Design and analysis of a highly nonlinear composite photonic crystal fiber for supercontinuum generation : visible to mid-IR

A Dissertation submitted towards the partial fulfilment of
the requirement for the award of degree of

Master of Technology in
Microwave and Optical Communication Engineering

Submitted by
Purniya Jamatia
2K14/MOC/13

Under the supervision of
Dr. Ajeet Kumar
Assistant Professor

Department of Applied Physics and Department of
Electronics & Communication Engineering

Delhi Technological University
(Formerly Delhi College of Engineering)

JUNE 2016

DELHI TECHNOLOGICAL UNIVERSITY

Established by Govt. of Delhi vide Act 6 of 2009

(*Formerly Delhi College of Engineering)*

SHAHBAD DAULATPUR, BAWANA ROAD, DELHI-110042

CERTIFICATE

This is to certify that the work which is being presented in the dissertation entitled " **Design and analysis of a highly nonlinear composite photonic crystal fiber for supercontinuum generation : visible to mid-IR** " is the authentic work of **Purniya Jamatia** under my guidance and supervision in the partial fulfilment of requirement towards the degree of Master of Technology in Microwave and Optical Communication Engineering jointly run by Department of Applied Physics and Department of Electronics & Communication Engineering in Delhi Technological University during the 2014-16.

As per the candidate declaration this work has not been submitted elsewhere for the award of any other degree.

Dr. Ajeet Kumar (Supervisor)
Assistant Professor
Department of Applied Physics

Prof. S. C. Sharma	**Prof. Rajesh. Rohilla**
(Head of Department)	**(Acting Head of Department)**
Department of Applied Physics	**Department of Electronics &**
	Communication Engineering

DECLARATION

I hereby declare that all the information in this document has been obtained and presented in accordance with academic rules and ethical conduct. This report is my own, unaided work. I have fully cited and referenced all material and results that are not original to this work. It is being submitted for the degree of Master of Technology in Microwave and Optical Communication Engineering at Delhi Technological University. It has not been submitted for any degree or examination in any other university.

Purniya Jamatia
M. Tech, MOCE
2K14/MOC/13

ABSTRACT

In this thesis, a novel composite photonic crystal fiber structure has been designed with tellurite as the cladding and chalcogenide as a core material. To increase the nonlinearity the rods of the chalcogenide glass material has been inserted around the core region. The reported structure offers very high nonlinearity of 1042 W^{-1} km^{-1} at 2800 nm pump wavelength with low and flattened dispersion approximately -11 $ps.nm^{-1}$ km^{-1}. Effective mode area of the propagating mode has been achieved as 6.46 μm^2 at pump wavelength. Such highly nonlinear composite photonic crystal fiber structure has potential candidate for nonlinear applications such as slow-light and supercontinuum generation. Pumping at 2800 nm results in supercontinuum spectrum spanning 0.5 to 6 µm using 8 mm long photonic crystal fiber pumped with femtosecond laser pulses of peak power of 3 kW. Such broadband supercontinuum has applications in field of telecommunication, optical metrology, medical science, cosmological studies, nonlinear microscopy, optical coherence tomography, cosmological studies and ultra-short pulse generation as most of these applications require to be operated in IR region.

LIST OF RESEARCH PRESENTATION & PUBLICATION

Journal Publication

- Purniya Jamatia, Than Singh Saini, Ajeet Kumar, Ravindra Kumar Sinha, "Design and analysis of a highly nonlinear composite photonic crystal fibers for supercontinuum generation: visible to mid-IR" *Optical Society of America Journal for Applied Optics*, Under Review (2016).

Conference Publication

- P.Jamatia, T.S Saini, A.Kumar, "Design and analysis of a highly nonlinear composite photonic crystal fibers" Conf. Proceeding OSA Young Student Congress on Photonic Technology, MNIT Jaipur,16-17 April, 2016, OSA_YSC_115, 38-40 (2016).

ACKNOWLEDGEMENT

I take this opportunity as a privilege to thank all individuals without whose support and guidance, I could not have completed my project successfully in this stipulated period of time.

First and foremost I would like to express my deepest gratitude to my supervisor **Dr. Ajeet Kumar**, Asst. Professor, Department of Applied Physics, for his valuable support, patience, guidance, motivation and encouragement throughout the period this work was carried out. I would also like to thank Than Singh Saini, Research Scholar, for valuable time and interest in this project. I am grateful to both for closely monitoring my progress and providing me with timely and important advice, their valued suggestions and inputs during the course of the project work.

I am deeply grateful to the **Prof. S. C. Sharma** (Head of the Applied Physics Department), **Prof. Prem R. Chadha** (Head of the Electronics and Communication Engineering Department), **Prof. R. K. Sinha**, **Prof. Rajiv Kapoor** and **Dr. Yogita Kalra** for their support for providing best educational facilities.

I also wish to express my heartfelt thanks to the classmates as well as staff at Department of Applied Physics and Department of Electronics & Communication of Delhi Technological University for their goodwill and support that helped me a lot in successful completion of this project.

Finally, I want to thank my parents, brother and friends for always believing in my abilities and for always showering their invaluable love and support.

Purniya Jamatia
M. Tech. MOCE
2K14/MOC/13

LIST OF CONTENTS

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 General

The research based on the photonic crystal fiber (PCF) is a great achievement in the field of optics and photonics as PCF has the property of guiding the light not only by the refractive index differences but also by the structural modifications of the photonic crystals [1]. Higher nonlinearity in the fibers is in much attention, as it has applications in supercontinuum generation (SCG), wavelength conversion, pulse compression, parametric amplification, etc [2,3]. Nonlinearity occurs in fiber due to intensity-dependent phenomena: (1) change in refractive index (RI) of the medium with optical intensity and (2) an inelastic scattering phenomenon [3]. First process is called the Kerr effects. Power dependence on RI takes place in Kerr effects. Three different effects result due to Kerr nonlinearity effects such as self phase modulation (SPM), cross phase modulation (CPM), and four wave mixing (FWM) [3]. Stimulated effects could be induced due to the inelastic scattering phenomenon at high power level such as stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS) [3]. For achieving high nonlinearity, highly nonlinear glasses such as chalcogenide and tellurite are highly desirable which has high nonlinear coefficient (i.e. γ) of ~3.0 x 10^{-18} m^2/W [4-5] and ~5.9 x 10^{-19} m^2/W [5-8] respectively. The high nonlinear coefficient counteracts the optical losses to a large extent [15, 16]. Due to high nonlinear coefficient, threshold power requirement is low, hence PCF using highly nonlinear coefficient possessing material such as As_2S_3 is suitable and attractive medium for SCG [8]. Laser pulses with narrow bandwidth are converted to pulses having very broad bandwidth in SCG. SC is usually generated by launching ultra short pulses (femto-seconds or pico-seconds) in a highly nonlinear PCF with pumping near the zero dispersion wavelength (ZDW). ZDW is the wavelength where the waveguide dispersion and material dispersion cancel one another. Different wavelengths travelling with different speeds in a fiber result in material dispersion. Waveguide dispersion is dependent on a structure as the wave's phase velocity is dependent on its frequency due to its structure's geometry. The As_2S_3 based chalcogenide glass usually operates in the region of the infrared (IR) and mid-IR [6, 8]. It has high linear refractive index, high optical nonlinearity, ultrafast nonlinear response, low to moderate TPA (Two Photon Absorption) effect and long wavelength transparency [8]. Strong characteristics vibrational transitions of the most of the molecules occur in IR region, which could be used for aiding in the diagnostics dealing with physical, chemical, biological issues [13].

With the help of multi-physics solution software "COMSOL" the effective area and nonlinearity are calculated for sets of value of different wavelengths and dispersion curve is plotted, as SCG relies on the dispersion profile and its input characteristics.

1.2 Thesis objectives

- To study the characteristics of photonic crystal fiber and its applications.
- To study the recent advancements in the field of photonic crystal fibers.
- To purpose a new structure of photonic crystal fiber, made of composite materials-

  Tellurite as a cladding material and chalcogenide material as a core with small chalcogenide rods around it, for nonlinear applications using software tools i.e. COMSOL.
- To calculate effective mode area, nonlinearity, dispersion for the supercontinuum generation using software tools i.e. COMSOL, MATLAB.
- To study the simulation results for different parameters of composite photonic crystal fibers.

1.3 Thesis organization

The report is organized as follows:

Chapter 2 includes the literature review of the research papers and survey papers that were studied during the course of the project. Different photonic crystal fiber structures made of different materials were discussed in this chapter.

Chapter 3 includes the theories and concepts related to the design structure.

Chapter 4 includes the results and simulations of the implementations performed on the software platform – COMSOL, & MATLAB.

Chapter 5 includes the different approaches to model the design structure.

Chapter 6 includes design structure of the composite PCF made of tellurite as a cladding material and chalcogenide as a core material with small chalcogenide rods around it. Characteristics are studied with the variations in the parameters of the PCF.

Chapter 7 discusses the conclusions withdrawn from the results obtained and the future scope in the direction of the project.

CHAPTER 2
LITERATURE REVIEW

Non-silica glasses like chalcogenide glasses As_2S_3 and As_2Se_3 are the two most widely used for the nonlinear applications as it has very high nonlinear coefficient as compared to silica (~100 times larger)[8,25] and operate in infrared (IR) and mid-IR [6,8], due to which optical transparency upto 25 µm could be achieved [13]. With silica material, the broadening in the SC spectrum is limited by the material absorption beyond 2.5 µm, hence limits the spectrum into mid-IR region [13]. The propagation losses of silica, ZBLAN and tellurite fibers are very large beyond 5 µm, hence chalcogenide fibers are used instead of these fibers to achieve the broadband SC in the mid-IR region [16]. Even though As_2Se_3 has high nonlinearity compared to As_2S_3, it has higher loss compared to the latter hence As_2S_3 is more attractive to be used for nonlinear applications [17]. As_2S_3 glasses also have lower TPA coefficient in the telecommunication wavelength range and higher material stability compared to As_2Se_3 [8], hence As_2S_3 has been chosen as the material in this project. Operation in visible to IR region is of great significance in the field of optics, as it has been reported that visible to near-IR wavelengths are used for several biological applications as absorption by tissues in this spectral window is relatively low [13, 28]. Such a source has potential applications in optical coherence tomography [32] and coherent anti-Stokes Raman specrtooscopy [33]. Since the SC spectrum extends to the visible wavelengths, it covers the transparency window of water, which is of much importance for biology. So this finds applications in realizing visible broadband sources for Raman spectroscopy [32], optical coherence tomography [32] and frequency metrology.

Experiments on nonlinear applications in IR region have already been presented by many researchers [12–27].

1. SC generation through dispersion engineering of chalcogenide microstructured fibers have been presented by Karim *et al.* [12], producing a spectrum ranging from 1.3 µm to 11 µm with peak power of 3 kW at a pump wavelength of 3.1 µm.
2. Saini *et al.* [13] modeled a triangular core graded index-PCF using As_2Se_3 chalcogenide glass generating broadband mid-IR SC spectra spanning 2-15µm.
3. Saini et al. [14] generated SC spectrum spanning 1.2 – 15 µm using 8 mm long equiangular spiral PCF structure pumped with 50 fs laser pulses of peak power of 500 W.

4. Feng *et al*. [15] presented the fabrication of holey fiber using tellurite for nonlinear application such as SC with band ranging from 0.9 to 2.5 µm with 9 cm of the fiber.
5. Liao *et al*.[16] fabricated and characterized chalcogenide-tellurite composite miscrostructure fiber resulting in SC spectra ranging 800-2400 nm.
6. Domachuk *et al*. [17] reported broadband mid-IR SC ranging from 789 nm to 4870 nm measured at 20 dBm below the spectral power. ZDW is the most dependent parameter in choosing the pump wavelength for the SC generation.
7. Many researches on ZDW have been already reported with different materials. Chaudhari *et al.* [18,19] designed a fiber for zero chromatic dispersion using As_2S_3 material and obtained the ZDW at 1.5 µm using core size of 500 nm.
8. Wide researches on SC generation have already been reported using silica fibers and non-silica fibers too. Ranka *et al*. [20] presented optical continuum of 550 THz width using air-silica microstructured optical fiber with 100 fs pulse duration of kW peak power near infrared region.
9. Xia *et al*. [21] proposed SC generation using silica fibers with spectrum ranging from ~0.8 to 3 µm in less than 4 mm fiber using nanosecond pulses. Extensive studies and researches using non-silica fibers for nonlinear applications have been on the attention lately.
10. Non-silica fibers such as chalcogenide, tellurite possess high nonlinear coefficient [4-8], making it suitable for broadband SCG. Liao *et al*. [22] designed a fiber using tellurirte material made of hexagonal core diameter of 1 µm. Changing the diameter ratio of holey region to core (DRHC), Liao *et al.* [22] succeeded in generating one octave flattened SC with pump wavelength of 1064 nm picoseconds laser.
11. Hudson *et al.* [23] demonstrated octave spanning spectrum in a sulphide based chalcogenide tapered fiber using only 77 pJ pulse energy.
12. Granzow *et al.*[24] studied SC generation in chalcogenide-silica step index fiber resulting in the broadband SC out to 4 µm in a length of 1cm, pumping at 1550 nm.
13. Liao *et al.* [5] modeled composite PCF structure using As_2S_3 glass and tellurite resulting in higher nonlinearity as high as 31.37 W^{-1} m^{-1} at 1.55 µm wavelength with significantly large effective mode area.
14. Xie et *al.* [25] studied and generated spectrum covering from 2.1 µm to 3.2 µm in a 1 mm length of fiber pumped at a wavelength of 2.5 µm using 100 fs pulse.

15. Chaudhari *et al*.[26] presented a design made of chalcogenide core and tellurite cladding ,generating SC spectrum of 20 dB ranging from 800 nm to 2400 nm using 1.85 µm pump wavelength.
16. Kudlinski *et al*. [27] designed dispersion-engineered PCF structure and succeeded in generating SC from 650 nm to 1380 nm with an average power of 19.5 W.

From the studies it could be noted that wide research on PCF structure made of highly nonlinear materials such as chalcogenide and tellurite have proved fruitful in generating the broadband SC which could not be achieved with standard fibers. Chalcogenide being highly nonlinear material of the order of 10^{-18} m^2/W, increases the nonlinear coefficient, which inturns decreases the effective area of the fundamental mode. Flat dispersion with small slope is desirable for SCG. SC highly relies on dispersion curve and has smooth profile when PCF has flat dispersion with small slope and a zero crossing wavelength near or at the pump wavelength [13,23]. From the study it could be inferred that the need of high power is reduced with a pumping near a zero dispersion wavelength (ZDW) with higher nonlinearity. Generated SC power gets smoothened with pumping near ZDW [24]. It is also noted from the survey that there is a dependence of the geometrical parameters on the dispersion curve, which is also dependent on the effective index of the PCF. This ultimately has effects on the spectrum of the SCG. Highly nonlinear composite PCF is designed so as to counteract the need of using a very high pump power. Using the property of chalcogenide having high nonlinearity coefficient, the desired flattened dispersion curve is achieved with very high nonlinearity.

CHAPTER 3

PHOTONIC CRYSTAL FIBERS

3.1 Introduction

PCF is a special fiber where the optical properties are based on position, geometry and size of the air holes arranged in an particular array [9, 10]. It has internal structure made of capillaries of air holes arranged in an array usually a hexagonal array [9, 10]. Removing one or more capillaries in the PCF result in the defects. Array could be symmetric or asymmetric. Light propagates due to its defects in the fiber structure [9, 10]. There are many limits related to the conventional optical fibers which could be overcome by the new class of optical fiber i.e PCF. Limited core diameter in the single mode regime, limited material choice, modal cut off wavelength are some of the limitations faced by the conventional optical fibers[9]. PCF has the properties of an optical fiber and the unique property of confining light in its defect , hence advantageous than the conventional fibers. Design of the PCF structure is very flexible as the characteristics are dependent on the parameters of the structure. Type of lattice, lattice pitch, air hole shape, diameter and refractive index of the material used could be manipulated to get the desired propagation [9]. It is also possible in manipulating the dispersion properties of the fiber which is difficult in conventional optical fiber. With the selection of the materials, zero, low or anomalous dispersion could be achieved in the visible, IR wavelengths. Nonlinearity being one of the attractive features in the fibers, could be achieved with the PCF as combining anomalous dispersion with small mode field area results in high nonlinearity [9].

3.2 Guiding mechanisms in PCF

Propagation in PCF divides into two classes [9, 10]: (1) index-guiding PCFs (2) Photonic Band-Gap (PBG) guiding fibers. In index-guiding PCF, propagation occurs by total internal reflection (TIR) which occurs due to the index difference between the core and the cladding [10]. TIR occurs only if the core refractive index is greater than the refractive index of the cladding material. Index –guiding PCF has the solid core surrounded by microctructured cladding. Presence of air holes in the structure results in decrease of the effective refractive index of the cladding than the core, due to which the TIR propagation takes place. Photonic Band Gap guidance uses the concept of energy-band structure. Usually PCF with hollow core follows PBG guiding mechanisim. Guiding mechanism is same as in solid-state physics as the electron conduction mechanism in materials with energy-band structure [9].

3.3 Applications

- PCF based Sensor: Since all the modes such as core, cladding and hybrid modes can be excited and measured in a controlled fashion; PCF is suitable for sensing application [9, 31].
- PCF for mid and far-IR guidance: Development of new generation laser in the IR region from 2 to 10 µm has the potential to operate in this spectral window for power delivery etc. [31].
- PCF for terahertz guidance: Application in medical science, image, and spectroscopy operates in the wavelength range of 10 µm to 3 mm.
- PCF based lasers and amplifiers: This has advantage of low operating costs, high beam quality, high efficiency, maintenance free lasers and low weight too compared to other solid state lasers.[31]
- Nonlinear properties [9]: Supercontinuum generation (SCG) is the most intensively studied property as it has applications in optical coherence tomography, metrology, spectroscopy etc.

3.3.1 Supercontinuum generation in PCF.

Supercontinuum(SC) generation is a phenomenon in which extreme spectral broadening of optical pulses occurs due to various nonlinear phenomena like self-phase modulation (SPM), cross-phase modulation (XPM), self-steepening, four-wave mixing (FWM), stimulated Brillouin scattering(SBS), stimulated Raman scattering (SRS) along with third order dispersion and other higher order dispersion [8,10]. SPM is a Kerr effect, where the refractive index (RI) changes due to high optical intensity . This high intensity introduces varying shift in RI , inducing a phase delay which is time dependent. XPM is related to SPM only the difference is the operation of two co-propagating optical fields instead of one. FWM also occurs due to Kerr nonlinearity effect causing interaction of four co-propagating waves. Raman scattering (RS) is a process where new frequency components are generated because of the interaction of photons with optical phonons. Laser pulses with narrow bandwidth are converted to pulses having very broad bandwidth in SCG. SC is usually generated by launching ultra short pulses (femto-seconds or pico-seconds) in a highly nonlinear PCF with pumping near the zero dispersion wavelength (ZDW). Shifting in the ZDW is achieved with the variation in the PCF geometrical parameters, hence generating the SC in a desired spectral region. It is popular

in the field of telecommunication, optical metrology, optical coherence tomography, nonlinear microscopy, cosmological studies and ultra-short pulse generation [9]. PCF has the advantage in SC generation as group velocity dispersion (GVD) and zero dispersion wavelength (ZDW) can be engineered over a wide range [10, 24]. Dispersion can be designed to facilitate SC generation in a specific region with PCF, which is one of the factors in the generation of SC spectrum. Low and flattened dispersion curve is desired to have a broader spectrum which could be designed with changing the geometry in the PCF which includes radius of the core, radius of air hole etc.

CHAPTER 4
PCF MODELING METHOD

4.1 Effective index approach

It is based on the simple scalar model using effective cladding index [34-36]. Firstly an effective index of the arrayed hole-in-chalcogenide structure is evaluated and effective index of the cladding region is properly chosen which results in equivalent step index fiber (SIF). Using this theory, qualitative information about PCFs with hexagonal geometry could be obtained. The effective cladding index is calculated using the propagation constant of the lowest order mode- fundamental mode propagating in the hexagonal arrayed hole-in- chalcogenide structure. Space filling modes are considered to be the propagating modes in an cladding material, whose propagation constants are strongly dependent on the operating wavelength λ. The resulting propagation constant of this mode β_{FSM} is calculated to define the effective cladding index $n_{FSM} = \beta_{FSM}/k0$, where k0 is the free-space wavenumber [34].

4.2 Basis-function expansion approach

Modal properties such as dispersion or birefringence could be more accurately predicted by this approach compared to the first approach. These properties are dependent on the geometries of the PCF design. Various basis function such as sinusoidal functions [37, 38], Hermite- Gaussian functions [39, 40], and cylindrical functions are used in this approach [41, 42]. In this approach a variational method which minimises the functional related to the wave equation generates matrix eigen value problem. Solving this problem modal fields and propagation constants may be found out.

4.3 Numerical approach

Complicated fibers with non uniform air hole structure or a varying structure comes under this approach. Among all the numerical approaches such as beam propagation method (BPM) [43-45], finite difference method (FDM) [46], finite element method (FEM) [47] etc, FEM is the most widely used in fibers. In this method wave equations are not solved, instead a variational method is applied to a corresponding functional is set up. Cross section of the fiber is divided into smaller elements; hence an equivalent discretized model is constructed for each element. All the discretized elements of the cross section are gathered and assembled to generate matrix eigenvalue problem with unknowns which are nodal variables. With further analysis solving matrix eigenvalue problem the modal fields are obtained.

CHAPTER 5

SOFTWARE & TOOLS

COMSOL 4.2 and MATLAB have been used for the simulation and analysis purpose.

5.1 COMSOL

It's a platform that is flexible to be used by users to model with any physical aspects of their designs. It can be explored deeper and the theoretical knowledge could be used to develop customized solutions based on the circumstances. COMSOL provides us to build the model in real-time. With usage of COMSOL, certain characteristic in it becomes apparent. Compatibility being the best feature in it. Every type of simulation that's included in the package should have the ability to combine with any other is the requirement of COMSOL.

This requirement actually helps in simulating based on real world applications. Taking an example, thermal effect is always present with electricity; these are fully compatible. Compatibility has been enforced to ensure consistent multiphysics models and a connection of a model if the COMSOL family of products expands. Adaptability is another trait of the COMSOL. Software too needs the changes as the modelling changes. If another physical effect has to be included we could just add it. We can just enter the formula if the model needs an input of formulas. Adapting to the ebbs and flows of our requirements is easy using the COMSOL tools like interactive meshing, parameterized geometry and custom solver sequences. This software also has various type of problem-solving benefits. COMSOL helps us understand when a new project is started. Geometrical and physical characteristics of the model could be tested and it could be implemented to solve the challenges faced with important designs. Further analysis are facilitated by the flexible nature of the COMSOL environment setting up " what-if" cases. Simulation level could be levelled up to the production level with optimisation of any aspect of the model design. Features of parameters sweeps and target functions executing in the user interface is present in this software too. COMSOL is a complete problem-solving tool. Experiencing and exploring it more and more brings confidence in computer simulation. It is easy to become a more efficient modeler, exploring it more.

COMSOL Multiphysics version 4.2 has organised model overview and streamlined model-building process which helps in bringing level of clarity to the simulation work. COMSOL has the feature of reducing clutter and redundant tasks which lets us focus on the design studies which results in increased productivity. Among the features of COMSOL, the user interface stands out the most, along with the features of power solvers and flexibility in physics.

COMSOL Multiphysics V-4.2 is used to design the structures, which is based on finite element method (FEM). FEM is the accurate numerical method to solve boundary value problems. It is a method of simple elements equations connecting to many smaller sub domains called finite elements, to solve the more complex equation over a larger domain.

5.1. 1 Finite element method:

The FEM is the method dividing the cross section of the fiber into patchwork of many triangular elements. The triangular elements could be of different sizes, shapes and refractive indexes. This way the geometry of holes in the cross section of PCF and HF are considered and taken into account resulting in high accuracy.

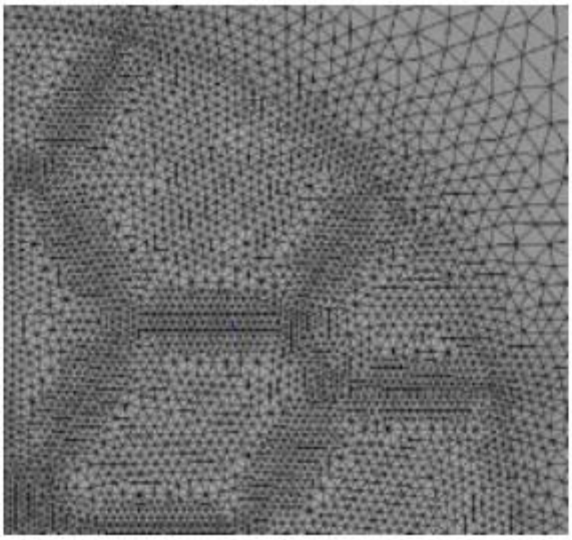


Figure 5.1: Details of the mesh used in the simulations.

Applying the variational finite-element procedure to the curl-curl equation:

$$\overline{\nabla} \times \left(\overline{\overline{\varepsilon_r}} \, \overline{\nabla} \times \overline{H} \right) - k_0^2 \overline{\overline{\mu_r}} \, \overline{H} = 0 \qquad (1)$$

Where $\overline{H}$ is the magnetic field , $\overline{\overline{\varepsilon_r}}$ & $\overline{\overline{\mu_r}}$ are the dielectric permittivity and magnetic permeability tensors respectively and $k_0=2\pi\backslash\lambda$ is the wave number in vacuum ,λ is the wavelength, the following eigenvalue algebraic problem:

$$\left([A]-n_{eff}^2[B]\right)\{h\}=0 \tag{2}$$

is obtained. The eigenvector {h} is the full vector of magnetic field distribution on the fiber cross section and n_{eff}^2 is the eigen vector which is effective index of the mode. The inverse of the group velocity given by:

$$\beta_1=\frac{1}{c}n_{eff}\lambda\frac{d_{neff}}{d\lambda} \tag{3}$$

and the group velocity dispersion parameter given by the relation:

$$D=-\frac{\lambda}{c}\frac{d^2n_{eff}}{d\lambda^2} \tag{4}$$

can be obtained by using finite difference formulas. The matrices [A] and [B] are sparse, following an efficient resolution of the equation by means of high performance algebraic solvers. In this work, high-order edge elements are used to provide very accurate effective-index values, and to avoid spurious modes in the guided-mode spectrum. In order to save computational efforts, structure symmetries can be exploited for the numerical simulations.

CHAPTER 6

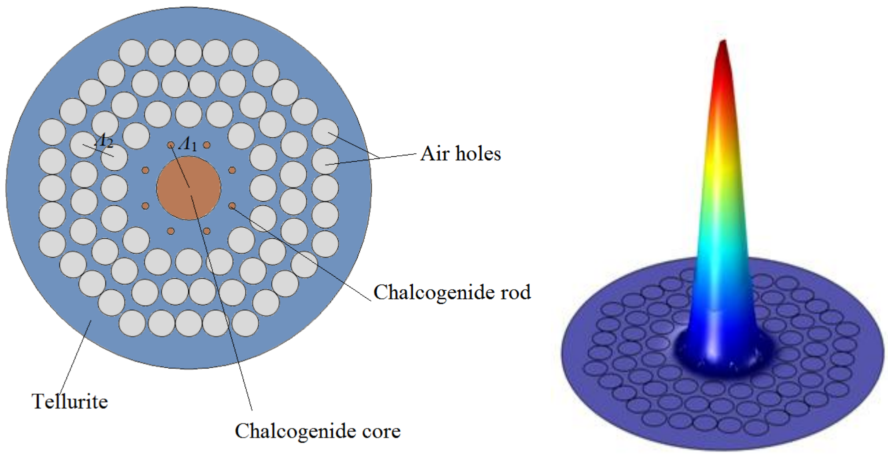
COMPOSITE PHOTONIC CRYSTAL FIBER

6.1 Introduction

Standard material silica has low nonlinear coefficient which is ~ 2.7 x 10^{-20} m^2/W. For broad SC spectrum generation there is a need of very highly nonlinear material in the composite PCF design. Chalcogenide glasses, tellurite glasses are some of the nonlinear materials with the nonlinear coefficient of the order of 10^{-18} m^2/W and 10^{-19} m^2/W respectively. The highly nonlinear materials etc have been used in this design as it aids in broadening the SC spectrum. Chalcogenide has the nonlinear coefficient (~100 times larger than silica) very much higher than the standard material –silica used in optics. Higher the nonlinearity coefficient broader the SC spectrum, as it is generated by launching ultra short pulses in femto-seconds or pico-seconds in a highly nonlinear PCF with pumping near the zero dispersion wavelength (ZDW). The SC generation is also dependent on the dispersion profile and its input characteristics. Smooth and flat dispersion curve is desired to have the broad SC spectrum. PCF structure has the ability to manipulate the dispersion properties as desired by changing the parameters and with the introduction of defects.

6.2 Composite PCF design

The proposed composite PCF (CPCF) design has been shown in fig.6.1. Silica is the standard material used in the optical communication. In this project instead of silica, tellurite and chalcogenide material have been used. Tellurite has been used as the cladding material and chalcogenide glass as the core in this composite PCF design. As shown in Fig. 6.1(a) it has chalcogenide core at the centre of structure with 1 ring of small chalcogenide rods around it. In addition to the chalcogenide rods, it consists of three rings of the air holes arranged in a hexagonal lattice pattern in the tellurite material. Introduction of the chalcogenide rods add to the decrease in effective mode area, resulting in increase in nonlinearity. Figure 6.1(b) shows the electric field distribution of the propagating mode in the core of the PCF structure.



(a) (b)

Fig. 6.1(a) Cross-sectional view of the proposed PCF, (b) Visualization of electric field distribution of propagating mode in the core of the PCF

The distance from the center to chalcogenide rods (i.e. Λ_1) around the core has been considered as 4.375 μm, distance from the central core to the centre of chalcogenide rods. While, the center to center distance of the air holes (i.e. Λ_2) in second, third and fourth rings has been considered as 3.125 μm. The diameter of the central chalcogenide core (i.e. d_1) is taken as 6 μm. Rc is the radius of the central chalcogenide core taken as $d_1/2$.The diameter of the chalcogenide rods in first ring around the central core is d_2 and kept constant as 0.625 μm. The diameter of the air holes in second, third and fourth rings is represented by d_3 and taken as 2.5 μm.

6.3 Numerical analysis

6.3.1 Effective index

In this work, tellurite glass and chalcogenide glass have been used as a composite PCF material. Sellmeir equation is used to calculate wavelength dependent refractive index of both materials. Tellurite material has the refractive index of the formula [5]:

$$n(\lambda) = \sqrt{1 + \frac{b_1\lambda^2}{\lambda^2 - c_1} + \frac{b_2\lambda^2}{\lambda^2 - c_2} + \frac{b_3\lambda^2}{\lambda^2 - c_3}} \quad (5)$$

Where b_1 = 1.67189, b_2 = 1.34862, b_3 = 0.62186, c_1 = 0.0004665 μm^2, c_2 = 0.0574608 μm^2, c_3 = 46.72542736 μm^2 at 25 ^{0}C [5, 11].

Chalcogenide material has the refractive index of the formula [5]:

$$n(\lambda) = \sqrt{1 + \frac{B_1\lambda^2}{\lambda^2 - C_1^2} + \frac{B_2\lambda^2}{\lambda^2 - C_2^2} + \frac{B_3\lambda^2}{\lambda^2 - C_3^2} + \frac{B_4\lambda^2}{\lambda^2 - C_4^2} + \frac{B_5\lambda^2}{\lambda^2 - C_5^2}} \quad (6)$$

Where B_1 = 1.8983678, B_2 = 1.9222979, B_3 = 0.8765134, B_4 = 0.1188704, B_5 = 0.9569903, C_1^2 = 0.0225 μm^2, C_2^2 = 0.0625 μm^2, C_3^2 = 0.1225 μm^2, C_4^2 = 0.2025 μm^2, C_5^2 = 750 μm^2 at 25 ^{0}C [5,11]..

6.3.2. Effective area

Effective area is the measure of electric field distribution of the fundamental mode propagation. The effective area equation is given as [5]:

$$A_{eff} = \frac{\left[\iint |E(x,y)dxdy|^2\right]^2}{\iint |E(x,y)dxdy|^4} \ \mu m^2 \quad (7)$$

Where, *E* is the transverse electric field of fundamental mode. Effective area depends on the refractive index of the material n (λ) which changes according to the operating wavelength λ. It is also dependent on the shape of the fiber. The effective indices are calculated by the formulas discussed in 6.3.1.

6.3.3 Nonlinearity

Nonlinearity depends on the nonlinear refractive index of the material. The nonlinearity in a photonic crystal fiber is calculated by [5, 14]:

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} W^{-1} m^{-1} \quad (8)$$

The nonlinearity coefficient is controlled by two parameters n_2 and A_{eff}. For broader SC the nonlinearity coefficient should be as high as possible. Certain materials like soft-glass and chalcogenide exhibit large value of nonlinearity. The value of γ can be enhanced by taking material with high non linear refractive index or by designing a PCF with low effective area. By increasing nonlinearity value it became suitable for supercontinuum generation.

6.3.4 Dispersion

The chromatic dispersion $D(\lambda)$ which is an another important factor involved in broadening of SC is calculated from effective index n_{eff} values versus wavelength λ using equation [5,14]:

$$D(\lambda) = -\frac{\lambda}{c}\frac{\partial^2 \mathrm{Re}(n_{eff})}{\partial \lambda^2} \tag{9}$$

where, c is the velocity of light in a vacuum. Flat and smooth dispersion profile is desired to achieve the broad SC spectrum. Manipulation in the dispersion properties to get the desired profile is possible in the PCF. Anomalous dispersion region with small effective area results in broad SC.

6.3.5 Supercontinuum generation

Numerical simulations were performed by solving the generalized nonlinear Schrödinger equation [14, 24]:

$$\frac{\partial A}{\partial Z} + \frac{\alpha}{2} A - \left(\sum_{n \geq 2} \beta_n \frac{i^{n+1}}{n!} \frac{\partial^n A}{\partial t^n} \right) = i\gamma \left(1 + \frac{i}{\omega_0} \frac{\partial}{\partial t} \right)$$

$$\times \left[A(\mathrm{z,t}) \int_{-\infty}^{\infty} R(t') \, | A(z, t - t') |^2 \, dt' + i\Gamma_R(z,t) \right] \tag{10}$$

by the split-step Fourier method. Equation (6) shows the change in pulse envelope A(z,t) during propagation. The transmission loss of the fiber is α (in the unit of [1/m]). The attenuation coefficient of the propagation is taken to be ~ 30 dB/km [28]. A(z,t) is the envelope of the optical field, T time, β_n is the nth derivative of the propagation constant β, which is the propagation constant and γ is the nonlinear coefficient. The nonlinear response function, R(T) is given by the Eq. [13,24]:

$$R(T) = (1 - f_r)\delta(T) + f_r h_r(T) \tag{11}$$

with f_r = 0.10, for chalcogenide glass As_2S_3[8]. The Raman response function h_r, can be calculated using raman period τ_1 and lifetime τ_2 which is given by the Eq. [32,24]:

$$h_r(t) = \frac{\tau_1^2 + \tau_2^2}{\tau_1 \tau_2^2} \exp\left(-\frac{t}{\tau_2} \right) \sin\left(\frac{t}{\tau_1} \right) \tag{12}$$

Where, Raman period τ_1= 15.5 fs and life time τ_2=230.5 fs for chalcogenide glass. Pump pulses used is emerging from the tunable femtosecond laser having hyperbolic secant field profile. The hyperbolic secant pulse can be expressed as follows [14, 24]

$$A(z=0,t)=\sqrt{p_0}\,\sec h\left(\frac{t}{t_0}\right)\exp\left(-i\frac{C}{2}\frac{t^2}{t_0^2}\right) \tag{13}$$

Where, $t_0 = T_{FWHM}/1.7627$, T_{FWHM} is the duration of full width half maximum pulses and P_0 is Peak power and C is the chirp coefficient. In our calculations we set the pump wavelength to 2.8 µm. Unchirped pulses with duration of T_{FWHM} = 50 fs with energy of 120 pJ are considered to study the supercontinuum generation.

Nonlinear length is given by[13] :

$$L_{NL}=\frac{1}{\gamma P_0} \tag{14}$$

Nonlinearity γ is 1.042 m^{-1}/W from the simulation and pump power P_0 is taken as 3 kW. Calculated value of nonlinear length is 3.2 x 10^{-4} m. Dispersion length is calculated using $t_0 = T_{FWHM}/1.7627$, taking T_{FWHM} = 50 fs.

Dispersion length L_D is calculated by the formula [13]:

$$L_D=\frac{t_0^2}{\beta_2} \tag{15}$$

Calculated value of L_D is 4.4 x 10^{-2} m.

The Soliton order, $N \approx \sqrt{(L_D/L_{NL})}$ is ~ 12 for this PCF. $L_{fiss} = L_D/N$ is the soliton fission length of 3.67 mm.

6.4. Simulation and results

Fig 6.2. shows the variation of the effective area with respect to wavelength. As from the refractive index wavelength dependence formula, the effective index could be calculated. It could be inferred from the graph with increase in wavelength, the effective area increases.

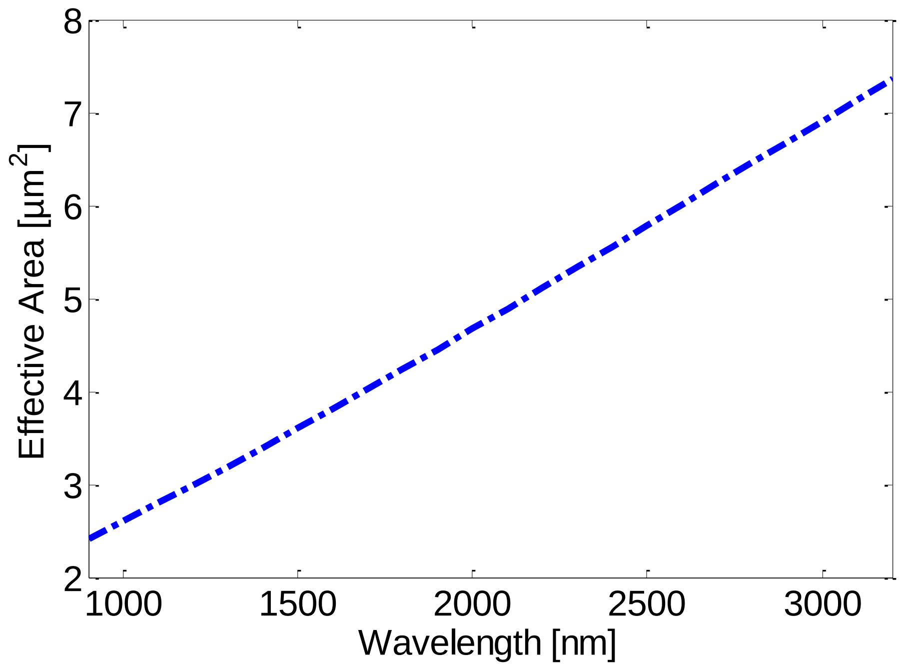


Fig. 6.2 Effective mode area dependence on Wavelength.

Figure 6.3 describes the nonlinearity variation as the wavelength varies. Nonlinearity is inversely proportional to the effective area.

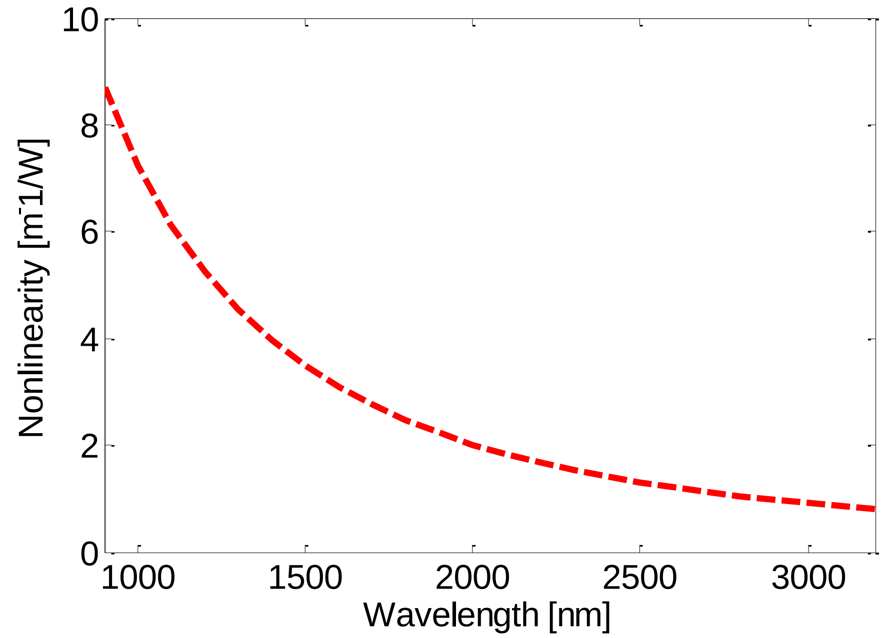


Fig.6.3. Nonlinear coefficient of proposed PCF structure vs. Wavelength.

Hence nonlinearity decreases as the wavelength increases, as it also could be seen from the graph.

Figure 6.4 describes the effect of change in radius of the core on dispersion. Changing the radius Rc of the core shifts the ZDW. It also depicts the dependence of chromatic dispersion on wavelength.

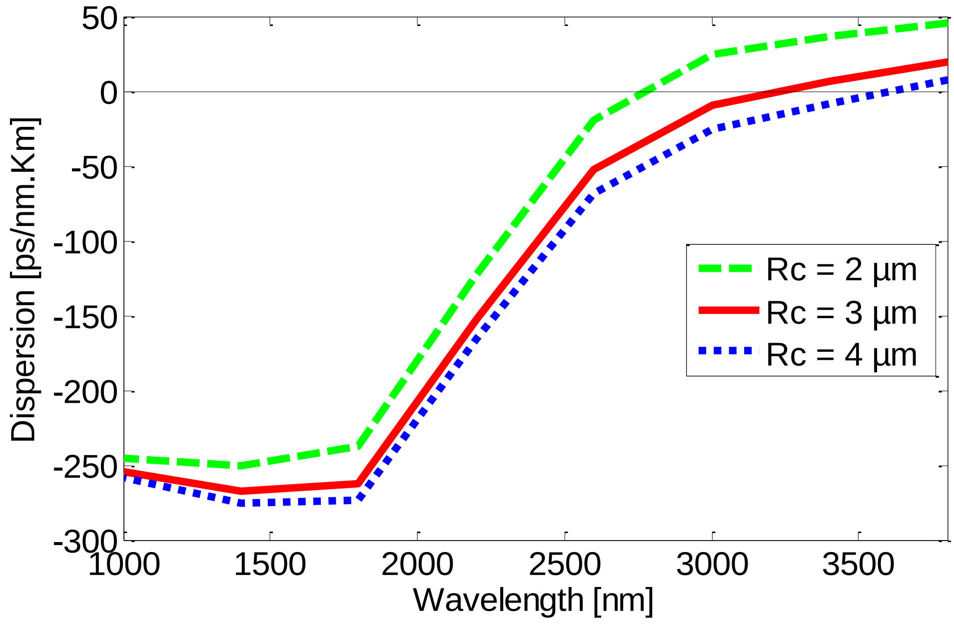


Fig.6.4 Chromatic Dispersion vs. Wavelength

From the graph it could be concluded that increase in the radius of the core results in shifting the ZDW at higher wavelengths. Hence accordingly pump wavelength usually taken near to ZDW is selected keeping in mind the availability of the laser. In this project the red line curve is selected taking pump wavelength at 2800 nm which is near to ZDW.

Figure 6.5 shows the SC broadening with different pump powers of 1kW, 2kW & 3kW in a length of 8 mm which is pumped at 2800 nm. Pulse duration is kept fixed, taken as 50 fs. As we can see from the Fig.6.5, most broadening occurs with pump power of 3kW, it can be concluded that increase in power results in more broadening of the SC spectrum. Hence for broadband SC relatively high power with flat dispersion profile is required.

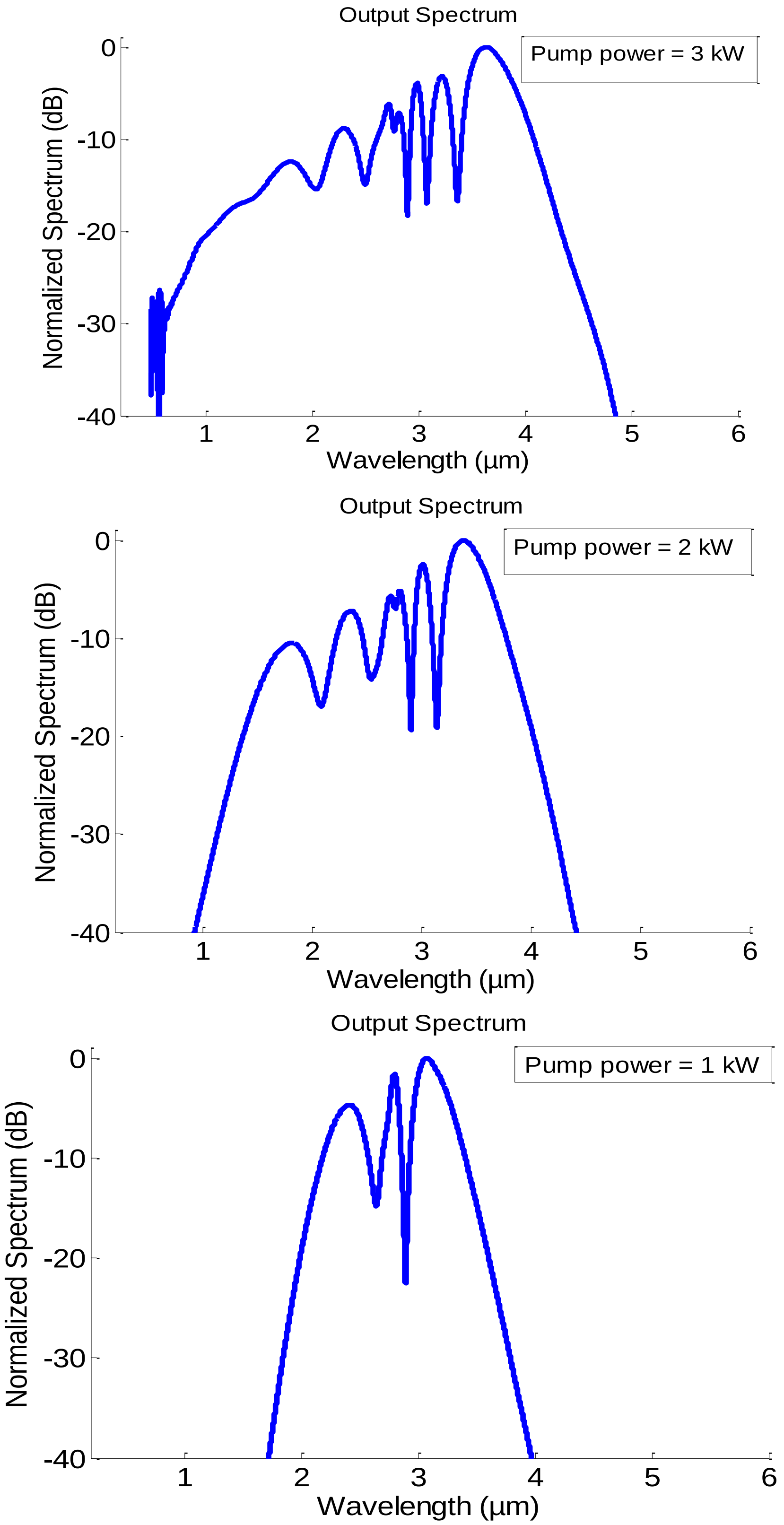
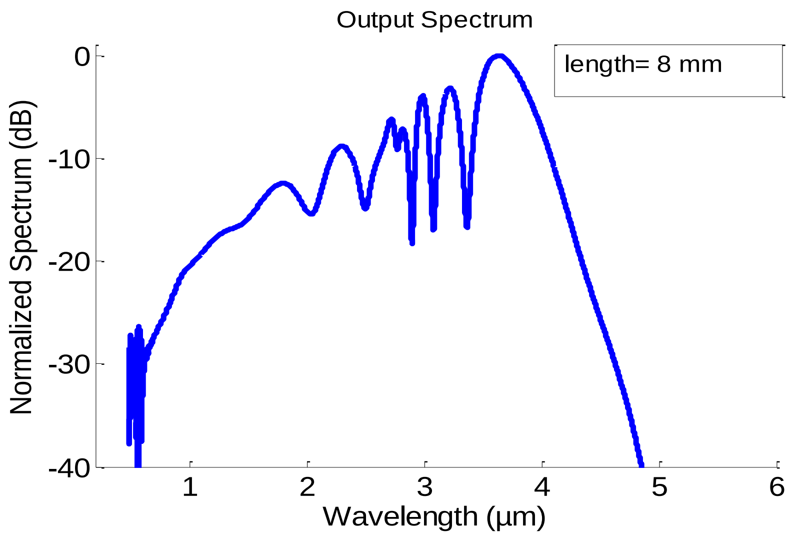
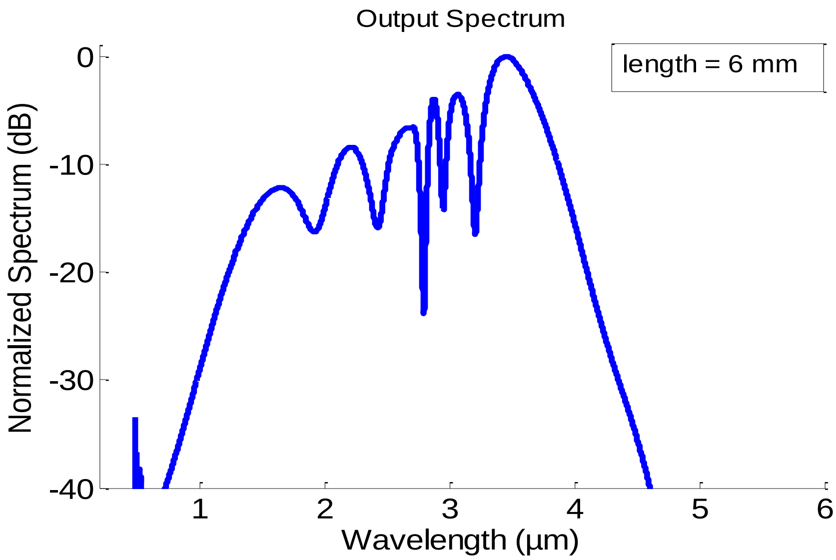


Fig 6.5 Supercontinuum broadening with different pump powers in a length of 8 mm, pumping at 2800 nm

Figure 6.6, illustrates the spectral broadening of SC spectrum in various length of the PCF structure when the PCF is pumped with 50 fs laser pulses of peak power of 3 kW at 2800 nm. Initially the spectrum shows no broadening as it is the input pulse, which when further launched into the length of the nonlinear fiber results in the broadening of the spectrum. The broadening in the SC spectrum increases with the length of the PCF. At 8 mm length of the PCF structure we are able to get the supercontinuum broadening from 0.5 μm to 4.8 μm. After increasing the length above 8 mm there is no significant change in the broadening of the spectrum as the soliton fission length limits to 3.67 mm.





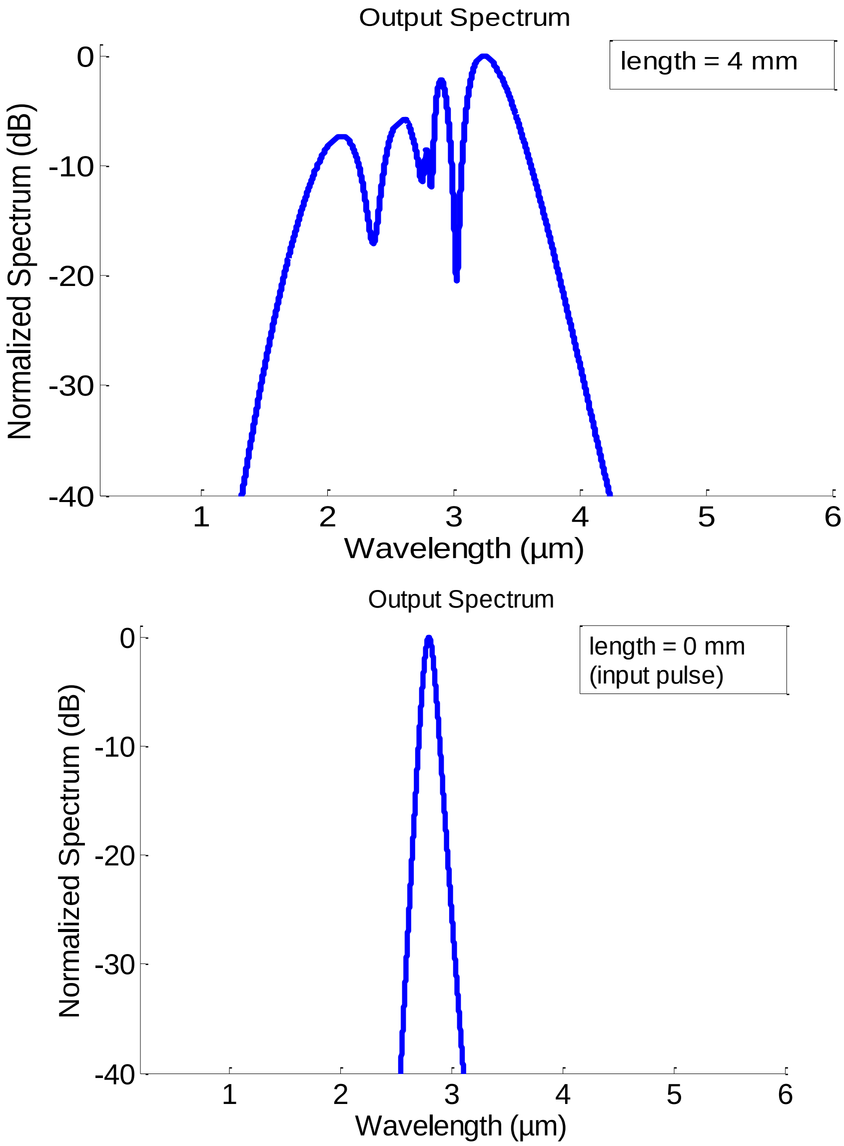
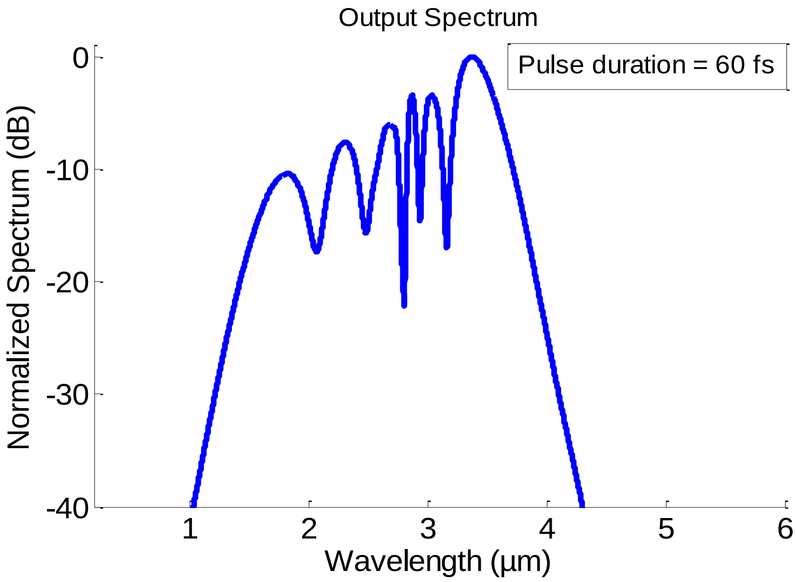
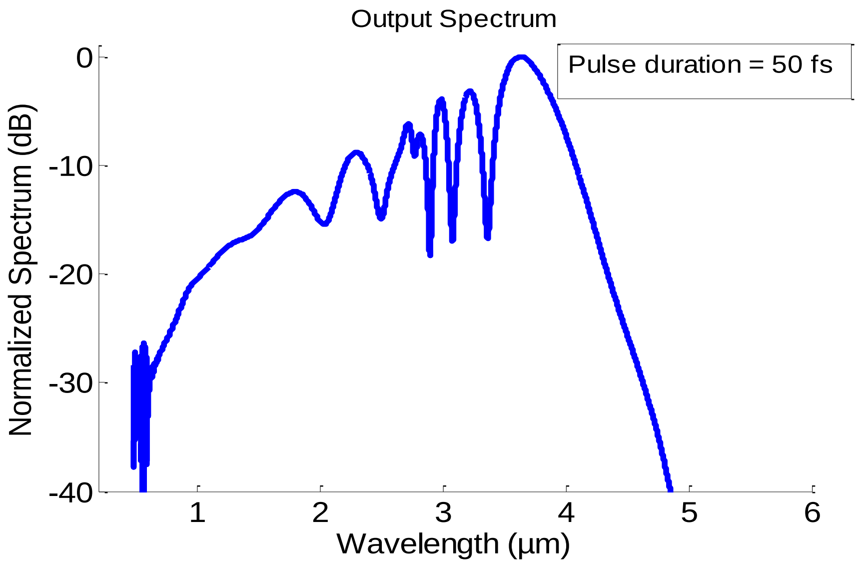


Fig.6.6. Supercontinuum broadening with pump power of 3kW at different lengths of PCF.

Initially the spectrum is symmetrical, but as the pump power increases the unsymmetrical broadening occurs. Initially launching the power with 1kW we can see with further increase in pump power to 3 kW ,the spectrum broadens to more than 2000 nm. Since femtosecond pulses are being used in this anomalous dispersion region, the soliton effects come into picture [27].

Figure 6.7, depicts the SC broadening at different pulse duration with pump power of 3kW in a length of 8 mm of fiber. Variations of the parameters responsible in the SC generation with respect to the wavelength is studied for the nonlinear applications. As there is increase in pulse duration the spectrum gets narrower, it is due to the SPM effect. Initially laser modulates its own phase as it travels through the length of PCF in SPM phenomena [28].





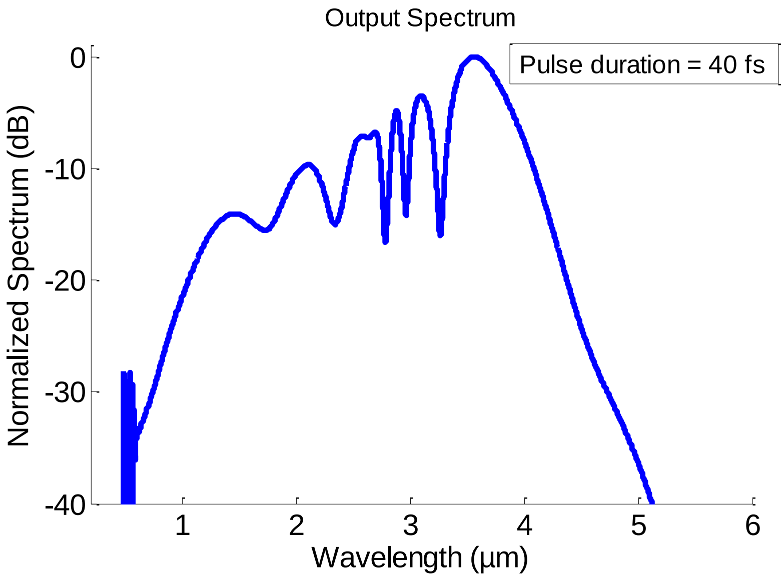


Fig.6.7 Supercontinuum broadening with pump power of 3kW at different pulse duration.

Further propagation adds the linear and nonlinear effects resulting in broadening of the spectra in the order of hundreds of nanometers [28]. Broadening is also dependent on pulse duration as the soliton fission length relies on dispersion length and nonlinear length of the proposed PCF, i.e., indirectly related to the T_{FWHM}. Increase in the pulse duration decrease the broadness of spectrum, hence spectrum with smaller pulse duration results in broader spectrum.

From simulation the most effective broadband SC spectrum is using 3 kW power in 8 mm length of the fiber with pulse duration of 40 fs resulting in SC spectrum from 0.5 to 6 μm. Our reported spectral broadening in SC spectrum is larger than that of reported in Ref. [19] and Ref.[22]

For the manufacturing point of view designed photonic crystal fiber structure can be made using pressure-assisted melt filling technique [19]. It can also fabricated by the method of stack and draw as presented in ref. [22].

CHAPTER 7

CONCLUSION AND FUTURE SCOPE

This proposed composite PCF design results in achieving high nonlinearity of 1.042 W^{-1} m^{-1} with significantly high effective mode area of 6.46 μm^2. High nonlinearity is desired to generate broad SC spectrum with the use of low pump power. The simulations resulted in SCG ranging from 0.5 µm to 6 µm with 8 mm length of chalcogenide photonic crystal fiber, pumping at 2800 nm. This is achieved with low pulse power of 3 kW taking 40 fs as pulse duration. Broadening of supercontinuum spectrum depends on dispersion profile of the fiber and its input characteristics, which can be controlled with this design by changing the parameters of the composite PCF. As this design is made of very highly nonlinear material, along with the flexibility to control chromatic dispersion has the potential in realising compact SC sources. This reported structure has the advantage to be operated in near-IR to IR region. This broadband supercontinuum has applications in field of telecommunication, optical metrology, medical science, cosmological studies, nonlinear microscopy, optical coherence tomography, cosmological studies and ultra-short pulse generation as most of these applications require to be operated in IR region.

Exploring more and understanding the underlying technology could lead to built efficient cost-effective and reliable laser source. Power scaling is also the enhancement to the laser source in the fiber. Optical power launched could be made more effective with the introduction of repeaters and amplifiers at required distance in the length of a fiber. Most of the studies on SC spectrum lies on the IR, visible region, but understanding the physics behind SC and exploring the spectrum more, it could be extended to the UV region as many biological issues could be operated with UV spectrum.

REFERENCES

1. S. Revathi, Dr. S. R. Inbathini, “Analysis of propagation characteristics in photonic crystal fiber for large negative dispersion,” Journal of Theoretical and Applied Information Technology 2012, 36(1), 129-133 .
2. G. P. Agarwal (2007), *Nonlinear Fiber Optics-4 ed*. New York: Academic, Elsevier Inc.
3. S.P. Singh and N. Singh, “Nonlinear effects in optical fibers: origin, management and applications,” Progress In Electromagnetics Research 2007 ,(73), 249–275.
4. J. S. Sanghera, L. B. Shaw, P. Pureza, V. Q. Nguyen, D. Gibson, L. Busse, I. D. Aggarwal, “Nonlinear properties of chalcogenide glass fibers,” Int. J. of Applied Glass Sc.2010 ,1(3), 296–308.
5. M. Liao, C. Chaudhari, L. Shuo and L. S. Guang, “Numerical analysis of photonic crystal fiber with chalcogenide core tellurite cladding composite microstructure”,. Chin. Phys. B.2013. 22 (7) 074206(1)-074206(5).
6. F. W. Glaze, D.H. Blackburn, J. S. Osmalov, D. Hubbard, and M. H. Black, “Properties of arsenic sulfide glass,” Journal of Research of the National Bureau of Standards 1957 ,59(2),83-92
7. V. V. R. K. Kumar, A. K. George, J. C. Knight, P. S. Russell, “Tellurite photonic crystal fiber,” Optics Express 2003, 11(20),2641–2645.
8. C. Xiong, E. Magi, F. Luan, A. Tuniz, S. Dekker,J. S. Sanghera, L. B. Shaw, I. D. Aggarwal, and B. J. Eggleton, “Characterization of picosecond pulse nonlinear propagation in chalcogenide As_2S_3 fiber,” Applied Optics 2009 ,48(29),5467-5474.
9. R. Buczynski, “ Photonic crystal fibers,” Acta Physica Polinica A 2004, 106(2),141-167.
10. J.B. Jensen, J. Riishede, J. Broeng, J. Laegsgaard, T. Tanggaard L, T. Sørensen, K. Hougaard, E. Knudsen, S.B. Libori and A. Bjarklev, “Photonic crystal fibers; fundamental properties and applications within sensors,” IEEE sensors. 2003(1), 269-278.
11. W. S. Rodney, I. H. Malitson, and T. A. King, “Refractive index of arsenic trisulphide,” Journal of the optical society of America 1958,48(9),633-636.

12. M.R.Karim, B.M.A.Rahman, Y.O. Azabi, A. Agrawal and G. P. Agrawal, “Ultrabroadband mid-infrared supercontinuum generation through dispersion engineering of chalcogenide microstructured fibers”, Journal of the Optical Society of America 2015, 32(11),2343-2351.
13. T. S. Saini, A. Kumar, and R. K Sinha, “Broadband mid-infrared supercontinuum spectra spanning 2–15 μm using As_2Se_3 chalcogenide glass triangular-core graded-index photonic crystal fiber,” Journal of lightwave technology 2015,33(18),3914-3920.
14. T.S.Saini, A.Baili, A.Kumar, R.Cherif, M.Zghal, R.K.Sinha, “Design and analysis of equianular spiral photonic crystal fiber for mid-infrared supercontinuum generation,” Journal of modern optics 2015, 62(19), 1570-1576.
15. X. Feng, W. H. Loh, J. C. Flanagan, A. Camerlingo, S. Dasgupta, P. Petropoulos, P. Horak, K. E. Frampton, N. M. White, J. H.V. Price, H. N. Rutt, and D. J. Richardson, “Single-mode tellurite glass holey fiber with extremely large mode area for infrared nonlinear applications,” Opt. Express 2008, 16(18), 13651- 13656.
16. M.Liao, C. Chaudhari, G. Qin, X.Yan, C. Kito, T. Suzuki, Y. Ohishi, M.Matsumoto, T. Misumi, “Fabrication and characterization of a chalcogenide-tellurite composite microstructure fiber with high nonlinearity”,. Optics Express 2009,17(24), 21608-21614
17. P. Domachuk, N. A. Wolchover, M. Cronin-Golomb, A. Wang, A. K. George, C. M. B. Cordeiro, J. C. Knight, and F. G. Omenetto, “Over 4000 nm bandwidth of mid-IR supercontinuum generation in sub-centimeter segments of highly nonlinear tellurite PCFs,” Opt. Exp.2008 ,16(10), 7161–7168.
18. C. Chaudhari, T. Suzuki, and Y. Ohishi, “Design of zero chromatic dispersion chalcogenide As_2S_3 glass nanofibers,” J. Lightwave Technoogy 2009, 27(12), 2095–2099..
19. C.B.Chaudhari, T.Suzuki, and Y.Ohishi, “Chalcogenide core photonic crystal fibers for zero chromatic dispersion in the C-band,” Opt. Fiber Commun Conf.2009, OTuC4,22-26.
20. J. K. Ranka, R. S. Windeler, and A. J. Stentz, “Visible continuum generation in air-silica microstructure optical fibers with anomalous dispersion at 800 nm,” Optics Letters 2000, 25(1), 25–27.

21. C. Xia, M. Kumar, M.Y. Cheng, O. P. Kulkarni, Md. N. Islam, A. Galvanauskas, F. L. Terry, M. J. Freeman, D. A. Nolan and W. A. Wood, “Supercontinuum generation in silica fibers by amplified nanosecond laser diode pulses,” IEEE journal of selected topics in quantum electronics 2007,13(3),789-797.
22. M. Liao, C. Chaudhari, G. Qin, X. Yan, T. Suzuki, Y. Ohishi, “Tellurite microstructure fibers with small hexagonal core for supercontinuum generation,” Optics express 2009, 17(14) ,12174-12182.
23. D. D. Hudson, S. A. Dekker, E. C. Mägi, A. C. Judge, S. D. Jackson, E. B. Li, J. S. Sanghera, L. B. Shaw, I. D. Aggarwal, and B. J. Eggleton, “Octave spanning supercontinuum in an As_2S_3 taper using ultralow pump pulse energy,” Optics Letters 2011,36(7), 1122–1124.
24. N. Granzow, S. P. Stark, M. A. Schmidt, A. S. Tverjanovich,L. Wondraczek, and P. St.J. Russell, “Supercontinuum generation in chalcogenide-silica step-index fibers,” Optics Express 2011,19(21), 21003-21010.
25. D.Xie, J.G.Wen, "Chalcogenide-tellurite composite microstructed fiber for low-threshold mid-IR supercontinuum generation,” Advanced Materials Research 2011, 308-310, 517-520.
26. C. Chaudhari, M. Liao, T. Suzuki, and Y. Ohishi, “Chalcogenide core tellurite cladding composite microstructured fiber for nonlinear applications,” Journal of lightwave technology 2012, 30(13),2069-2076.
27. A. Kudlinski, G. Bouwmans, M. Douay, M. Taki, and A. Mussot, “Dispersion-engineered photonic crystal fibers for CW-pumped supercontinuum sources,” J. Lightwave Technol.2009, **27** (11), 1556–1564.
28. J. M. Dudley, G. Genty, and S. Coen, “Supercontinuum generation in photonic crystal fiber,” Rev. Mod. Phys.2006 , 78(4), 1135–1184.
29. G.E Snopatin, M. f. Churbanov, A.A Pushkin, V.V. Gerasimenko, E.M. Dianov, V.g. Plotnichenko, “High purity Arsenic-Sulfide glasses and fibers with minimum attenuation of 12 dB/km,” Optoelectronics and Advaced materials – Rapid communications 2009,3(7), 669-671.

30. A. Ortigosa-Blanch, J.C. Knight, P.S.J. Russell, Pulse breaking and supercontinuum generation with 200-fs pump pulses in PCF, J. Opt. Soc. Amer. B 2002, 19(11), 2567–2572.
31. R.R.Alfano (1989), *The supercontinuum laser source*, 233 Spring Street ,NY,USA, Springer science & Business Media,Inc.
32. R. Leitgeb, W. Drexler, A. Unterhuber, B. Hermann, T. Bajraszewski, T. Le, A. Stingl, and A. F. Fercher, Ultrahigh resolution Fourier domain optical coherence tomography, Opt. Express2004, 12, 2156–2165.
33. H. Mikami, M. Shiozawa, M. Shirai, and K. Watanabe, Compact light source for ultrabroadband coherent anti-Stoke Raman scattering (CARS) microscopy, Opt. Express 2015, 23, 2872–2878.
34. K. Saitoh, and M. Koshiba, "Numerical Modeling of Photonic Crystal Fibers," Journal of lightwave technology 2005, 23(11),3580-3590.
35. T. A. Birks, J. C. Knight, and P. St. J. Russell, "Endlessy single-mode photonic crystal fiber," Opt. Lett. 1997, 22(13), 961–963.
36. J. C. Knight, T. A. Birks, P. S. J. Russell, and J. P. de Sandro, "Properties of photonic crystal fiber and the effective index model," J. Opt. Soc. Amer. A 1998, 15(3),748–752.
37. A. Ferrando, E. Silvester, J. J. Miret, P. Andrés, and M. V. Andrés, "Fullvector analysis of a realistic photonic crystal fiber," Opt. Lett.1999, 24(5), 276–278.
38. A. Ferrando, E. Silvestre, J. J. Miret, and P. Andrés, "Vector description of higher-order modes in photonic crystal fibers," J. Opt. Soc. Amer. A 2000, 17(7),1333–1340.
39. D. Mogilevtsev, T. A. Birks, and P. S. J. Russell, "Localized function method for modeling defect modes in 2-D photonic crystals," J. Lightw. Technol.1999, 17(11), 2078–2081.
40. T. M. Monro, D. J. Richardson, N. G. R. Broderick, and P. J. Bennett, "Modeling large air fraction holey optical fibers," J. Lightw. Technol.2000,18(1), 50–56.
41. M. J. Steel, T. P. White, C. M. de Sterke, R. C. McPhedran, and L. C. Botten, "Symmetry and degeneracy in microstructured optical fibers," Opt. Lett.2001, 26(8), 488–490.
42. T. P. White, R. C. McPhedran, C. M. de Sterke, L. C. Botten, and M. J. Steel, "Confinement losses in microstructured optical fibers," Opt. Lett.2001,26(21),1660–1662.

43. C. E. Kerbage, B. J. Eggleton, P. S. Westbrook, and R. S. Windeler, “Experimental and scalar beam propagation analysis of an air-silica microstructure fiber,” Opt. Express 2000. 7(3), pp. 113–122.
44. B. J. Eggleton, P. S. Westbrook, C. A. White, C. Kerbage, R. S. Windeler, and G. L. Burdge, “Cladding-mode resonances in air-silica microstructure optical fibers,” J. Lightw. Technol.2000, 18(8),1084–1100.
45. F. Fogli, L. Saccomandi, and P. Bassi., “Full vectorial BPM modeling of index-guiding photonic crystal fibers and couplers,” Opt. Express.2002, 10(1), 54–59.
46. Z. Zhu and T. G. Brown. (2002, Aug.). Full-vectorial finite-difference analysis of microstructured optical fibers. Opt. Express 2002. 10(17), 853–864.
47. F. Brechet, J. Marcou, D. Pagnoux, and P. Roy, “Complete analysis of the characteristics of propagation into photonic crystal fibers, by the finite element method,” Opt. Fiber Technol.2000, 6(2), 181–191.