International Journal of Scientific & Engineering Research Volume 10, Issue 5, May-2019
ISSN 2229-5518

Review: Nonlinear fiber optics and its applications in holey fibers

Vaibhav Gupta, Atul Kumar, Baibhav Ranjan, Sandeep Vyas

Abstract— With the sudden increase in demand and high data transmission speed, the requirement to use optical communication technology is also increasing. In the recent optical communication applications, supercontinuum generation (SCG) has given evidence of utility. Holes or microstructured optical fiber (MOF) plays a very advanced role in the implementation of SCG due to lack of power required. SCG is obtained when an ultra-short laser pulse passes through excessive nonlinear spectral broadening to produce broadband. Continuous production of Spectral is a result of inter-action between high-order dispersion and various non-linear processes. In this article, discussing the MOF and the recent application of Supercontinuum generation and its scope.

Index Terms— Nonlinear optics, Effective Mode Area, Chalcogenide Materials Supercontinuum Generation.

◆

1 INTRODUCTION

In the previous years, based on the enormous developments in fiber optics systems, research has focused on the development of fibers and fiber-based devices suitable for near and medium infrared wavelengths for various applications [1]. Supercontinuum (SC) fiber sources are the next generation light source and one of the most interesting topics for research in the optical field. The supercontinuum could have high brightness, a high degree of coherence, wide bandwidth and potential compactness. SC sources find many applications in the medium infrared region (MIR) such as frequency metrology, molecular spectroscopy, detection, optical coherence tomography. Perforated fiber or microstructured optical fiber (MOF), also known as photonic crystal fiber (PCF). Generally consists of a central solid defect lattice or triangular lattice with the same air hole diameter arrangement has been an essential requirement for SC sources because of the availability of suitable pump source and the design flexibility offered by silica-based PCFs around the available communication wavelengths [2].

MOF are suitable media for SC generation due to the design flexibility in their dispersive and nonlinear properties. The most coherent and flat SCs in the MIR are preferred since most molecules exhibit fundamental vibrational absorption in this region, which is very useful for optical coherent tomography (OCT) [3].

Applications in the MID-IR region, chalcogenide glass (S-SE-TE) have been found to be potentially very suitable due to some special properties, which could be exploited for the manufacture of devices intended for applications in this range of wavelength. The dispersion profile of these MOFs can be easily controlled by varying the diameter of the air hole (d) and the distance between the holes. The control of chromatic dispersion in MOF is a very important challenge for practical applications such as nonlinear optics, dispersion compensation, optical communication system, and many others [4]. Initially, SCG was demonstrated with the silica-based material but, in addition to silica, non-silica material can also be used as a base material for MOF. This is often the result of interesting optical properties of PCF due to the unique properties of underlying material [5]. A unique property is a nonlinearity, which controls the spectral broadening of optical pulses and can be maximized by adapting the effective area by selecting materials with higher nonlinear Kerr coefficients. Nowadays, some chalcogenide materials are becoming suitable for the development of active and passive optoelectronic devices for the mid-infrared region such as As_2S_3, As_2se_3, $Ge_{11.5}As_{24}Se_{64.5}$ [6].

2 THEORY

Many investigators use the FDTD (Finite-Difference Time-Domain) method to examine the optical properties of MOFs. The total dispersion or chromatic dispersion Dc can be computed using the given relation [7]

$$D_c(\lambda) = -\frac{\lambda}{c}\frac{d^2\eta_{eff}}{d\lambda^2} \quad (1)$$

where λ is the operating wavelength, c the speed of light in vacuum, and neff the real part of the effective index (neff = λβ/2π, with β being the propagation constant). The nonlinear coefficient γ is evaluated as [7],

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

n_2 indicates the nonlinear refractive index of the material, λ is the wavelength of the pump and A_{eff} the effective surface of the fundamental mode.

- *Vaibhav Gupta is currently pursuing bachelor degree program in electrical engineering in JECRC Jaipur, India. E-mail: vaibhavgupta216@gmail.com*
- *Atul Kumar is currently pursuing bachelor degree program in electronics and communication engineering in JECRC Jaipur, India.*
- *Baibhav Ranjan is currently pursuing bachelor degree program in electronics and communication engineering in JECRC Jaipur, India.*
- *Dr. Sandeep Vyas is currently working as Asso. Prof. in electronics and communication engineering in JECRC Jaipur, India.*

3 MATERIAL USED FOR PHOTONIC CRYSTAL FIBER

3.1 The primary material: Silica

In the early days, silica was used as a base material for photonic crystal fibers. The band gap of silica material is 1.1 eV at 300K. It has highly nonlinear refractive index of around 4.5×10-14 cmW^{-1} and also has two-photon absorption coefficient of around 7.9×10-10 cmW^{-1} [8]. Methods of producing silicon-based devices have been well defined. However, the band-gap of silicon is indirect, which leads to a long life of the free carrier and therefore to the absorption of the free carrier. Therefore, to avoid the absorption of the free carrier and the absorption of two photons, it is necessary to study other nonlinear materials.

3.2 Chalcogens

Materials that are using for non-linear optics, i.e. chalcogenide, can be used as the basis material for PCF. These chemical elements are present in group 16 of the periodic table called "chalcogens". It is made of selenium, sulfur, oxygen, polonium, and tellurium. Tellurium is a semiconductor material, while some allocations of selenium exhibit the properties of these materials.

3.3 Chalcogenide glasses

Chalcogenide glasses contain selenium, sulfur, tellurium or a combination of these elements. Its refractive index is between 2.35 and 3.5. The best feature is the highest nonlinear refractive index and the absorption of the lower photon [8]. In principle, there is no absorption of the free carrier at 1550 nm. Some of the most commonly used compounds in chalcogenide materials are $Ge_{11.5}As_{24}S_{64.5}$, $Ge_{11.5}As_{24}Se_{64.5}$, As_2Se_3, and As_2S_3. Among the many available chalcogenide materials, the most commonly used chalcogenide material is $Ge_{11.5}As_{24}S_{64.5}$ because it has an excellent ability to make thin films with high thermal and optical stability and chalcogenide [9].

4 APPLICATIONS OF NONLINEAR FIBER OPTICS

A. In 2016, S. Vyas, et al reported simulation result of $Ge_{11.5}As_{24}S_{64.5}$ material PCF with 5 layers of air holes with the different diameter and a different pitch used for ultra-broadband supercontinuum generation in the range 1-15 μm. The PCF is used for the numerical simulation of the SCG using pulses with a peak power of 85 fs of 3 KW at a wavelength of 3100 nm [10].

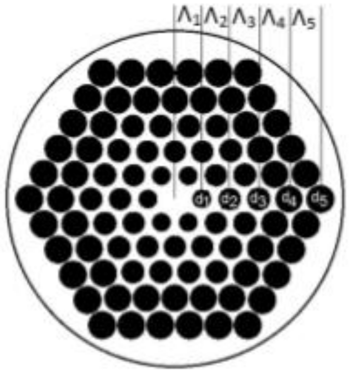
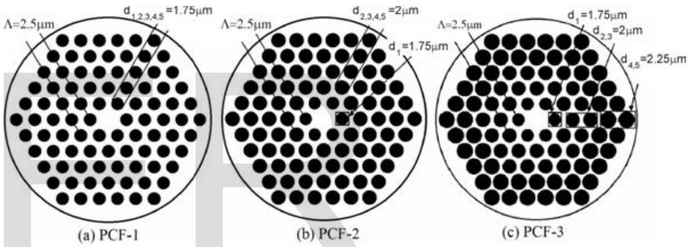


Fig.1. Structure of 5 layers hexagonal PCF

B. In 2016, S. Vyas, et al reported the effect of neff, when neff is decreased the dispersion curve will be flatter. with the nonlinear hexagonal photonic crystal fiber with a five-ring lattice structure and modifying the air hole diameter shown supercontinuum generation from 1-10 μm range, using the $Ge_{11.5}As_{24}S_{64.5}$ Chalcogenide glasses fiber [11].



(a) PCF-1 (b) PCF-2 (c) PCF-3

Fig.2. Structure of PCF with hexagonal cladding of air holes

C. In 2018, M. R. Karim, et al reported, A highly nonlinear TCF (triangular core fiber) with a GaAsSe core is used. The structure of the TCF is optimized by varying its lateral length (7 to 8 μm) for the generation of ultra-wide broadband SC in the MIR region greater than 15 μm. This proposed PCF can be used as fingerprint molecular spectroscopy, atmospheric gas detection, and biomedical imaging, as well as in many other fiber-based broadband applications [12].

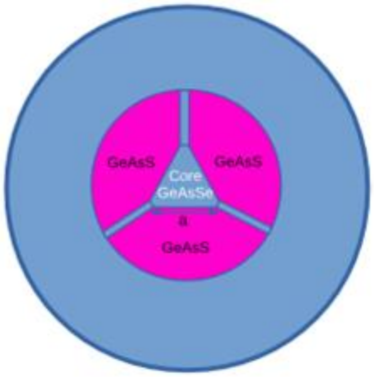


Fig.3. Triangular-core fiber geometry

D. A highly nonlinear of the proposed MOF having four rings around the core. The first air-hole ring is replaced by borosilicate rods. This optimized design is very helpful for MID-IR with 20db bandwidth of 740nm with an erbium-doped fiber emitting at 2.8µm as the pump source with a peak power of 350W with only a few centimeters of optimized fiber. The proposed fiber is very useful applications especially with the mature available technologies [13].

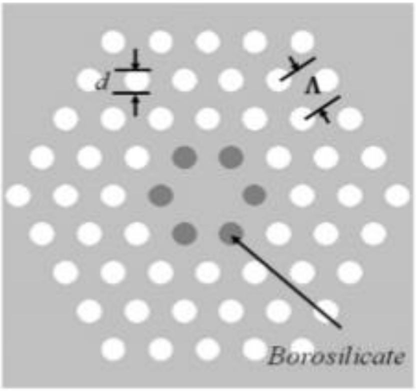


Fig.4. Structure of PCF having the first ring is replaced by borosilicate rods.

E. A highly nonlinear multi-material chalcogenide photonic crystal fiber is designed with borosilicate and As_2S_3 glass, where borosilicate is doped in a spiral shape in the cladding region of the fiber. The range of dispersion is from 1.8 to 8 µm. The results are suitable for broadband supercontinuum generation [14].

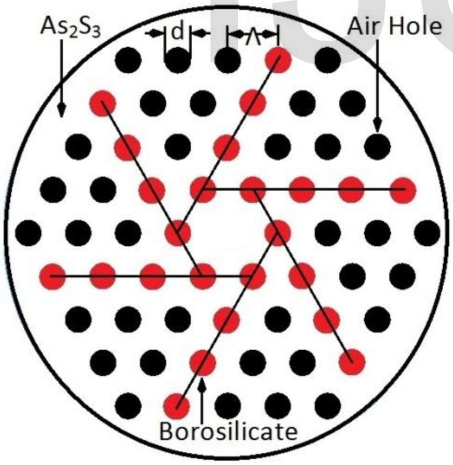


Fig.5. Structure of borosilicate doped spiral shape PCF

5 CONCLUSION

In this paper, the basics of the microstructured optical fiber along with its properties have been discussed. We have also discussed the basic guided properties of this new class of fiber. We also analyzed the recent application of microstructured optical fiber supercontinuum generation and its applications. It offers many applications such as optical coherence tomography, spectroscopy, frequent metrology, and wavelength conversion.

.

REFERENCES

[1] J. M. Dudley, G. Genty and S. Coen, "Supercontinuum generation in photonic crystal fiber," *Rev. Mod. Phys.*, vol. 78, pp. 1135–1184, 2006.

[2] V. Finazzi, T. M. Monro and D. J. Richardson, "Small-core silica holey fibers: nonlinearity and confinement loss trade-off," *J. Opt. Soc. Am. B*, vol. 20, no. 7, pp. 1427-1436, 2003.

[3] S. Vyas, G. Singh, M. Tiwari, and T. Tanabe, “Chalcogenide ($LiGSe_2$, LiGISe, $LiGaS_2$): A perfect material to design highly nonlinear PCFs for supercontinuum generation" *Proc. of the ICRCWIP*, DOI: 10.1007/978-81-322-2638-2638-3_47, pp. 409–413, @Springer Publication 2016.

[4] S. Kalra, S. Vyas, T. Ismail, M. Tiwari, and G. Singh, “Multi-material Photonic Crystal Fiber in MIR region for Broadband Supercontinuum Generation”, *International Conference on Optical & Wireless Technologies (OWT 2017)*, pp. 199-209, March (18th-19th) 2017 @Springer Publication. DOI: 10.1007/978-981-10-7395-3_23

[5] S. Kalra, S. Vyas, M. Tiwari, G. Singh, “Numerical modeling of borosilicate doped photonic-crystal fiber for MID-IR supercontinuum generation” *IEEE International Conference Progress In Electromagnetics Research Symposium-2017 (PIERS-2017)*, 19-22 November 2017, Singapore. DOI:10.1109/PIERS-FALL.2017.8293418

[6] S. Vyas, T. Tanabe, M. Tiwari, and G. Singh, “Mid-infrared supercontinuum generation in $Ge_{11.5}As_{24}Se_{64.5}$ based chalcogenide photonic crystal fiber,” *IEEE International Conference Advances in Computing, Communications and Informatics (ICACCI)*, pp. 2547-2552, September (21st-24th) 2016. DOI: 10.1109/ICACCI.2016.7732436

[7] G. P. Agarwal, “Nonlinear Fiber Optics”, 4th ed. (Academic, 2007).

[8] Marcel Spurny, “Photonic Crystal Waveguides in Chalcogenide Glasses”, April 2011. http://hdl.handle.net/10023/2111

[9] S. Vyas, T. Tanabe, G. Singh, and M. Tiwari, “Broadband Supercontinuum Generation and Raman Response in $Ge_{11.5}As_{24}Se_{64.5}$ based chalcogenide Photonic Crystal Fiber,” *IEEE International Conference on Computational Techniques in Information and Communication Technologies (ICCTICT)*, pp. 562-566, March 2016. DOI:10.1109/ICCTICT.2016.7514651

[10] S. Vyas, T. Tanabe, M. Tiwari, and G. Singh, “A Chalcogenide Photonic Crystal Fiber for Ultraflat Mid-infrared Supercontinuum Generation”, *Chinese Optics Letter*, vol. 14, no. 12, pp. 123201-1 - 123201-5, 2016. DOI: 10.3788/COL201614.123201

[11] S. Vyas, T. Tanabe, M. Tiwari, and G. Singh, “Ultraflat broadband supercontinuum in highly nonlinear $Ge_{11.5}As_{24}Se_{64.5}$ photonic crystal fibers”, *Ukrainian Journal of Physical Optics*, vol. 17, no. 3, pp. 132-139, 2016. DOI: 10.3116/16091833/17/3/132/2016

[12] M. R. Karim, H. Ahmad, and B. M. A. Rahman, “Design and modeling of dispersion–engineered all-chalcogenide triangular-core fiber for mid-infrared region supercontinuum generation”, *Journal of the Optical Society of America B*, vol. 35, no. 2, pp. 266-275, 2018. DOI: 10.1364/JOSAB.35.000266

[13] P. S. Maji and P. R.Chaudhuri, "Design of all-normal dispersion based on multi-material photonic crystal fiber in IR region for broadband supercontinuum generation," *Applied Optics*, vol. 54, no. 13, pp. 4042-4048, 2015. DOI: 10.1364/AO.54.004042

[14] S. Kalra, S. Vyas, M. Tiwari, O. Buryy, G. Singh, “Highly nonlinear multi-material Chalcogenide spiral photonic crystal fiber for Supercontinuum Generation”, *Acta Physica Polonica A journal*, vol. 133, no. 04, pp. 1000-1002, 2018. DOI: 10.12693/APhysPolA.133.1000