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Review on Photonic crystal fiber as dispersion compensating fiber

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ABSTRACT

This paper provides an overview of PCFs, outlining their design principles and mechanisms. Photonic crystal fibers (PCFs) have garnered significant attention due to their unique optical properties, not achievable with traditional optical fibers. By integrating optical and photonic crystal features, PCFs offer distinct advantages such as tailored dispersion, high nonlinearity, and minimal confinement loss. Unlike conventional fibers, PCFs overcome structural limitations, providing endless single-mode operation, high sensitivity, and strong birefringence. It focuses on dispersion management within PCFs, crucial for optimizing their performance in various applications. With their exceptional characteristics, PCFs find utility in diverse fields including ophthalmology, dentistry imaging, and military applications.

Keywords: Photonic Crystal fiber, Dispersion compensating fiber, Dispersion

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INTRODUCTION

A communications infrastructure should be developed so that it has significant capacity, fast speeds, and also exceptional reliability, since the expansion of telecommunications both at the international and national levels and the requirement for users to obtain modern services promptly. The transmitter, receiver, and compatible medium for transmission comprise optical communications. Signals containing light are able to sent using optical fiber or in empty space. Optical fibers offer benefits over electric connections, including minimal loss, a wide bandwidth, and an incredibly little chance of unwanted occurrences. Chromatic dispersion among optical fiber is one of those most important factors for optical fiber telecommunications [1]. Optical messages spread as they travel throughout an optical fiber due to dispersion. Broadening of light signals lowers the transmission of data volume and makes finding information more challenging [9]. For single-mode fiber utilized as the communication media in optical network, chromatic dispersion is high. Data could be erroneously or entirely lost as a consequence of the broader electromagnetic wave that arises from increased dispersion in the fiber. As fiber chromatic dispersion makes it difficult to deliver data during high bit rates over long distances. The degradation of optical information at the point of receiver prior to the final identification is avoided by using optical fiber having negative dispersion to serve as compensator within certain areas of optical system[1] Dispersion requires to be adjusted for long-haul optical transmission networks to reduce the spreading of light pulses.[9].

Dispersion mitigation involves the procedure of designing the fiber and making adjustments to certain parts of the transmission channel in order to minimize overall dispersion. The adjustment of total chromatic dispersion will be referred to as dispersion correction in other contexts [2].On the other hand a strong negative dispersion can only be generated by DCF utilizing traditional fibers on a specific wavelength, not across a broad band. We require substantial negative dispersion for the purpose to shorten the DCF which will considerably reduce the cost. Using the traditional DCFs, it is challenging to obtain large negative dispersion. Also required for use in broadband communication systems is strong negative dispersion of DCFs over a large wavelength range. So both dispersion as well as dispersion slope compensation are needed at the same time [4]. This led to the development of an appealing alternative fiber. By merely changing its structural dimensions, photonic crystal fiber provides great design versatility. A particular kind of optical fiber termed a photonic crystal fiber has a micro structured arrangement that covers low index materials with material with greater refractive index. Typically, PCF's base material is silica in its purest form. It is also known as "holey fibers" because the whole length of the fiber is wrapped by many air holes, each of which surrounds a core fault. The main distinctions between

PCF and conventional fiber lies in the core/cladding index profile. Compared to traditional fibers, photonic crystal fiber offers greater design flexibility for optical properties such dispersion, birefringence, effective area, confinement loss and nonlinearity [3]. Because of its unique optical qualities, such as design freedom, single mode operation and flattened dispersion characteristics, PCFs have been revolutionizing optical communication systems. The PCF is used in many different digital circuit implementations, including multipliers and demultipliers, logic gates, polarization splitters (couplers), optical sensors, and medical detection, among others [2]

Types of photonic crystal fiber:

Photonic Crystal Fiber (PCF) is a structure made up of a core and clad that ensures 100% internal reflection, just like a regular fiber. Similar to how these ionic structure impacts electrons inside solids, periodic geometries have an impact upon photon mobility. It appears natively in the form of the structure's colorings. This specific fiber's core is comprised entirely of silica and may be a solid as well as hollow. Because the fiber is surrounded by air holes, it is referred to as a "holey" or "micro-structural" fiber. As a result of this structure, light is constrained and transmitted throughout the core of the fiber, which functions like a cavity [3]

According to various structures, it often consists of two types:
Photonics band -gap fiber
The index guided photonics crystal fiber

Photonic band-gap fiber:

The structure that results when the core portion of air gap array is just substituted with a considerably larger hole that is significantly greater in diameter compared to the neighbouring holes results in photonic band-gap fiber. Its optical characteristics are altered as a result of the periodicity's broken structure's deformity. In the hole, none electromagnetic modes are allowed to repeat. In photonic crystal band-gap fiber, in which the wavelength regulates light in the small index core area, its effect is visible. The fiber's ability to control light depends upon the frequency of the outside light; if it coincides with the band-gap frequency, the light is constrained in the holes and similarly guided throughout the length of the fiber. Therefore, a higher centre refractive index is not necessary.

The index guiding photonics crystal fiber:

Complete internal reflection among a solid core and different air holes cladding focuses PCF light in index guiding. Unadulterated silica covering with a refractive index of 1.462 surrounds a solid core of file regulating PCF with an extremely small size elementary demonstrate of air holes. The total internal reflection, that is entirely a component of wavelength, centers the light due to the significant difference in refractive indices among air (1.000) and silica (1.462). The stage delayed per unit of length in PCF relative to stage's delay in the vacuum is effectively measured by the efficient refractive index (ERI)[3].

Dispersion compensation:

By altering the fibre profile of refractive index, significant negative waveguide dispersion is achieved in dispersion compensating fibers. For the purpose of compensating the dispersion, both the basic mode and the higher order modes may be used. The fundamental mode is the foundation for dispersion compensation fibre modules that are available on the market. Some dispersion compensating fibers exhibit a dispersion slope which is flat. Due to the communication fibers' dispersion slope, they can only properly compensate the dispersion of only one channel and possibly over or below compensate for the dispersion of additional channels. The wide band compensating fibers having both negative dispersion and dispersion slope are necessary to compensate the dispersion characteristics of all channels in order to get the best efficiency for extremely fast DWDM systems. The fibre core needs to possess a large refractive index and a narrow core width in order to obtain considerable negative dispersion and dispersion slope of basic mode. The fibre mode field width and associated mode area consequently minimal.

The average effective area values range between 15 and 20 μm^2. Concerns of fibre non-linear effects have been highlighted because to the narrow effective area. But at this stage, it doesn't appear to be a significant issue. There are some appealing advantages when utilizing HOMs during dispersion adjustment. Wideband dispersion and dispersion slope corrections are both possible with HOM dispersion compensating fibers, just like with basic mode fibers. Another advantage is that they have less fibre nonlinearity since they have a bigger effective area than basic mode dispersion compensation fibers. However, HOM dispersion adjustment has two flaws. Firstly, two mode-converters are needed to accomplish small splice loss, which increases complexity and expense. This is because the fundamental mode of a transmitting fibre and the greater-order mode of a HOM fibre have different mode field distributions. A very difficult problem to address is the presence of multiple path interruption (MPI) that can be caused by the many modes found in HOM fibre.

Condition of dispersion and dispersion slope compensation:
Dispersion correction is a method to eliminate positive dispersion produced by typical single mode fibers. The formula for wideband dispersion compensation is provided by

Work related to PCF:
Here we are reviewing the papers based on Photonic crystal fiber for dispersion compensation.

F. Gerome et al. designed a photonic crystal fiber for chromatic dispersion compensation, based on a certain regular pattern of air holes and pure silica is utilized. Two distinct capillaries sizes are used to create a two-concentric-core arrangement, which has an incredibly high negative chromatic dispersion of □2200 ps/nm/ km on 1550 nm was accomplished with a fiber design that used just pure silica and air holes of various diameters to provide a variation in refractive indices among the two cores. The novel design streamlines the realization of a preform and does away with the pricey MCVD process compared to the traditional MCVD DCCF. Depending on the total number of air hole layers within the two cores, the chromatic dispersion development can be easily changed to wavelength-division multiplexing purposes or single-band correction [5].

Gautam Prabhakar et al. have combined the ideas of an all-solid dual-core DCF and a DC-PCF to present a unique micro structured dual-core DCF. Two concentric circles of air holes have been added to the inner coating of the fiber to create the structure. This present fiber design's dispersion characteristics have been investigated with the full-vectorial finite-difference time-domain approach. The mode area was 67μm^2, and a narrow-band DCF demonstrates very substantial negative dispersion of about □42,000 ps/nm/ km within the wavelength range 1.543-1.547μm. This high negative dispersion achieved due to the air holes' introduction of a significant index difference among them and the silica In order to compensate the cumulative dispersion in a 100 km traditional single-mode fiber having such substantial negative dispersion, about 40 m of the fiber will be required resulting in a significant reduction in fiber length compared to earlier findings. In the spectrum of wavelengths of 1530–1560 nm, a dispersion value within- 860 and -200ps/nm/km has been found for wideband DCF designs. In long-distance optical communication networks, the fiber design ought to be beneficial in offering dispersion compensation [6] The PCF's dual-core circular structure, still will make manufacturing difficult. In addition, the designs failed to address nonlinearity which is a crucial PCF characteristic for optical transmission..

M. Imran Hasan et al. has been suggested that a photonic crystal fiber with latent dispersion adjustment have an oval core and an octagonal shape having isosceles triangular-latticed cladding. To explore the guiding qualities, a finite element approach having circular exactly matching layer is adopted. It is shown that it is attainable to achieve ultrahigh birefringence of 2.2× 10^{-2} and nonlinear factor of 52.7 W^{-1}km^{-1} at the wavelength of 1.55 μm in order to achieve averaged dispersion 544.7 Ps/nm/km the wavelength spectrum between 1.46-1.70 μm. The suggested PCF's design simplicity, or the fact that there aren't many design criteria, is its key benefit. The idea for fiber makes an excellent choice for retaining single polarization, compensating for residual dispersion, or using nonlinear optical communication due to its exceptional optical characteristics [7].

Jianfei Liao et al. developed an easy helical photonic crystal fiber design with an oval soft-glass tube within core area to simultaneously manage the dispersion characteristic and improve the effectiveness of birefringence and nonlinearity. Depending on the full-vector finite element technique, the optical characteristics of the basic transverse polarization modes are mathematically explored in depth. The numerical findings demonstrate that the basic x-polarized as well as y-polarized modes at 1.55 μm can have nonlinear parameters as high as 450.2 W^{-1} km^{-1} and 817.5 W^{-1} km^{-1} correspondingly, by using a high-index oval SF57 rod in the fiber central region. At 1.55 μm, the x-polarized phase dispersion values was as small as -491.16 ps/(nm.km) and the y-polarized phase dispersion value was as small as -399.98 ps/(nm.km), accordingly .The proposed helical PCF may be beneficial in extremely effective broadband signal processing applications by leveraging the benefits of ultra-flatten negative dispersion, huge nonlinearity, and ultrahigh birefringence [8].

Mahmood Seifouri et al. introduce an innovative circular micro structured glass fiber utilizing the photonic band gap light guidance approach during dispersion compensation within optical transmission networks. Silica material forms up the C-MOF core, and As2Se3 chalcogenide substance has been employed to fill the cladding network's pores. Because As2Se3 has a greater refractive index compared to silica, it may be employed to effectively manage the optical properties of C-MOF, especially dispersion. The confinement losses and dispersion of the proposed C-MOF at 1.55 μm are determined to have the following values respectively 0.013 dB/m and-2450 ps/nm/km by choosing the proper parameters of geometry of the structure. At 1.55 μm, the C-MOF's comparative dispersion slope measures approximately 0.00332 nm^{-1}. The suggested C-MOF may be used in wavelength division multiplexing, optical fiber transmission systems and dispersion-compensating devices [9].

Feroza Begum et al. designed a new wide-band high -speed gearbox system using DC-PCFs having nine rings that compensate dispersion. It is assumed that the analyzed PCFs' substance is silica (n = 1.45). An air holes network in the shape of a triangle makes up the cladding. The leading properties are studied using finite-difference approach with an asymmetrical completely matched absorbing sections boundary conditions. With just a few design factors, it can be achieved to achieve confinement losses below 10 $^{-4}$ dB/m in the whole S+C+L communications wavelengths as well as a bigger negative dispersion coefficient and improved dispersion slope compensation. In the spectral range of 1.46-1.63 µm. It is discovered that the recommended DC-PCFs exhibits a greater negative dispersion parameter of approximately -230 to-435 ps/(nm.km). The suggested device can be employed in optical fiber communication networks 40 Gb/s dense wavelength division multiplexing systems [10]**.** For the purpose of compensating the persistent dispersion in an optical communication connection, a PCF-in-PCF design is examined analytically by **D. C. Tee et al**. The concept of PCF-in-PCF is based on the notion that when the light crosses through the inner core to its outer core at phase-matching wavelength, dual-core PCF can yield an extremely significant negative dispersion. The structure that was suggested was examined using an established full-vectorial finite-element programme (COMSOL).

Within the spectral range of 1360 nm to 1690 nm, the optimized design exhibits a flatten and high mean dispersion of-457.4 ps/nm/km. For real-world situations, the response of the fiber dispersion characteristics to a ±2% change in the ideal values was investigated .Efficient mode area at 1550 nm was 9 µm^2 exhibiting a nonlinear coefficient of 11.26 W^{-1} km^{-1} as well as a splice loss of nearly 4.3 dB [11]. In range of wavelengths from 1350 to 1700 nm has been recommended by **Md. Mostafa FARUK** for an incredibly not linear dispersion compensating with five rings index guided photonic crystal fiber having drilled core. FEM are applied to study the numerical evaluation. Alternatively of a squared PML, a circular precisely match boundaries layer is employed to reduce confinement loss. Based on simulated studies, it will be feasible to modify the structural factors of the presented BC-HPCF to achieve high nonlinearity of 111.6 W^{-1} km^{-1} and dispersion of –2102ps/nm/km at 1550 nm. Furthermore, the suggested BC-HPCF is simply fabricated utilizing the present manufacture method. As a result, the idea for BC-HPCF can be used for a variety of nonlinear uses, including sensing, exceptionally fast optical communication networks and supercontinuum generation [12].

According to **Bikash Kumar Paul et al.** a transmission window with a very large negative dispersion can be observed in an improved squared photonic crystal fiber design. By using an effective full-vector finite element approach using anisotropic precisely matching layers (PMLs) for accurate computation of PCFs, the design is effectively validated. For the operating wavelength λ= 1550 nm, it simultaneously provides strong negative dispersion about -2357.54 ps/nm/km, mode are about 1.8 µm^2 and the nonlinearity almost 74.68 W $^{-1}$ km^{-1}. However, the planned fiber assures single mode functioning over the desired band, which extends from wavelength 1340 nm to 1580 nm. Using these exceptional optical properties, MS-PCF stands out as a dispersion compensating fiber in optical communication equipment[13] Mode coupling features, dispersion, confinement loss for the fiber, and the impact of certain structure factors on dispersion are calculated with full-vector finite element technique for a all-solid dispersion-compensating photonic crystal fiber that has been recommended by **Zhaolun Liu et al.** This study all-solid dual-concentric-core dispersion-compensating photonic crystal fiber was given analyzing a connection among phase matched wavelengths and coupling power with the changing of fiber structural parameters. In this design pure silica serves as the basic substance. A high-germanium-doped silica section serves as the central part of the fiber, and a low-doped fluoride or boron-doped silica section serves as the exterior core or cladding. The refractive index (RI) of this doped rod is kept to around ± 0.05.

The suggested fiber, according to findings, has a significant negative dispersion coefficient of □8465 ps/(nm.km) at 1550 nm. Splicing loss to the common single mode fiber and mode area and correspondingly, are 1.89 dB and 12.8 µm^2 at 1550 nm. Less than $1 \times 10^{\square 3}$ dB/km of confinement loss and less than $1\times10^{\square 2}$ dB/km of bending loss are observed at 1550 nm. But fabricating the PCF will be difficult because of its dual-core concentric design. Additionally, nonlinearity, another crucial PCF feature for optical communication, was not reported in this design. [14]. A novel round photonic crystal fiber provides efficient dispersion compensation including E to L spectrum ranges spanning from 1360-1625 nm has been presented by **M. M. Haque et al.** Using the finite element method and a precisely matching layer absorbed boundaries condition, its guiding characteristics are examined. According to the numerical simulation, the planned C-PCF exhibits both a relative dispersion slope (RDS) that is precisely comparable the value of a single mode fiber at 1.55 µm wavelength and a significant negative dispersion of between -248.65 and -1069 ps/(nm.km) spanning the E to L spectrum ranges. For wavelength of 1.55 µm, the actual area of the designed five rings C-PCF is 1.574 µm^2. Splice loss is caused by small efficient area, along with curved intermediate PCF may be utilized to appropriately interface among the envisioned C-PCF and SMFs. Therefore, we think that our suggested C-PCF can be connected to SMF without experiencing any serious difficulties. Additionally, it is discovered that the residual dispersion following the comparison of a 40 km longer SMF falls within 62 ps/nm, ensuring the deployment of C-PCF in a high rates WDM system[4]. A extremely negative dispersion-compensating photonic crystal which was hexagonally arranged annular air holes within the claddings of silica-based index-guiding PCF offered by Following the summary of research done by researcher is shown in table1

Table 1

Study	**Dispersion(ps/km/nm**	**Wavelength (nm)**	**Effective area(μm^2)**	**Nonlinearity(W^{-1} km^{-1})**	**Method/Technique**	**References**
D.C Tee	-457.4	1360-1690	9	11.26	Full vectorial finite element method	11
Jianfei Liao	-491.16 -399.98	1550	_	450.2 817.5	Full vectorial finite element method	8
M.Imran Hasan	-544.7	1460-1700	1.93	52.7	Finite element method	7
Feroza Begum	-230-(-435)	1460-1630	_	_	Finite difference method	10
F.Gerome	-2200	1550	_	_	Finite element method	5
Bikash Kumar Paul	-2357.54	1550	1.8	74.68	Full vectorial finite element method	13
Md.MostafFaruk	-2102	1550		111.6	Finite element method	12
Zhaolun Liu	-8465	1550	12.8	_	Full vector finite element method	14
Mahmood Seifouri	-2450	1550	15.8	6.2	Photonic band gap guiding mechanism	9
M.M Haque	-248.65-(-1069)	1360-1625	1.574	_	Finite element Method	4
Gautum Prabhakar	-42000	1544	67	_	Finite difference time domain method	6

CONCLUSION

Photonic crystal fibers (PCFs) represent a promising avenue for dispersion compensation in optical communication systems. Through their unique design, PCFs offer precise control over dispersion properties, enabling efficient compensation for the dispersion effects that degrade signal quality in fiber optic networks. Moreover, PCFs exhibit low loss and high nonlinear coefficients, making them suitable for a wide range of applications beyond dispersion compensation, such as nonlinear optics and sensing. Additionally, their compatibility with existing fiber optic infrastructure facilitates seamless integration into current communication networks. As the demand for higher data rates and longer transmission distances continues to grow, the need for effective dispersion compensation becomes increasingly critical. In this context, photonic crystal fibers offer a compelling solution, promising enhanced performance and versatility compared to conventional alternatives.

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