, Opt Lett., vol. 13, no. 1, pp 56-58

U. R. Rao, and B. K. Lande (2009) , Photonic crystal fiber as dispersion compensator, In Proceedings of International Conference on Advances in Computing, Communication and Control, ICAC3 ’09, pp. 217-119, Available:978 -1- 60558-351- 8

U. R. Rao, and B. K. Lande (2006), Development of erbium doped fiber amplifiers using photonic crystal fibers as gain media, International journal of recent trends in engineering, vol. 2, no. 7, pp. 34-36

U. R. Rao, and B. K. Lande (2010), Pulse Broadening in Photonic Crystal Fibers due to Self Phase Modulation, Seventh International Conference on Wireless and Optical Communications Networks WOCN 2010, Colombo, Sri Lanka.