Bahria University Journal of Information & Communication Technologies Vol. 10, Issue I, June 2017

Optimum Hollow Core Fiber Design for Long Haul Optical Communication System

Mamoona Khalid and Irfan Arshad

Abstract — **Photonic Crystal Fibers (PCF) are gaining great importance now a days in the field of photonics and optical communication due to their wide range of nonlinear applications with reduced fiber losses. It is an alternative fiber technology with improved optical properties due to light confinement within the air holes of its cladding along with the light propagation through the core. In this research we have designed, optimized and then analyzed light through hollow core PCF to obtain its characteristics. Different optical properties such as waveguide dispersion, confinement loss, attenuation and signal to noise ratio is investigated. Low attenuation of signal is reported as the length of fiber is increased. Purpose of this research is to present a design of HC-PCF that can be used in long haul optical communication where low but a non- zero chromatic dispersion is required for a low attenuation as we move along the fiber. Non-linearity in the signal causes attenuation which in case of PCF can be minimized to reduce the signal attenuation. Signal to Noise ratio is automatically improved when the signal is not getting attenuated along the length of the fiber. Main purpose of this research was to introduce a new structure and design of latest field of microstructured fiber technology instead of conventional optical fiber technology. We have investigated our design of HC-PCF for telecommunication application over range of wavelength from 1000nm to 1650nm.**

Index Terms — **Attenuation, Dispersion, Long Haul Systems, Photonic crystals, Optical communication, Optical fibers, Photonic Crystals, Photonic Crystal Fibers.**

I. INTRODUCTION

Due to the ever increasing demand of high speed optical communication with maximum transmittance, low losses, greater slope efficiencies and high signal to noise ratio researchers are striving for better designs of optical fibers for this purpose. Every possible effort is being made to improve data transmission with high accuracy and encryption to make it secure. A number of materials are being utilized these days for the development of optical fibers according to their application instead of only silica. Other materials including Phosphates, chalcogenides, Heavy metal oxides and fluorides are among the most extensively being studied these days for the fabrication of optical fibers and waveguides in order to propagate light through them. Optical fibers fabricated from silica material limits the use of these fibers for nonlinear applications like four wave mixing, supercontinnum generation and spectroscopic applications. This limits the use of conventional optical fibers for nonlinear applications. In 1990 through consistent research and experiments researchers developed a new class of optical fibers named as microstructured fibers out of which Photonic Crystal Fiber is one of its types. These fibers have the useful crystal properties with a core in the center and a cladding consisting of periodic structure of air holes with many layers. The structures of PCF is divided into two parts with respect to the core, Solid Core and Hollow core PCF. In solid core PCF the core of the fiber is formed by producing a defect in the center of hexagonal structure of periodic air holes while in hollow core PCF, core is a cylindrical structure in the center of the air holes.

Due to PCF confinement property it can be classified into different operation modes. These modes define the high nonlinearity of PCF. Due to the advancement of PCF manufacturing this technology has a great standard in optical communication which has shown promising results in terms of minimizing dispersion properties, confinement loss and attenuation thereby improving the signal quality providing better SNR.

Photonic crystal fibers are latest advancement of optical fibers. Their non-natural crystalline microstructure produces a variety of characteristics that are very scarce and valuable. They have the ability to allow light to propagate through them not only through well-known total internal reflection mechanism but also using photonic band gap effect [1]. PCFs have unique features to control light that is used in different applications such as medical and sensing. PBG confines light in hollow region which reduces nonlinearities [2]. By changing the properties of PCF and achieving different optical parameters better structure of PCF can be achieved according to the application.

PCF has a flexible structure therefore is preferred over conventional optical fibers for a number of applications including but not limited to telecommunication, medical science, sensing, LASERs, optical communication etc. Guidance of light in PCF occurs by TIR (Total Internal Reflection) or PBG (Photonic Band Gap). A superior and primary division of PCF is the photonic band gap fibers, from which hollow-core fibers are special subclass. The band gap is formed by creating a periodic matrix of high index-differences (typically air holes in silica) along the length of the fiber [3]. Fig. 1 shows the structure of hollow core fiber and its cross sectional view.

In this research, hexagonal structure of photonic crystal fiber is designed and optimized. We have used latest FDTD approach to optimize the proposed design and then analyzed the optical properties such as dispersion, confinement loss, attenuation and signal to noise ratio. To optimize our structure we designed a number of PCFs by setting up different parameters such as core diameter, pitch and the radius of air holes. Apart from this we also used other lattice structures for before proposing the optimized PCF structure like honeycomb, Triangular, circular and Hexagonal. By

---

Mamoona Khalid and Irfan Arshad are with Department of Electrical Engineering, University of Engineering and Technology, Taxila.
Email: mamoona.khalid@uettaxila.edu.pk, irfan.arshad@uettaxila.edu.pk

Manuscript received on Feb 19, 2017 revised on April 21, 2017 and accepted on May 04, 2017

increasing the wavelength and hole diameter low values of confinement loss is studied. Moreover, high negative dispersion can be studied if air hole diameter is increased. These optical properties play a significant role in telecommunication and sensing applications. Our concern in this research is to present a PCF design and lattice structure that gives minimum attenuation and high signal to noise ratio so that it can be easily used in long haul optical communication as an alternative of optical fibers [4].

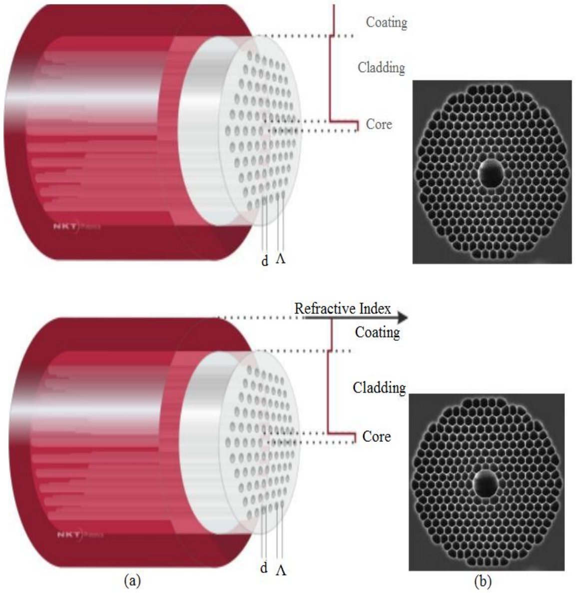


Fig.1 (a) Hollow core fiber structure (b) Cross sectional view of HC PCF core and cladding

PCF is one of the basic optical fiber class having photonic crystal properties. Photonic crystals are constructed with the help of air holes in the fibers. It has confinement ability which is not fascinated in conventional fibers. It uses TIR principle to confine light and having cladding index that is very low. Photonic crystal fiber has best uses in Optical communication. In Photonic Band Gap Fiber (PBGF) certain bands are allowed to pass. Geometry of conventional fiber involves different fabrication materials. Core has higher refractive index than cladding. PCF entails air hole cladding which is surrounded by the core that can be solid or hollow. According to the geometry, PCF is divided into two main families first one is Solid Core PCF and the other being Hollow Core Periodic Crystal Fiber [4].

The array of air holes in the cladding gives PCFs significantly different guidance properties from conventional TIR guiding fibers. This is because the index contrast between the core (typically pure silica) and the cladding can be varied by altering the size of the cladding air holes that changes the effective refractive index of the cladding region [3]. In gradient index optical fiber RI (Refractive Index) of core become less with the distance from axis of the fiber. Light wave shows sinusoidal structure if the core has larger refractive index than cladding. Graded index fiber has parabolic results [5].

The property of fiber naming the effective refractive area is of great importance. This quantity was first defined as a measure of non-linearity. In order to achieve high density of power required for these non-linear effects to become noteworthy, lower effective refractive area is required [6]. Band gap is forbidden area of energy it occurs due to the periodic potential present in the crystal. Periodic potential electron does not have any energy. Band gap concept arises due to the variation in the quantity. Photonic band gap relies on the crystal's geometry where it can be altered by varying the parameters.

During the simulation and fabrication process different physical parameters of the fiber should be controlled depending upon the kind of fiber to be produced. During the production of Single Mode Fibers, the only parameter of great concern to be controlled is its core diameter while during the manufacturing of PCFs there are three physical parameters to be controlled, its core diameter, its pitch and the radius of air holes in the cladding area [7]. Fiber dispersion occurs due to material dispersion and waveguides. Optical fiber performance is adjusted witch varying attenuation. Due to absorption or scattering phenomenon power of fiber optics decreases with increasing distance [8].

Propagation of light through PCF can be achieved using one of the two interesting mechanisms seen in the PCF fiber which are responsible of confining electromagnetic waves within the core of the fiber [9]. The mechanism named Total Internal Reflection is the same as occurring in the conventional optical fibers while the other mechanism seen in PCF is the Photonic Band Gap effect. This effect occurs when the average refractive index of the core is lower as compared to the combined effect of effective refractive index of air holes that make up the cladding region of the fiber [10]. Waveguide characteristics of both fibers differ by varying the glass material composition and the arrangement of holes in the optical fiber. Photonic Crystal Fiber has flexibility in design by varying the parameters of its geometry thus it offers great flexibility in design. PCF has great impact in lasers and sensors due to guidance mechanism in HC region.

The main concerned parameter in almost all the optical fiber systems is the attenuation per unit length measured in dB/km. This parameter defines the optimum distance that is must between repeaters (approximately 80 km) within a communication system [7]. Till now research has shown that traditional optical fibers have set a limit of approximately 0.2 dB/km at a λ = 1550nm. This limit is due to the effect of Rayleigh scattering, bending losses, diffraction and other dispersions due to nano-scale imperfections within the glass Due to scattering the absorption power decreases with distance. Therefore, coefficient of attenuation can be defined in terms of decibels as dB/km. attenuation coefficient can be denoted by α. Dispersion or loses in fiber can be calculated by varying the hole size of the fiber [11].

In order to use PCF for practical applications in optical communication systems and nonlinear optics it is vital to control the chromatic dispersion property of PCF. Till now research has shown that the researchers have been able to develop PCFs with remarkable dispersion characteristics. Completely zero and flattened dispersion PCFs have been developed and reported in literature in the wavelength range from visible to near infrared [11]. Now research is being done in mid-infrared fiber technology as well [12]. Different layout can be designed if we change the diameter of the hole. By varying the values of refractive index different layout of the materials can be created. Less confinement loss occurs with increasing diameter and pitch ratio. Preference is always given to diameter enhancement for achieving better confinement. High negative dispersion is visualized if the diameter value is increased.

During the evaluation process of performance and quality of system, one of the most important considerations is the input signal and its format. This consideration is vital as it directly distresses the recognition of transmitted signals. The precision of signals reproduced by repeaters rely on the intensity of the signal received, processing speed and linearity of the receiver and the noise levels shaped in the communicated and received signals [11]. LED uses the wavelength between 850-1310 nanometer. Lasers bandwidth falls between 1310- 1550 nanometer. Light Emitting Diodes operates for less distance because of power and bandwidth limitation. For high data rates and long distance communications, laser diodes are used. LD (Laser Diode) has output power greater than Light Emitting Diode therefore, it is able to transmit at longer distances.

II. RESEARCH METHODOLOGY

PCF has gained great attention in different applications. It is used to make oscillators, amplifiers and lasers. By arranging the PCF air holes, it gives a structure similar to the crystal. By air hole arrangement and changing the diameter, new Photonic Crystal Fiber is produced that is used in many other applications. PCF shows many properties like confinement loss, dispersion etc. Pitch and diameter is important elements for Photonic Crystal design. Air hole diameter and lattice pitch ratio can be adjusted for redesigning Photonic Crystal Fiber structure for confinement loss and dispersion. In SC (Solid Core) PCF (Photonic Crystal Fiber) wavelength decreases with increasing the refractive index values. Confinement loss and dispersion can be adjusted by changing the PCF internal properties. Therefore, by changing the wavelength, diameter, pitch ERI (Effective refractive index), dispersion loss and confinement also change.

Analysis of light through hollow core PCF is visualized by considering the optical characteristics like waveguide dispersion, Confinement loss, attenuation and optical signal to noise ratio. These properties are investigated using five ring PCF by varying air hole diameter, its pitch and length of fiber. It is observed that increasing or decreasing the hole diameter has a particular effect on confinement loss, attenuation, high negative PCF dispersion and some other factors like attenuation and OSNR.

The main purpose of the research is to analyze light through a model of HC-PCF that can provide minimum possible attenuation and losses to guarantee the transmission of noise free data. By varying different parameters of PCF design we optimized the optical properties of HC-PCF. Most important parameters that play an important part for this purpose is the distance between two consecutive air holes of the cladding usually known as the pitch represented by Λ, the diameter of the core represented by d and the number of air hole layers in the cladding increasing or decreasing which controls the confinement loss.

III. RESULTS AND DISCUSSION

For the analysis of light through hollow core PCF, a hexagonal HC-PCF structure with five rings is designed. The pitch between the air holes was fixed to 2.0 µm with radius of air holes equal to 0.7 microns, radius of the core was selected to be 1µm. These specific parameters when compared with the designs available in literature gave us less confinement loss, dispersion, attenuation and ultimately high signal to noise ratio which is the requirement of data transmission over long haul communication systems. We also designed and analyzed other structures of PCF such as honeycomb structure and triangular structure of air holes but the best and optimum results were obtained using the hexagonal air hole structure. The material used was fused quartz with value of refractive index ‘n’ equal to 1.46. The structure was designed for varying hole diameters d = 0.55, 0.65, 0.75, 0.85, 0.95 µm with decreasing pitch size from a= 2.3, 2.2, 2.1, 2, 0.8, 0.4 and 0.2 microns. For effective refractive index (ERI) and confinement loss (CL) wavelength ranges from 650 nm to 1800 nm was taken. For waveguide dispersion wavelength ranges 1.5, 1.52, 1.54, 1.56, 1.58.1.6, 1.62 µm was taken. Furthermore FDTD modeling was used for the simulation of PCF structure (modeling is being described in another research). From PCF simulation effective refractive index values were obtained consisting of real and imaginary parts. These values were used to calculate the confinement loss and dispersion. MATLAB tool was used to sketch the plots.

Fig 2 shows the simulation parameters of hexagonal PCF using FDTD tool. Fig.3 shows the real and imaginary parts of simulation results of our proposed design.

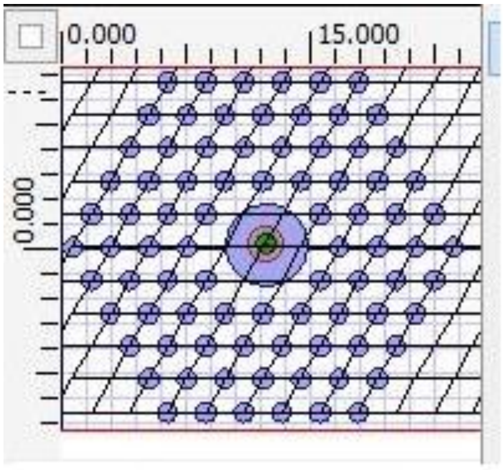
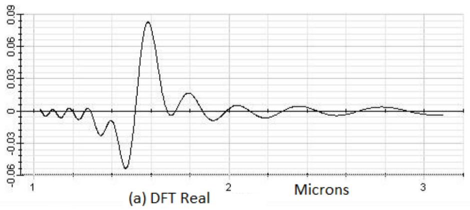


Fig. 2 Cross Section of designed HC-PCF



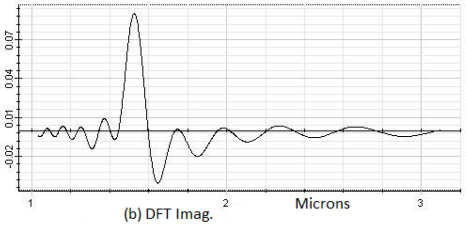


Fig. 3 (a) Real part of DFT Analysis with respect to wavelength (b) Imaginary part of DFT with respect to Wavelength.

Data obtained for the imaginary part is then coded and in MATLAB to obtain confinement loss. Fig.4 a and b shows the simulation results. The minimum confinement loss is obtained at wavelength range from 1000 to 1300 nm but is also very low in the range of 1550 nm and can therefore easily be utilized in DWDM as well as long Haul communication systems.

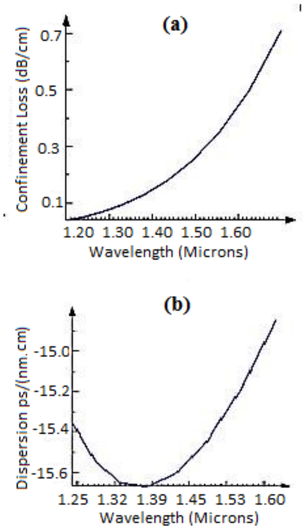


Fig. 4 (a) Confinement loss of HC-PCF (b) Dispersion associated with designed PCF

Confinement loss is calculated from the following Equation 1.

$$L_{confinement} = 8.68\, k_0\, I_m\, [n_{eff}]$$
(1)

k_0 indicates the wave number and $I_m\, [n_{eff}]$ indicates the imaginary part (effective refractive index). It is obvious from Fig. 4 (a) that confinement loss decreases as we increase the hole diameter. Best confinement Loss is achieved under the PCF hole diameter d = 0.55, 0.65, 0.75, 0.85, 0.95 μm. Confinement loss can be minimized by changing the PCF aspects such as diameter as well as the pitch of the air holes. When the number of holes is increased Confinement Loss rapidly decreases. Moving further waveguide dispersion was calculated by using equation 2 and then simulated to obtain results given in fig.5b.

$$D_{waveguide} = \frac{-\lambda}{c}\,\frac{d^2 R_e[n_{eff}]}{d\lambda^2} \qquad (2)$$

λ indicates the wavelength and velocity of light is indicated by c. Second derivative of eff (effective refractive index) was taken and solved by FDTD numerical method technique.

Waveguide dispersion is the second important parameter to be analyzed. With increasing the hole diameter more negative waveguide dispersion is obtained. Fig.4 (b) shows the result of waveguide dispersion. Dispersion can be investigated by effective refractive index of silica with the help of the equation 2. Waveguide dispersion relates to the PCF structure which can be changed for desired characteristics. Fig.4(b) yields a very promising result of waveguide dispersion as at 1550 nm we obtained decreasing dispersion which goes on decreasing as we move along the length of the fiber.

Signal to noise ratio is calculated from the data obtained earlier, Fig.5 shows the results of signal to noise ratio. Signal to noise ratio is calculated at different frequency by considering different values of distance. In our research we have improved the loss, dispersion and attenuation properties of HC PCF but a bit more working is required with the SNR along the fiber length. It can be improved more by using PCF structure within another PCF structure.

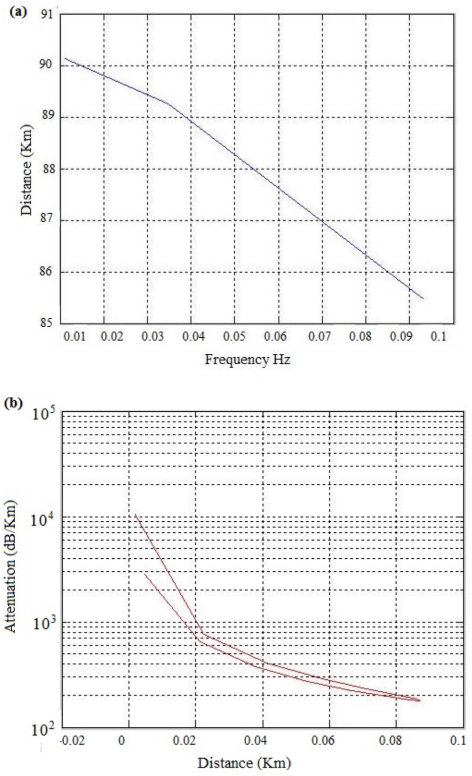


Fig. 5 (a) Signal to noise Figure (b) Attenuation vs Distance of proposed Design

Attenuation (dB/km) is calculated by taking the power in mW over distance in km. The extracted values of power vs distance are coded in MATLAB. Fig. 8 shows the results obtained from MATLAB simulation. Attenuation from the above data is calculated as losses in decibels: $10\ log_{10}(P_O/P)$. It is obvious in the graph given Fig. 5 b attenuation decreases as the distance or the length of the fiber increases. After a certain length of 25 Km losses again start to increase and the signal to noise ratio drops. To avoid this situation optical amplifiers and repeaters like EDFA are required to regenerate the signals and then pass it onward to the destination with full capacity.

IV. CONCLUSION

In this research work, light through an optimized version of hollow core Photonic Crystal Fiber was used to observe the properties of hexagonal layout of PCF by varying the air hole diameter and the pitch of fiber. The material used was Fused quartz with refractive index 1.46. Different Optical properties such as waveguide dispersion, Confinement loss, attenuation and optical signal to noise ratio were studied by changing the PCF structure. It was observed that the confinement loss was reduced as we move along the fiber, low confinement loss is achieved by increasing wavelength and hole diameter. Increasing air hole diameter is more operative for achieving low confinement loss. High negative dispersion is obtained by increasing the hole diameter. From our design we also obtained low attenuation of signal as we increase the length of the fiber. A little improvement in SNR is still required which can be achieved by inserting a PCF structure with elliptical air holes in the core of another PCF structure with circular air holes, we are in the process of investigating such structure under specific boundary conditions using the same FDTD approach. These optical parameters which we achieved for our design are very important in telecommunication applications especially long haul communication where we are more concerned about the attenuation of a signal.

REFERENCES

[1] W.H. Reeves, J.C. Knight, P. St. J. Russell and P.J.Roberts, “Demonstration of ultra flattened dispersion in photonic crystal fivers,” Optics Express, vol. 10, pp. 609-613, July 2002.

[2] N. A. Issa, M. A. van Eijkelenborg, M. Fellew, F. Cox, G, Henry, and M. C. J. Large, “Fabrication and study of microstructured optical fibers with elliptical holes,” Opt. Lett., 29, 1336-1338, 2004.

[3] K.K.Sharma, Pranaw Kumar, “Some novel photonic crystal fiber structures based on Pascal’s triangle and their dispersion behaviour" ICECT 2012, Kanyakumari, India, April 6-8,2012.

[4] Dinesh Kumar Prajapati, Ramesh Bharti, “Dispersion analysis of a Hybrid Photonic Crystal Fiber”, International Journal of Recent Research and Review, Vol. VII, Issue 2, June 2014.

[5] Soeun Kim, Yong Soo Lee, Chul-Sik Kee, Chung Ghiu Lee “Hybrid Lattice Photonic Crystal Fiber” 18th European Conference on Network and Optical Communications & 8th Conference on Optical Cabling and Infrastructure ISBN: 978-1-4673-5822-4, Graz, Austria, July 10-12, 2013.

[6] Jose A. Sánchez-Martín, José Miguel Álvarez Abenia, Miguel Ángel Rebolledo, Miguel V. Andrés, and Antonio Díez, “Amplifiers and Lasers Based on Erbium-Doped Photonic Crystal Fiber: Simulation and Experiments”, IEEE Journal Of Quantum Electronics, Vol. 48, No. 3, March 2012.

[7] O. Frazao, J. P. Carvalho, and H. M. Salgado, “Low-loss splice in a microstructured fibre using a conventional fusion splicer,” Microw. OptTechnol. Lett., vol. 46, no. 2, pp. 172–174, Jul. 2005.

[8] L. M. Xiao, W. Jin, and M. S. Demokan, “Fusion splicing small core photonic crystal fibers and single-mode fibers by repeated arc discharges,” Opt. Lett., vol. 32, no. 2, pp. 115–117, Dec. 2007.

[9] T. Ritari, et al., “Gas sensing using air-guiding photonic bandgap fibers,” Opt. Express, vol.17, 4080, 2004.

[10] B. T. Kuhlmey, R. C. McPhedran, and C. M. de Sterke, “Modal cutoff in microstructured optical fibers,” Opt. Lett., vol. 27, no. 19, pp. 1684–1686, Oct. 2002.

[11] K. Furusawa, T. Kogure, J. K. Sahu, J. H. Lee, T. M. Monro, and D. J. Richardson, “Efficient low-threshold lasers based on an erbiumdoped holey fiber,” IEEE Technol. Lett., vol. 17, no. 1, pp. 25–27, Jan. 2005.

[12] G. Y. Chen, D. G. Lancaster, and T. M. Monro. (2015, November) Angle-resolved characterization of optical fiber preparation techniques. *ANZCOP/ACOFT*, pp. 72-74.

[13] P. Koska, P. Peterka, J. Aubrecht, O. Podrazky, F. Todorov, M. Becker, Y. Baravets, P. Honzatko, and I. Kasik. (2016, January) Enhanced pump absorption efficiency in coiled and twisted double-clad thulium-doped fibers. *Opt. Express*. 24(1), pp. 102-107.

[14] Mamoona Khalid and Irfan Arshad ,“A Novel Design of Photonic Crystal Fiber with Flattened Dispersion and Reduced Confinement Loss” published in “Pakistan Journal of Engineering and Applied Sciences” University of Engineering and Technology, Lahore, Pakistan. Vol. 16, Jan., 2015 (p. 93–99)

[15] M. Khalid, I. Arshad , “Estimation of Low Loss and Dispersion of Hollow Core Photonic Crystal Fiber designs for WDM Systems” Published in “Technical Journal” University of Engineering and Technology, Taxila, Pakistan. Vol.19 (2014), No.4. pp. 9-13.

[16] Mamoona Khalid, I. Arshad and M.Zafrullah, “Design and Simulation of Photonic Crystal Fibers to evaluate Dispersion and Confinement Loss for Wavelength Division Multiplexing Systems” published in “The Nucleus” Vol. 51. (2014) No. 2, pp. 249-258.

[17] Mamoona Khalid, I. Arshad , “Analysis of Light propagation through PCF with reduced losses” Published in Proceedings of IEEE International Conference on Intelligent Systems Engineering, January 2016.