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Highly Non-Linear PCF for Spectrum Broadening in Communication Systems: A Review

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Abstract

As the next-generation optical communication is expected to route the high density and high-speed traffic of gigabit wireless systems, the conventional source in optical communication would be inadequate to accommodate the increased number of possible channels. Hence, the generation of supercontinuum using Photonic Crystal Fiber (PCF) would be an ideal solution, which needs specialized techniques and materials for its generation. Supercontinuum is a revolutionary concept where a spectrum broadened laser pulse with a continuous spectrum is the very property of it. The plethora of literature is available, where those works are aimed at presenting the various methods of supercontinuum generation, materials used, physical, electrical and optical characteristics associated with supercontinuum. This paper is confined to investigation on supercontinuum generation methods using highly non-linear PCF, the design factors affecting the dispersion and non-linearity during the generation of supercontinuum for spectrum broadening. In addition, a five-ring non-linear PCF with appropriate geometrical modifications has been proposed to achieve better values of dispersion and non-linearity at a communication wavelength of 1550 nm.

Keywords: Supercontinuum; Optical Communication; Photonic Crystal Fiber; Spectrum Broadening; WDM; Non-linear optics

1. Introduction

In an era of modern communication, a basic need of an end-user would be a high-speed communication to access internet resources, or any knowledge bases through IP based connections. Broadcasting through satellite communications naturally introduces a time delay of 1ms as a round trip delay. Further drawbacks of satellite communications include regular maintenance costs and installation expenses. Hence, optical communication established using fiber-optic links is more expected to satisfy the user needs. Possible signal degradation sources such as noise, fading effects and interference are almost nullified in optical communications. Multiplexing more number of channels in any communication link is a figure of merit. Super continuum would be an ideal choice to get benefits of multiple channel multiplexing.

Dispersion and non-linearity are mandatory to be evaluated to study the characteristics of supercontinuum. [12]. While lesser the dispersion and higher the non-linearity, a fiber is highly suitable for SC generation. Hence, these two metrics are targeted in order to evaluate the fitness of generated SC. A better choice to generate and analyze an SC is to make certain geometrical modifications and using certain simulation tools. If the evaluated parameters are very near to ideal values, it would be simple to meet the constructional procedures for core and cladding.

Supercontinuum which is highly nonlinear [1] is generated in a photonic crystal fiber, where the silica core is surrounded by air holes running throughout the fiber length [2]. Supercontinuum includes endlessly single-mode operation [3] in which the spot-size is easily controllable. A hexagonal, five ring structure has been taken as a base platform, where the diameter of rings has been modified to achieve better values of dispersion and non-linearity. Prior to the analysis of the recommended geometrical structure, findings of the detailed survey such as earlier achievements in the generation of supercontinuum, number of channels could be accomplished, amount of spectrum broadening, quality factor, cross talk and other essential characteristics related to supercontinuum.

Generating supercontinuum, not only depends on the source but by the way of transmission also. Since the property of SC is to be preserved, it needs a lightwave transmission through a fiber with highly non-linear characteristics while ensuring a less dispersion. Conventional optical fibers, consists of two concentric glass cylinders, with different refractive indices. This difference ensures a total internal reflection in the core-cladding boundary and hence the light wave propagation is confined inside the core. But commonly available fibers could offer only ~0.1% and hence several properties of the fiber are still subject to analysis [26].

Kaiser and Astle [46] suggested introducing certain microstructures in fiber, in order to modify the refractive index profile for better guiding properties. But, it was a very tough part of work to introduce such structures in the common fiber fabrication process. There exists a motivational work by [47], in which, lightwave propagation through the photonic bandgap effect was dealt with. With advent developments in fiber fabrication, the microstructures can be easily placed as per the required guiding characteristics [48]. PCF could be the best choice to achieve this nonlinearity as it allows much stronger mode confinement. It is shown in [14], the reduced diameter of the air holes in the first ring could produce less dispersion, and keeping the diameters of other rings larger could decrease the confinement loss value. Hence, it is a good choice to vary the geometrical values of microstructures to achieve the spectrum broadening.

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The rest of the paper is structured as follows: Section 2 describes the generation of supercontinuum and spectrum broadening. Section 3 describes the various designs of Photonic Crystal Fiber (PCF) for supercontinuum generation. Section 4 describes the optical parameters which can be optimized to enhance the supercontinuum generation. Section 5 describes the various applications of supercontinuum generation over measurements and communication. At last, Section 6 deals with the modified structure of PCF with results and discussions associated with the modified structure and conclusions are carried out with Section 7.

2. Generation of Supercontinuum and Spectrum Broadening

There exist no standards of how much spectrum broadening is needed and how much is the optical power output is expected from a generated supercontinuum [42]. In [4], a simple method of generating the supercontinuum has been presented. While fusing the two fiber structures by tapering it, a common narrow waist structure is obtained [4]. Couplers with 85mm long and diameter of 2 um and tamper transition of 35 mm were taken for supercontinuum generation. The spectrum was broadened over 400 to 1500 nm and this fused coupler is very useful where two optical sources are needed. These two independent supercontinuum sources will have intensity distributions and dispersion characteristics.

In [5], photonic crystal fibers are designed to provide high birefringence by introducing stacking capillaries and rods as reported in [6]. Ti-Sapphire laser was used to set up the pulses with different energies (875 nm, 76 MHz repetition frequency, 200 fs full width half maximum pulse duration) into the fiber in different polarization states. Spectrum broadening was obtained ranging from 400 to 1100 nm.

In [2], simulations were conducted to observe the pulse spectra broadening phenomena through the simulations with and without the presence of noise. An important fact had been unveiled through this simulation work. The presence of noise in the input photons affects the shape of the spectrum of the supercontinuum. The parameters used in [7] were used to maintain the generality. Simulations were first carried out in the absence of noise on the input pulse, using hyperbolic secant input pulses of 10 kW peak power and 850 nm of wavelength. When the pulse durations of full-width half maximum of (a) 50 fs and (b) 150 fs, was kept and simulated, spectral and temporal evolution at various points along the fiber was found to be good and the spectrum was available from 600 nm to 1400 nm at a fiber distance of z=10 cm.

In [8], an attempt has been made to improve the spectrum broadening range of 600 – 1500nm to a new range of 400 - 1700nm. The supercontinuum was generated by launching ultrashort pulses from Ti Sapphire laser in a highly birefringent PCF. The laser produces 100 fs pulses with a repetition rate of 80 MHz. The fiber length was taken as 5 m long with an elliptical core of dimensions 1.2x2.4 um^2. The zero-dispersion wavelength of the fiber has been calculated to be in the vicinity of 650 nm. The performance was analyzed by varying the pump laser polarization and respective spectrum broadening was observed. When the peak input power was 140mW and ultra-broad supercontinuum was obtained. Any further increase in the input power did not produce any significant changes in the spectrum broadening. Further, intensity variations were observed in supercontinuum while changing the wavelength of the input power source at 100 mW. It was found that supercontinuum was broader when the pump is adjusted to lay away from the zero-dispersion wavelengths.

In [9], index guided triangular PCF was analyzed by pumping with 140 fs pulses at several wavelengths in the positive slope anomalous dispersion region. Processes initiating supercontinuum generation are governed by the higher-order solitons fission, which leads to the soliton self-frequency shift (SSFS) by intrapulse Raman scattering associated with blue-shifted Cherenkov type phase-matched radiation. Supercontinuum spectra obtained at deep anomalous dispersion site exhibits broad bandwidth at relatively low P_0. The input P0 to achieve a saturated supercontinuum is decreased by increasing the degree of anomalous dispersion.

In [10], a cancellation of SSFS has been attempted. Basically, a broader spectrum is needed for higher channel requirements. Of course, there are requirements where a narrow bandwidth is needed over a range of wavelengths. It was proposed to use cross-phase modulation (XPM) which could possibly cancel the Raman SSFS. The central frequency of the interacting pulses is shifted by an XPM between a probe and a co-propagating pump pulse, (i.e.) either it is shifted down or shifted up depending whether it moves with the leading or the trailing edge of the pump pulse. Thus a balance is achieved where XPM induced up-shit compensates the Raman SSFS. The spectrum was within the wavelength limits from 870 - 900nm. This literature reveals a fact that how spectrum widening or thinning could be influenced by cross-phase modulation.

One fine application of supercontinuum generation in optical frequency metrology particularly applicable to all-optical atomic clocks. Since the fibers are exposed to high optical powers the functionality of the fiber degrades is a major limitation. In order to overcome this limitation and to generate supercontinuum with less optical power [11], it gives a proposal to use sub-wavelength diameter waveguides. The order of magnitude lower power requirement is lower against the existing limitation.

In literature [12], a preform to fiber fabrication has been presented. Through this method a microstructured fabrication with nonlinear chalcogenide glass, supercontinuum light was generated at near-infrared wavelengths. These types of fibers allow one to predict the presence of optical power or not. Hence, this could be applicable to high-end applications such as industrial, medical and defense areas.

3. Various Designs for Generation of Supercontinuum

Certain works of literature such as in [13], attempt to design a new type of highly nonlinear PCF with flattened dispersion properties. By varying certain geometrical configurations, it is highly possible to achieve this. Through simulations, an ultra-flattened dispersion of 0.5 ps/nm/km in a 1.45 um to 1.66 um wavelength with low confinement loss less than 0.06 dB/km. An eight ring PCF with an octagonal with isosceles triangular lattice cladding has been proposed to fabricate a novel PCF. Through this peculiar structure, a nonlinear coefficient of $27W^{-1}km^{-1}$ was obtained at 1.55 um wavelength. With such several figures of merits, apart from supercontinuum generation, this type of PCF can be used for optical parametric amplification, wavelength conversion, and ultra-short soliton pulse transmission. Almost similar geometry varying approach has been done in [14], where PCF with hexagonal, 6 rings microstructure has been proposed. This work claims to be applied for optical coherence tomography with ultra-high resolution and optical communication systems. The flattened chromatic dispersion of 4.0 ps/(nm.km) and is from 1.06 to 1.68 mm wavelength range (620 nm band) is showed by this type of highly nonlinear PCF (HN-PCF). Here, the confinement losses are less than 10^{-1} dB/km in the targeted wavelength range.

The nonlinear coefficients of the HN-PCF are more than 102.0, 70.0, and 51.0 $[Wkm]^{-1}$ at 1.06, 1.31, and 1.55 um respectively. Under the same family of geometry varying approach, in [15], another novel construction of PCF has been attempted. Hexagonal 6 ring microstructure has been proposed as shown in fig.1, but with hole diameter d_1 at the center, innermost two rings d2, and the outer ring d3 are in such a way that d1<d3<d2. The fiber can be pumped at 1.55 m using a laser source with an average power of 5 mW. This type of PCF has two zero-dispersion wavelengths at 1388 and 2068 nm with a very high nonlinearity of 500 $[Wkm]^{-1}$ at 1550 nm. The supercontinuum generation of this fiber is shown in Fig.1.

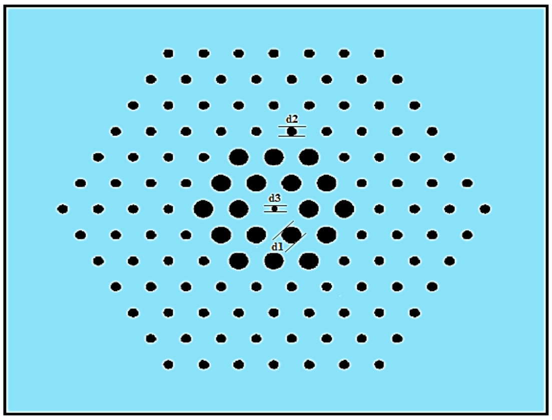


Fig 1. Hexagonal 6 ring PCF with d1=0.8μm, d2=0.4μm and d3=0.04μm

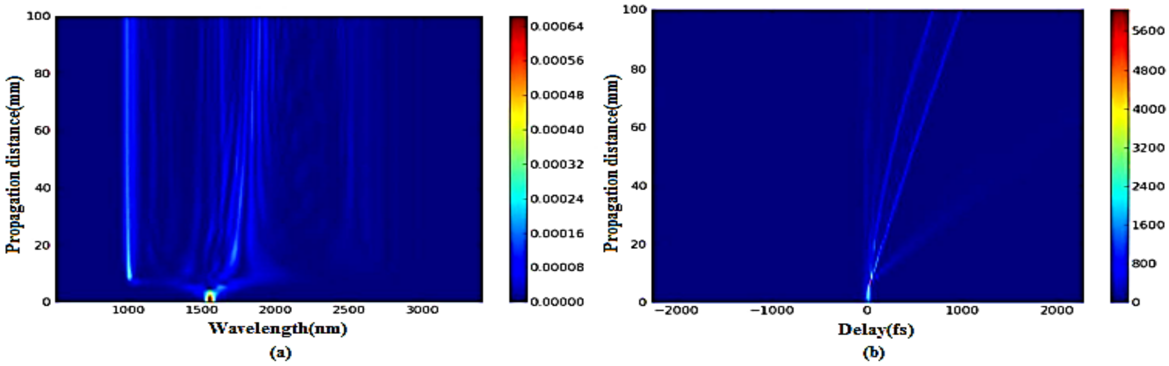


Fig. 2. Pule Broadening in (a) Spectral-Domain and (b) Time Domain

Yet another innovation has been presented in [16] where the core is kept hallow and the cladding are selectively filled using polymers in an 8-ring hexagonal PCF. This literature opens new prospects for PCFs. The simulation and numerical analysis prove the existence of white single-mode guided light in the air core. The transmission window of supercontinuum around occurs in the infrared range 1400–1750 nm, where the vacuum dispersion line (or air-line) crosses. Researchers have attempted to modify even the core shape as an ellipse which consists of an array of circular cores as mentioned in [17]. The transverse cross-section of the PCF is hexagonal on the outermost 5^{th} ring and approximated to circular ring in 2^{nd} ring. The first ring is elliptical, the diameters of the air holes specified promise to generate supercontinuum with zero dispersion wavelength with less confinement loss.

From the various works of literature, it is clearly known that, by changing the geometrical shapes, varying the diameters of air holes, varying the number of rings, several different characteristics are obtained. In [18], a triangular air core is proposed with a total of 4 rings. The diameters of the rings vary from to inner to outer is as d1<d2<d3<d4. Only the inner ring is of triangular shape and the remaining rings have been modeled as hexagon. While such a PCF manufactured with As2Se3 Chalcogenide Glass is pumped with 50 fs laser pulses of peak power of 3.5 kW at 4.1 μm, it offers the nonlinear coefficient as high as 1944 W−1 ·Km−1 at the pump wavelength.

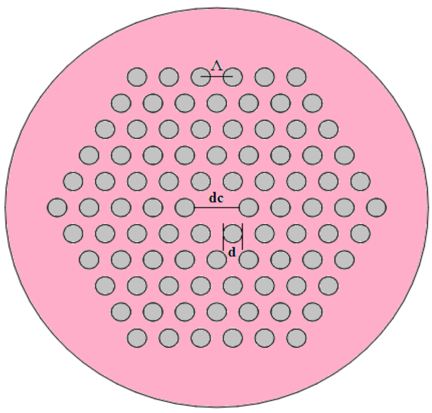


Fig. 3. Hexagonal 5 ring PCF with chalcogenide glass as a core with diameter dc=7μm, air-holes of diameter d=3 μm and hole-to-hole spacing Λ=5 μm.

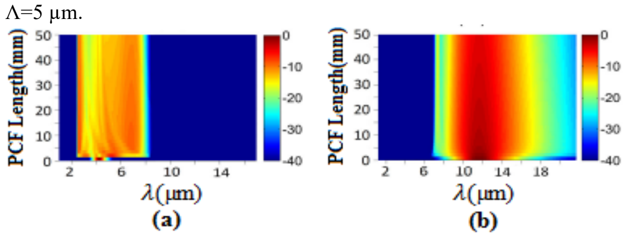


Fig. 4. Spectral broadening at (a) λ=4.25 μm and (b) λ=12 μm.

The supercontinuum in PCF with such broadband spectra of 2-15um is generated is the highest record in spectrum broadening. Almost a similar work has been done in [19], offering the ripple-free broad-spectrum, but with $As_{40}Se_{60}$

Chalcogenide glass with a total of 5 rings with all rings in hexagonal shapes as shown in fig.3. This literature reveals a fact that with the same background materials as used in PCF, step-index fiber (SIF) also could be used to generate supercontinuum with spectrum width as broad as 10 µm. Whereas a PCF could generate 13 µm when 100 fs input pulses of 10kW and 50kw peak powers at a wavelength of 4.45 µm and 12 µm are applied to PCF respectively as shown in Fig.4.

Wavelength Tunable optical sources are always attractive in various research fields because of their tuning properties [20-24]. Hence it is worthy literature that studies the various possible tuning methods in continuum generation that have been presented in [25] using a three fiber and two fiber cascaded structure. 1.2 to 1.4um tunable range of spectrum has been obtained in this work. A source of 24 W single-mode, randomly polarized, Continuous Wave (CW) Yb-fiber laser at 1071.5 nm was pumped into cascaded 3 fibers consisting a highly nonlinear PCF, a normal-dispersion highly nonlinear fiber, and a standard single-mode fiber. In [44], a circular air core is proposed with a total of 5 rings. The diameter of the air hole is varied from 0.5µm to 0.9µm and the pitch is varied from 2.10µm to 2.60µm. It offers a flattened dispersion of 0 ± 11.2 ps/nm/km. The structure and its confinement at the wavelength of 0.7µm are shown in Fig.5. In [45], an octagonal core with an air hole diameter 0.3 µm and pitch 1 µm is proposed as shown in Fig.6. It offers flattened dispersion and fundamental field distribution as like step-index fibers as shown in Fig 6.

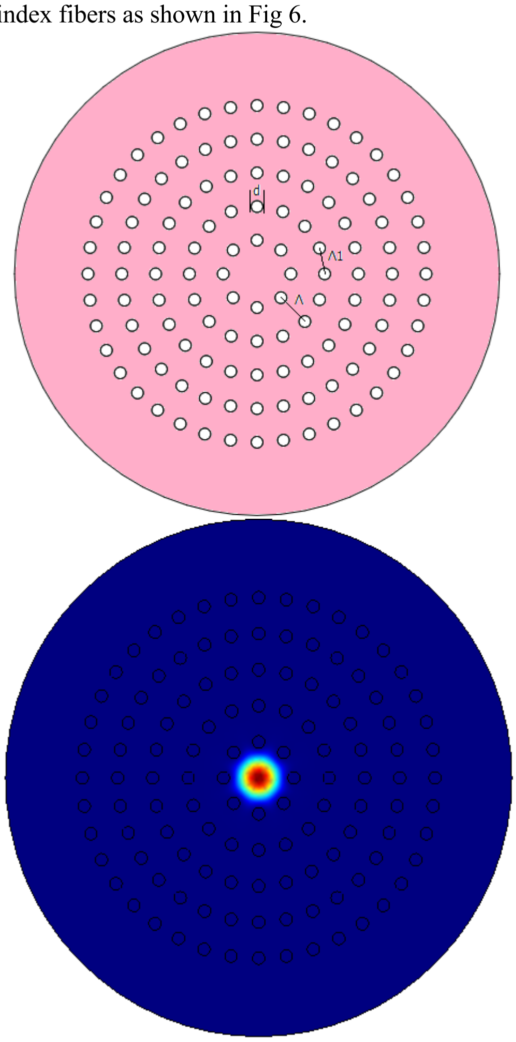


Fig. 5. Circular ring PCF with air hole diameter d=0.4 µm and pitch Λ=1 µm and its confinement of light

It is convenient always to generate supercontinuum with various pump sources over a wide range of wavelengths, with microstructured optical fiber with enhanced confinement along with the possibility to engineer the zero-dispersion wavelength (ZDW) into spectral regions [1, 26]. Hence a new design of 4 ring microstructure fiber with two ZDWs has been presented in [27]. Pumping at 1535 nm around the second ZDW yields almost flat supercontinuum over a range of 1350–1700 nm.

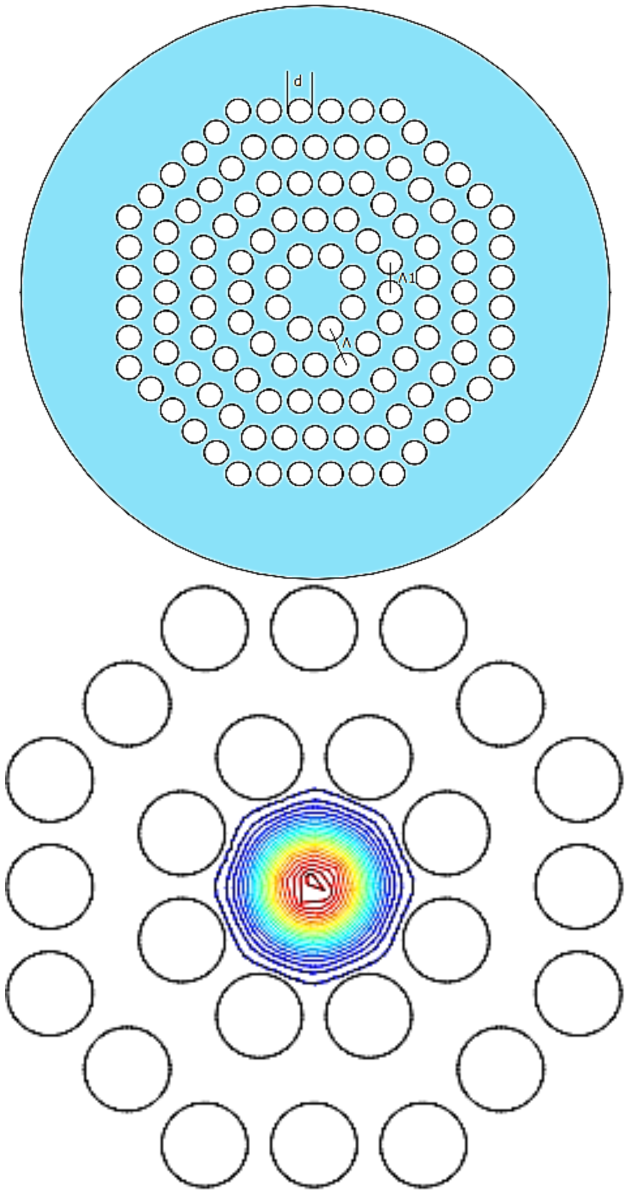


Fig. 6. Structure and Field distribution of the Octagonal PCF with d = 0.3 µm and Λ = 1 µm

The repetition rate of 3.3 kHz, the average power of 17 mW was produced at 1535 nm in a Q-switched microchip cobalt laser by launching a nominal pulse length of 3.1 ns. The laser beam was injected into the microstructured fiber by means of a 20-microscope objective and the spectra were recorded using an optical spectrum analyzer (OSA), [27].

An enhanced supercontinuum generation by properly engineering the dispersion has been presented in [28]. The dynamics of the spectral broadening has been studied in this literature; found that the zero-dispersion wavelength slightly decreases as a function of a length over 200 m. The resulting supercontinuum source spans from 650 nm to 1380 nm with an average output power of 19.5 W. The nonlinear mechanisms were investigated with the support of numerical simulations. [29] Reveals a fact that a noise burst obtained from an Erbium-doped fiber amplifier (EDFA) can be used as a pumping source instead of femtosecond pulse trains to generate a high average power supercontinuum from a PCF. Usually, the spectrum of supercontinuum obtained consists of ripples which depend on the input pulse distortions [30]. This normally happens in femtosecond pulse trains. Hence Amplified spontaneous emission (ASE), noise burst has been used in this work to generate a supercontinuum of wavelength 900 to 1400nm at 1um. Through this method, a stable operation could be achieved with a spectral density over -20dBm/nm with high dispersion tolerance.

4. Design Parameters that Enhance Supercontinuum Generation

The parameters that enhance the supercontinuum generation are as follows:

(1) Dispersion
(2) Nonlinearity
(3) Fiber length

As a thumb rule, the source should be operated, in a zero-dispersion wavelength close to the center frequency of the pumping source and in the lower half of the wavelength in the desired range. The process in which the pulse changes per unit distance of propagation is known as dispersion D (λ) (i.e. ps / (nm.km)) [26]. As a result of different frequency components of the pulse which travels at different velocities, a short pulse of light spreads in time due to D (λ).

The dispersion D is given as

$$D(\lambda) = \frac{d\beta_2}{d\lambda} = \frac{d}{d\lambda}\left(\frac{1}{v_g(\lambda)}\right) = -\frac{2\pi c}{\lambda^2}\beta_2 = -\frac{\lambda}{c}\frac{d^2 Re[n_{eff}]}{d\lambda^2} \quad (1)$$

where the operating wavelength is denoted as λ and effective index is denoted as n_{eff}, β_2 is denoted as dispersion parameter and velocity of light in a vacuum is denoted as c.

Dispersion can be controlled by modifying the geometrical parameters such as core diameter (d), Number of rings of air-holes in cladding, core material and very important parameter the hole-to-hole spacing known as pitch (Λ) [26]. The ratio between the core diameter and the pitch also plays a vital role in enhancing the supercontinuum generation. This ratio is commonly known as Normalized value that decides the mode of propagation. For a single mode of propagation, the normalized value should be less than or equal to 0.45 which is highly applicable for communication-related applications [26].

Non-linearity in PCF arises due to the dependence of refractive index on the optical power going through the core material [26]. The pulse broadening can be achieved by increasing the nonlinear property of PCF. The nonlinear co-efficient γ is given as:

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \quad (2)$$

where the wavelength is denoted as λ and n_2 is the refractive index of the core material cut-off wavelength λ_0. Non-linearity is inversely proportional to the effective mode area A_{eff} which is known as modal field distribution [26]. Its value should be less to increase the nonlinear effects of PCF. It depends on the parameters such as the diameter of the mode field and the core-cladding difference. The required length of the fiber depends on the pump source pulse length, (i.e.) shorter fibers for faster pulses and longer fibers for slower pulses are selected [26].

From the values taken from various works of literature, the relation of normalized value with dispersion and non-linearity for chalcogenide core PCF is shown in Fig 7. It is clear that for higher values of d/Λ dispersion is low and nonlinearity is high and for the lower value, it is vice versa. Where for silica core PCF as shown in Fig 8(a) & 8(b), for higher values of normalized value, the dispersion decreases and nonlinearity increases. Similarly, the variation of optical parameters with respect to the value of pitch is shown in Fig 9. For lower values of pitch both dispersion and nonlinearity increases whereas for lower values it is vice versa. These values tuned to obtain nearly zero dispersion and high nonlinearity to enhance the supercontinuum generation.

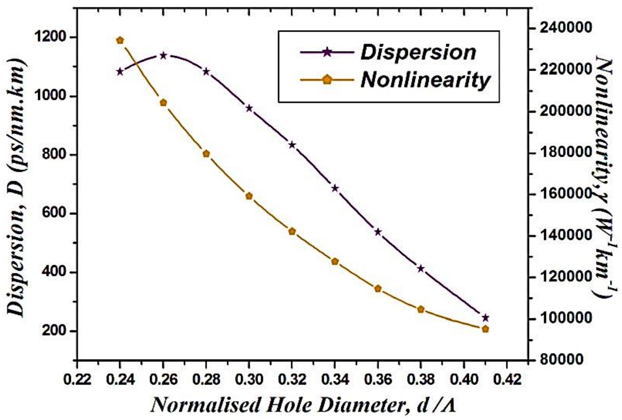


Fig. 7. Relation between Normalized value vs Optical Parameters of Chalcogenide PCF

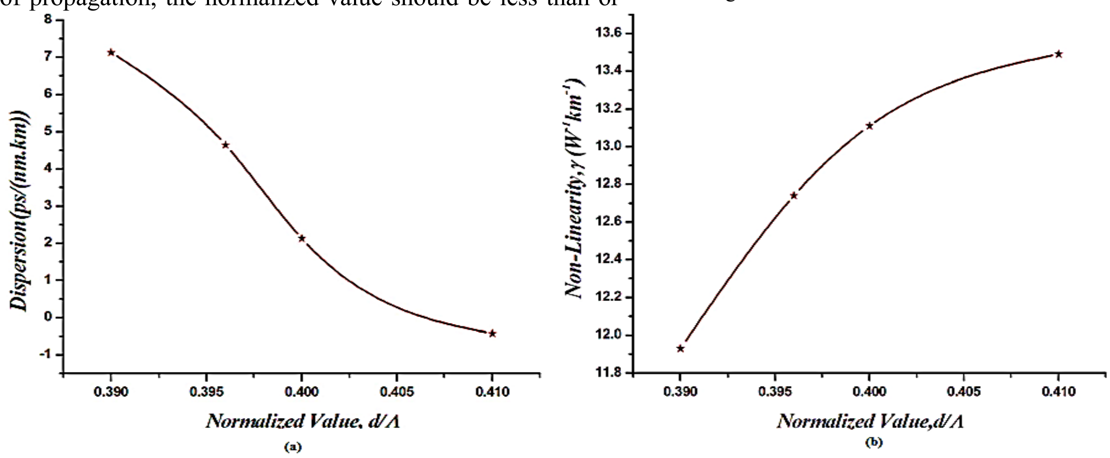


Fig. 8. Relation between Normalized value vs (a) Dispersion and (b) Nonlinearity of Silica core PCF

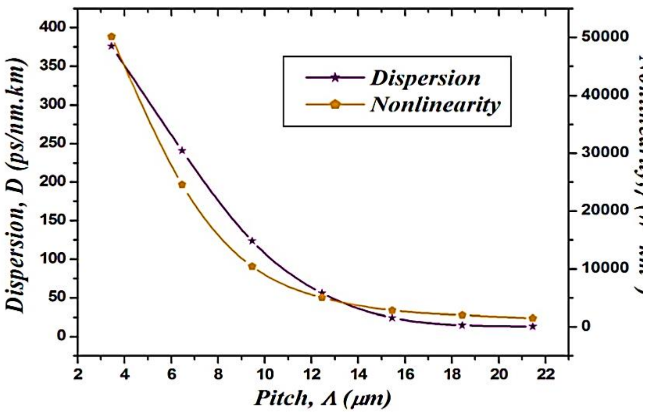


Fig. 9. Relation between Pitch vs Optical Parameters

The wavelength of the input source also plays a vital role in enhancing the supercontinuum generation. From various literature values, the comparison between wavelength vs optical parameters such as dispersion and nonlinearity are shown in Fig. 10.

From the graph, it is clear that for shorter wavelengths we obtain less dispersion and high nonlinearity whereas for longer wavelengths we obtain high dispersion and low nonlinearity. This can be overcome by increasing the number of air hole rings in the cladding region and air filling fraction of the air holes.

5. Supercontinuum in Measurements and Communications

Supercontinuum is capable of characterizing a 3D micro object trapped. So, as a whole, it could be used as optical tweezers [31-32]. A detailed experimental procedure has been presented in [43], which shows the possibility of trapping a 3D micro object and to obtain the scattering properties which are dependent on the nature of micro object such as, size, shape and its refractive index.

The measurement of the dispersion of PCF has been carried out in [33]. This method is highly suitable for designing high-speed optical communication networks at smaller wavelengths around 1300nm. This approach permits the direct monitoring of ultra-broadband (600 – 1200nm) group velocity dispersion in a test PCF

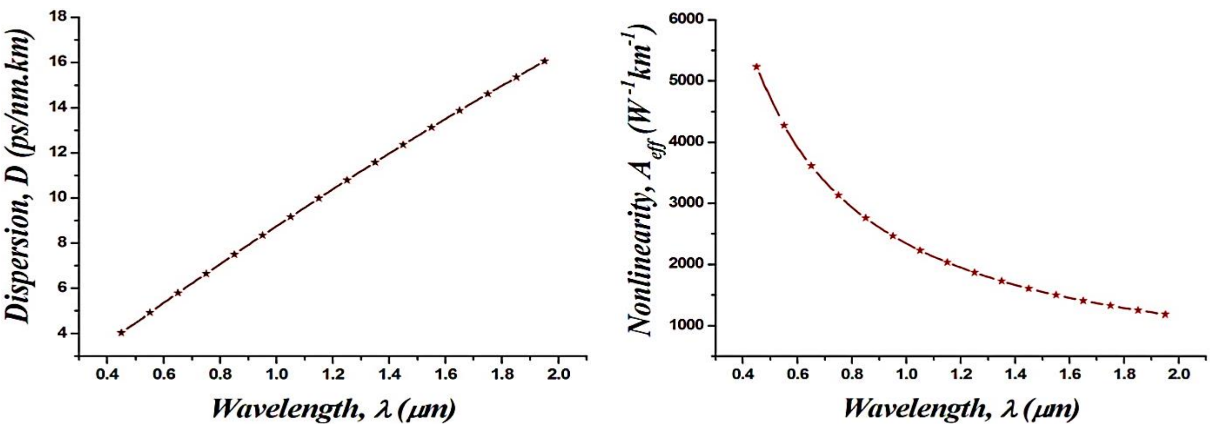


Fig. 10. Comparison between Wavelength vs Optical Parameters

Literature [34], is a possible method to apply supercontinuum for CLSM (Confocal Laser Scanning Microscopy) of biological samples prepared with a single fluorophore. In conventional optical sources, and existing supercontinuum sources, the intensity fluctuations were around 50% under certain input parameters. Hence it would not be the right choice for CLSM. Whereas a white light supercontinuum could have only less than 1% amplitude variation when it was employed to perform sequential CLSM of multiple-labeled guinea pig detrusor.

Measurements of dispersion in optical fibers can be performed using a variety of time-of-flight, phase-shift, interferometric [35], or degenerate-four-wave-mixing-based techniques [36]. A new technique has been proposed in [37] to measure the dispersion using the time of flight method with the help of supercontinuum.

An etalon has been employed to impose a spectral fringe pattern on the broadband pulse, to measure the dispersion with a high spectral resolution (< 1 nm) over a several-hundred-nanometer wide spectral region. Through this method, an error of less than 0.1% was obtained in dispersion values. Since supercontinuum based optical sources are common in research laboratories and other standard spectrum analyzers, photodiodes and oscilloscopes can be employed for detecting supercontinuum [37].

Broader the spectrum, more number of channels could be accommodated in the communication system. Supercontinuum enjoys the broadened spectrum is the main reason to use it in optical communication systems. Earlier systems were with several hundreds of channels, facing difficulties with multiple optical sources and less channel spacing. Over 100-channel wavelength division-multiplex (WDM) transmission has been demonstrated [38-39]. Supercontinuum Multi-Carrier Source (SC-MCS), such as 110-channel, 25 GHz-spacing transmissions, and 313-channel, 50 GHz-spacing transmissions were demonstrated in [40,41] respectively. In [42], an experimental setup generated a supercontinuum and it was tested in a fiber optic communication system of 1046 channels. 785 channels out of 1046 could have Q factors above 15.6dB and BER of 10^{-9} without forward error correction (FEC). The cross-talk was under -21/dB when the channel spacing was 6.25GHz. An average Q factor of 11.1 dB was obtained for all 1046 channels which correspond to BER of 10^{-14} while using FEC.

The following research areas related to supercontinuum would be worth to concentrate to make a new era of modern optical systems.

1. Ultra-wideband (greater than 13um)
2. Easily tunable with less number of tuning parameters.
3. High power availability of supercontinuum
4. Less amount of dispersion losses.
5. Less number of spikes in the broadened spectrum.
6. Ease of manufacturing the proposed PCF.
7. Generation of supercontinuum with less input optical power.
8. Cost of the background materials to be kept as less as possible.
9. Nonlinearity more than 1944 $W^{-1} \cdot Km^{-1}$
10. Accommodation of channels more than 1046 in optical communication systems

6. Modified Structure of PCF

Taking into the consideration of supercontinuum in optical communication, we aim to design a PCF with low dispersion and high nonlinearity using a finite element method (FEM) [14]. The core of a proposed design is a solid core made of silicon which provides better confinement of light. The cladding consists of the number of circular air-holes [14] [49]. Low dispersion and high nonlinearity can be achieved by decreasing the core diameter (d) and air - hole distance (Λ) [49]. If the normalized value $d/\Lambda \leq 0.45$ then the PCF act as single-mode fiber [49] [50] [51]. With this motive, this work proposes a low dispersion and high nonlinearity by introducing five circular ring-air cladding with a solid core of the hexagonal structure.

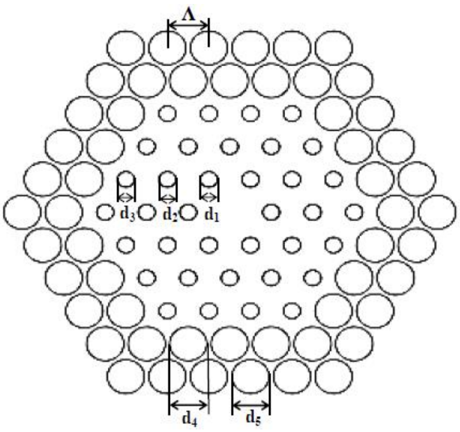


Fig. 11. Geometrical Structure of the Modified PCF.

The geometrical structure of the proposed PCF is shown in Fig.11. This PCF comprises five rings of air holes arranged in silica background. The air-hole diameter and hole-to-hole spacing are denoted as d and Λ, respectively. The design parameters of the proposed PCF are $d/\Lambda = 0.41$ and $\Lambda = 1.9\mu m$. Here, we assign the diameter of the circular air-holes in the first three rings to be the same and the diameter is slightly increased in the last two rings (i.e., d1=d2=d3 < d4=d5). We clearly demonstrate that the variation in the diameter of the first three rings helps in tuning the optical properties in favor of SC.

7. Results and Discussions

Optical properties of PCF such as dispersion and nonlinearity are compared by varying the diameter of the first three rings periodically and keeping the diameter of the last two rings and pitch as constant and also compared the properties such as effective mode area (Aeff) and effective indices (neff) that are highly useful in calculating the dispersion and the nonlinearity values.

Dispersion: As denoted in Eq. (1), Dispersion, $D(\lambda)$, is directly proportional to the effective index (n_{eff}), thus it decreases with decreasing neff. Figure 12(a) shows the variation of effective indices along the wavelength and Figure 12(b) shows the variation of dispersion along the wavelength (from 1μm to 1.65 μm).

Fig.12 (a) shows that an effective index reduces with increasing wavelength, which is directly proportional to dispersion. As a result, dispersion increases with increasing wavelength as shown in Fig.12 (b). But, we can make zero in communication window i.e. 1.55μm wavelength which is highly applicable for SCG. In this we obtained nearly zero dispersion, D = -0.4311 ps / (nm.km) at 1.55 μm wavelength for d1=d2=d3=0.7775μm.

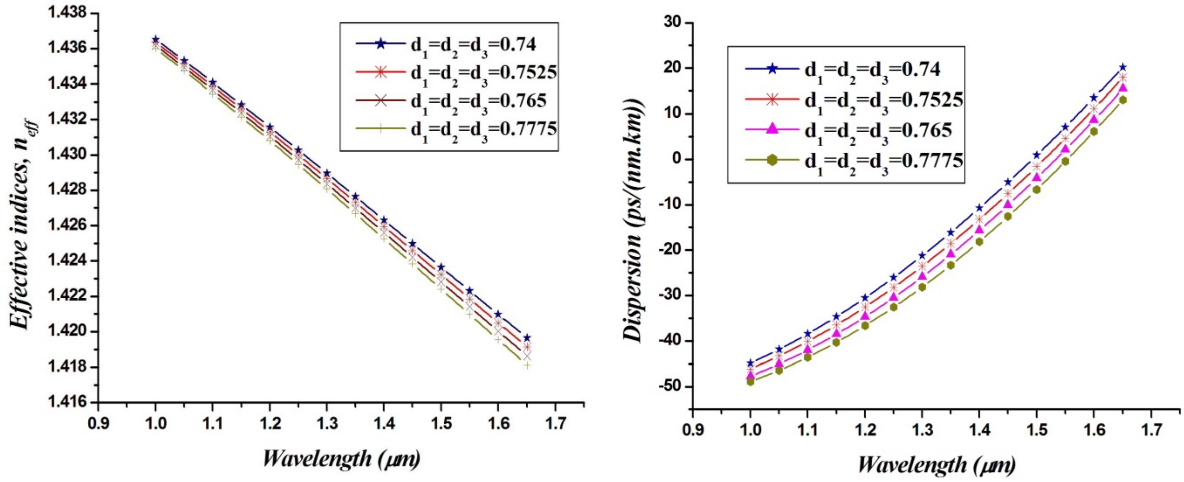
***Nonlinearity*:** The Nonlinearity (γ) as denoted in eqn.2 is inversely proportional to the effective mode area (A_{eff}), thus it increases with decreasing A_{eff}. The effective mode area is denoted as A_{eff} and it is defined as

$$A_{eff} = \frac{\left(\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}|E|^2\,dx\,dy\right)^2}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}|E|^4\,dx\,dy} \quad (3)$$

where E is defined as the electric field derived by solving Maxwell's equations [14]. Fig.13(a) shows the variation of effective mode area along the wavelength and Fig.13(b) shows the variation of nonlinearity along the wavelength (from 1μm to 1.65 μm).

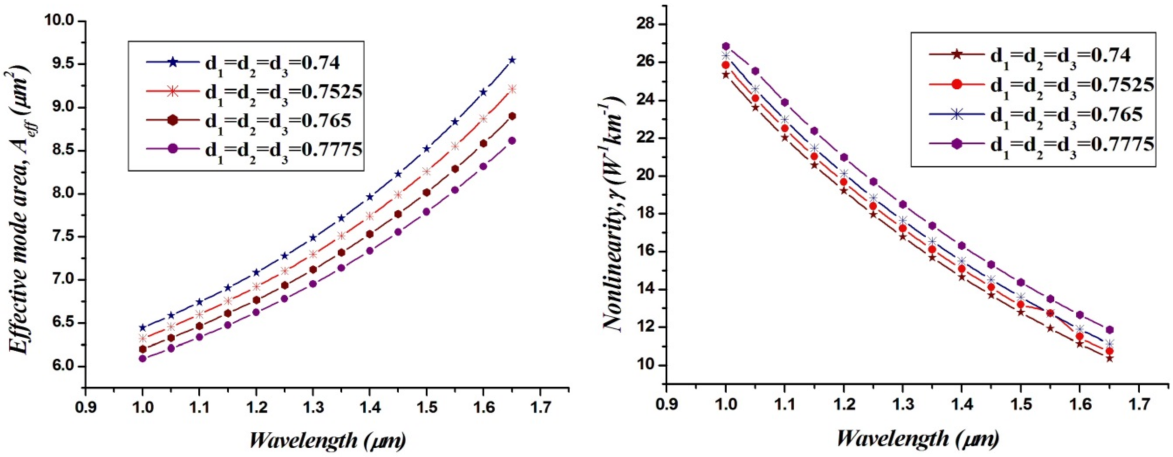
Fig.13(a) shows that an effective mode area increases with an increasing wavelength which is inversely proportional to nonlinearity. As a result, nonlinearity decreases with increasing wavelength as shown in Fig.13 (b). But, we can increase nonlinearity in the communication window i.e. 1.55μm wavelength which is highly applicable for SC. In this we obtained comparatively high nonlinearity, $\gamma = 13.11\ W^{-1}km^{-1}$ at 1.55 μm wavelength for d1=d2=d3=0.7775 μm.

Parameters	**[29]**	**[44]**	**[17]**	**[18]**	**[51]**	**Proposed work**
Core Material	Erbium (or) Ytterbium	Silica	Silica	As_2Se_3 chalcogenide	Lead Silicate	Silica
λ (nm)	1040	800 - 2800	1550	4100	1550	1550
D(λ) (ps/nm.km)	Zero	0 ± 8.2	-562.52	-	40	-0.4311
γ ($W^{-1}km^{-1}$)	37	-	130.20	1944	923	13.11



(a) (b)

Fig. 12. (a) Variation of Effective indices along the wavelength and (b) Variation of Dispersion along the wavelength



(a) (b)

Fig. 13. (a) Variation of Effective mode area and (b) Variation of nonlinearity along the wavelength.

8. Conclusion

The values of the optical parameters of the proposed structure are compared with the previously reported works in Table.1. It is evident that the proposed PCF provides low dispersion compared to the dispersion of prior works. This result is achieved in a telecommunication wavelength of about 1.55µm. The nonlinearity obtained is not as much as better when compared to the nonlinear properties of the prior structures of PCF. Based on the earlier worthy researches prior to two decades, it is well observed that, supercontinuum generation plays and still would play a vital role in modern optical communications at incredibly higher data rates. Not only in the field of communication, has supercontinuum found its application in various measurement areas, where its high non-linearity property is highly useful. Since the research topics in any domain of science are eternal, at any time, a saturation point could never arrive. The works of literature may be sometimes contradictory to each other, as pointed out in this survey. The main idea to design PCF is to get a broader spectrum than in SIF. But certain works of literature refereed in this survey reveal that, by changing the background materials, it is possible to generate supercontinuum in SIF itself. It would be a challenging task for a researcher in the area of supercontinuum generation to break all the milestones achieved in earlier works. A systematic approach with sufficient mathematical background and sufficient knowledge on the simulation environment, one can arrive at a newer enhanced result in supercontinuum related issues. At last, PCF with low dispersion and high nonlinearity for supercontinuum generation has been successfully designed at 1.55 µm by increasing the geometric parameter d/Λ and a constant pitch (Λ). In this design, dispersion decreases and nonlinearity increases with increasing d/Λ, which is very much suitable for supercontinuum generation.

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