International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161

Available at http://inpressco.com/category/ijcet

Research Article

Guiding Properties of the Ge-Based Square Lattice Photonic Crystal Fibers

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Received 01 May 2025, Accepted 15 May 2025, Available online 16 May 2025, **Vol.15, No.3 (May/June 2025)**

Abstract

The dispersion properties of the Ge composed square lattice photonic crystal fibers (PCFs) are thoroughly analyzed for the first time. The influences of air hole size and hole-to-hole spacing on dispersion are also reported. For the smallest air filling fraction 0.1, flattened dispersion D(λ) of 6 ps/km-nm was obtained from 1200 nm to 1600 nm, spreading over 400 nm wide wavelength range. As a multimode fiber, the mode profiles of the fundamental and second order modes are clearly presented. They are strongly localized in the core and guided through the photonic crystal fiber. This fiber with flattened dispersion is more appropriate than silica PCFs and a good candidate for using in optoelectronic components, optical telecommunications, WDM optical fiber transmission system successfully.

Keywords: *Square-Lattice, photonic crystal fiber, chromatic dispersion*

Introduction

Photonic-crystal fiber (PCF) is a novel type of optical fiber based on the properties of photonic crystals [1], [2], [3]. Here, light is guided by structural modifications, and not only by the total internal reflection mechanism. Photonic crystals (PCs) [4] are a novel class of optical media represented by natural or artificial structures with periodic variation in the dielectric constant or, equivalently, periodic variation in the refractive index (refractive index, $n = \sqrt{\varepsilon}$, where ε is the dielectric constant). Photonic crystal acts as a cladding for guiding the light, whereas the fiber core may be solid or hollow. Photonic crystal fiber is a completely new field of research that was first proposed by P. Russel. The properties of these fibers can be altered by modifying the design of crystal structure and/or by filling air core with gas or liquid which itself is a biggest advantage. Other major advantages of these fibers include efficient light guiding, single mode operation over enhanced wavelength range [1], small nonlinearities [5], dispersion controlling [6], [7], [8] and polarization maintaining [9], [10], [11], [12]. The present applications of these fibers include telecom components [13], sensors [14], [15], high power lasers [16], amplifiers [17], [18] and medicine [19].

PCFs, which are also known as **hole-assisted fiber, holey fiber, microstructure fiber, or microstructured optical fiber** [4] possess the especial attractive property of controlling chromatic dispersion by varying the hole diameter and hole-to-hole spacing. Control of chromatic dispersion in PCFs is a very important problem for practical applications to optical communication systems, dispersion compensation, and nonlinear optics [8], [20].

As photonic crystals are artificial structures, their designs are limited only by human imagination. Some most important designs are triangular patterns, square patterns, honeycomb patterns etc. Different physical phenomenon providing the guidance of light may be obtained depending on these designs.

We studied the dispersion properties of the square lattice air holes in Ge background for the first time. Recently, a lot of studies have been done on the dispersion properties of PCF made of silica [5], [6], [8], [20], [21], [22], [23]. A study on Ge doped core pcf has been done [24]. But, no research article has been published on Ge PCF. Our PCF composed of Ge showed interesting properties. We studied their effective index, chromatic dispersion properties, V number and magnetic field distribution at 1.5 μm.

(a) Index guided fibers and

(b) photonic band gap fibers

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DOI: https://doi.org/10.14741/ijcet/v.15.3.5

Guiding Properties of the Photonic Crystal Fibers

The chromatic dispersion is related to the effective index. The effective refractive index is a number quantifying the phase delay per unit length in a waveguide, relative to the phase delay in vacuum. For any mode, this is just the ratio of the modulus of the **k**-vector and the mode frequency. Mathematically,

$$n_{eff} = |\mathbf{k}|/\omega \qquad (1)$$

Once n_{eff} is computed from (1) within a wavelength range, the chromatic dispersion [24],[22] is readily computed by using the following expression,

$$D = -\frac{\lambda}{c}\frac{d^2 n_{eff}(\lambda)}{d\lambda^2} \qquad (2)$$

In a conventional fiber, the number of bound modes is governed by the V number, which increases without limit as the wavelength decreases. For a PCF, an effective V number [25] is defined that indicates accurately whether or not a fiber is single-moded:

$$V_{eff} = (2\pi\Lambda/\lambda)\sqrt{n_0^2 - n_{eff}^2} \qquad (3)$$

Where, Λ is the lattice period (pitch), n_0 is the core index and n_{eff} is an effective cladding index. The effective cladding index can be considered as the effective index of the first radiation state, which is equivalent to find the lowest mode in the band structure of the plain lattice.

Beam popagation method:

The beam propagation method (BPM) is an approximation technique for simulating the propagation of light in slowly varying optical waveguides. The usual assumption is made that a single-frequency component of the electric field satisfies the scalar Helmholtz equation [26],

$$\frac{\partial^2 \emptyset}{\partial x^2} + \frac{\partial^2 \emptyset}{\partial y^2} + \frac{\partial^2 \emptyset}{\partial z^2} + k(x,y,z)^2 \emptyset = 0 \qquad (4)$$

Here the scalar electric field has been written as $E(x,y,z,t) = \phi(x,y,z)e^{-i\omega t}$ and the notation $k(x,y,z) = k_0 n(x,y,z)$ has been introduced for the spatially dependent wavenumber, with $k_0 = 2\pi/\lambda$ being the wavenumber in free space. The geometry of the problem is defined entirely by the refractive index distribution $n(x,y,z)$.

Considering that in typical guided-wave problems the most rapid variation in the field ϕ is the phase variation due to propagation along the guiding axis, and assuming that axis is predominantly along the z direction, it is beneficial to factor this rapid variation out of the problem by introducing a so-called slowly varying field u via the ansatz,

$$\emptyset(x,y,z) = u(x,y,z)e^{i\bar{k}z} \qquad (5)$$

Here k-bar is the reference wavenumber to be chosen to represent the average phase variation of the field ϕ. Substitution of Eq. (5) into Eq. (4) gives the following equation for the slowly varying field:

$$\frac{\partial^2 u}{\partial z^2} + 2i\bar{k}\frac{\partial u}{\partial z} + \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \left(k^2 - \bar{k}^2\right)u = 0 \qquad (6)$$

Eq. 6 is completely equivalent to the exact Helmholtz equation, except that it is expressed in terms of u. It is now assumed that the variation of u with z is sufficiently slow so that the first term above can be neglected with respect to the second; this is the familiar slowly varying envelope approximation and in this context it is also referred to as the paraxial or parabolic approximation. With this assumption and after slight rearrangement, the above equation reduces to:

$$\frac{\partial u}{\partial z} = \frac{i}{2\bar{k}}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \left(k^2 - \bar{k}^2\right)u\right) \qquad (7)$$

This is the basic BPM equation in three dimensions (3D) [27], [28], [29], [30], [31]; simplification to two dimensions (2D) is obtained by omitting any dependence on y. Given an input field, $u(x,y,z=0)$, the above equation determines the evolution of the field in the space $z>0$. Starting from the effective index values, the dispersion curves have been derived using the beam propagation method.

Square lattice Ge core Photonic Crystal Fibers

The guiding properties of photonic crystal fibers (PCFs) depend on the geometric structures of the air-holes in their cross-section, and have been applied in different applications successfully. In particular, the dispersion properties of the square PCFs can be engineered by changing the hole-to-hole spacing and the air-hole diameter. It is interesting to analyze how a regular square arrangement of air-hole and Ge rod can affect the characteristics of the guided mode.

We consider a photonic crystal fiber with a square array of circular air rods in a background of Germanium (Ge), having a Ge core as shown in fig. 1. The first ring comprises of six air-holes. The pcf has a period of, Λ =2.3 μm, which is the distance of the six air-holes of the first ring from the core center. The width of the air holes is, d = 1.15 μm. The Ge core has a width of, d_{core} = 2Λ - d= 3.35μm.

The real part of the effective refractive index n_{effr} versus wavelength λ for this lattice is shown in fig. 2 for five different width-period (d/Λ) values - 0.1, 0.3, 0.5, 0.7, 0.9.

The properties of the square lattice PCFs have been accurately studied through BeamPROP of the RSOFT software package, based on the Beam Propagation Method (BPM) [4, 11, 12].

The effect of the geometric parameters pitch Λ and width-period ratio d/Λ on the real part of the effective refractive index has been investigated in the wavelength range of 1.2 μm -1.6 μm as shown in fig. 2 and fig. 3. $n_{effr}(\lambda)$ was calculated considering two values of the hole-to-hole spacing Λ, that is 1.3 μm and 2.3 μm.

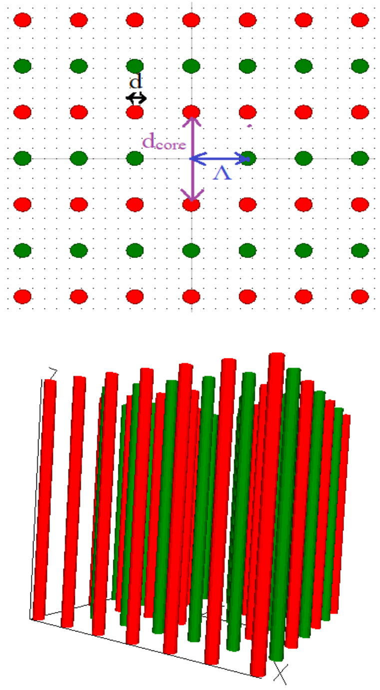

Figure 1: Geometry of a square lattice photonic crystal fiber composed of air holes in Germanium background

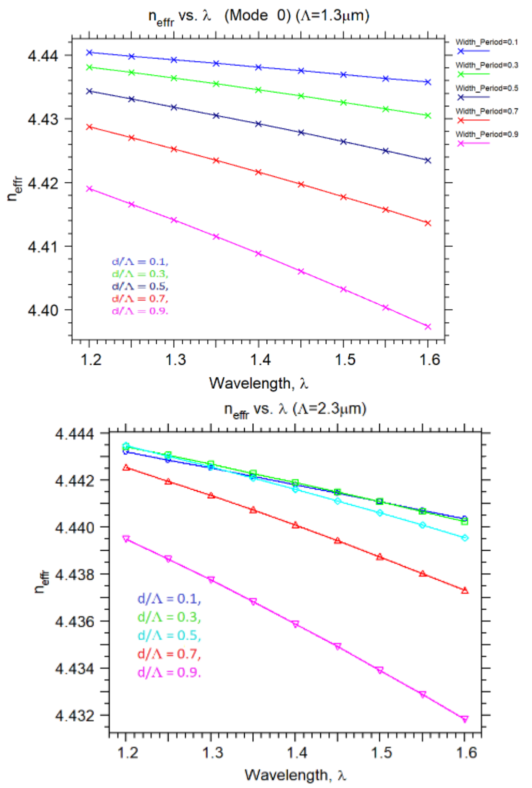

Figure 2: The effective index n_{effr} versus the wavelength of the square lattice Ge PCFs with a) Λ=1.3 μm and (b) Λ=2.3 μm for different d/Λ values of 0.1, 0.3, 0. 5, 0.7, 0.9.

From from fig. 2(a), we found that at a fixed pitch value Λ=1.3 μm, the highest value of n_{effr} is 4.440 for d/Λ=0.1. For d/Λ=0.3, n_{effr} is 4.438. For d/Λ=0.5, n_{effr} is 4.434. For d/Λ=0.7, n_{effr} is 4.428. For d/Λ=0.9, n_{effr} is 4.419. Thus, we see from fig. 2(a) that the effective index n_{effr} is inversely proportional to the width-period d/Λ. This is also justified for other pitch value Λ=2.3 as shown in fig. 2(b).

The effective index of a fiber mode lies between the cladding index and core index. The power distribution in the cladding and core determines the value of the effective index. If most of the power is propagted in the core, the effective index value is closer to the core refractive index; if most of it propagates in the cladding, the effective index is closer to the cladding refractive index [32]. Here, neffr values are close to the Ge core index. So, most of the power is contained in the core.

In a fiber, the light energy of a mode propagates partly in the core and partly in the cladding. The effective index of a mode lies between the refractive indices of the cladding and the core. The actual value of the effective index between these two limits depends on the proportion of power that is contained in the cladding and the core. .

Fig. 3 shows the effect of period on the effective index. From this figure we see that with the increase of the pitch Λ, n_{effr} increases for all air filling fraction d/Λ. So, the effective index n_{effr} is directly proportional to the width-period d/Λ.

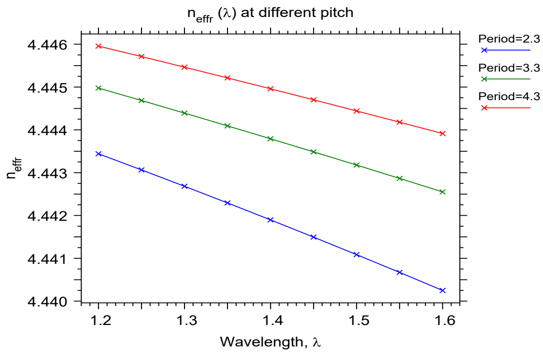

Figure 3: The variation of the effective index with the pitch of the square lattice.

The wavelength response of chromatic dispersion D(λ) of the square lattice Germanium photonic crystal fiber is shown in fig.4 for optimum design parameters. Varying the parameter d/Λ from 0.1 to 0.9 with a fixed increment of 0.2, almost flat chromatic dispersion curves were obtained. For the smallest air filling fraction 0.1, flattened D(λ) of 6 ps/km-nm was obtained for all wavelengths of light modes from 1.20 μm to 1.60 μm. We obtained positive dispersion slopes for higher air filling fractions. These positive chromatic dispersion fibers can be used for terrestrial systems.

Fig. 5 shows how D(λ) changes with pitch for a fixed d/Λ value. We found that D(λ) increases with increasing pitch for a air filling fraction of d/Λ=0.3. At the communication wavelength 1.55 μm, our newly designed fiber has a very small dispersion, that is 5.68 ps/km-nm for Λ= 2.3 μm and 6.80 ps/km-nm for Λ=3.3 μm.

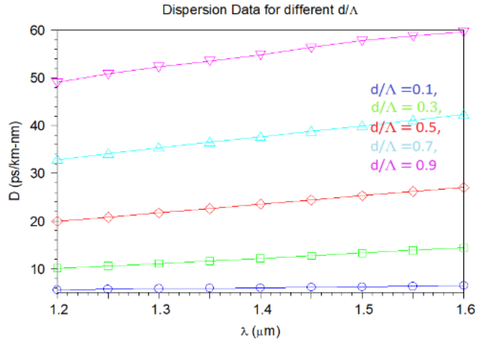

Figure 4: Wavelength response of chromatic dispersion of the square lattice Germanium photonic crystal fiber with Λ = 2.3 μm for five different width-period of 0.1, 0.3, 0.5, 0.7, 0.9.

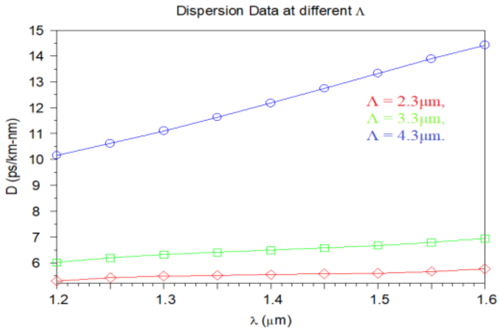

Figure 5: The variation of chromatic dispersion with the pitch of the lattice with d/Λ=0.3.

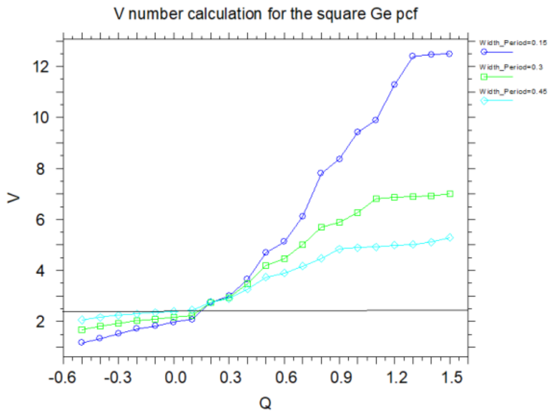

Figure 6: V number calculation for the Ge-Based square-lattice photonic crystal fiber.

In fig. 6, we calculated the V number for this Ge-based square-lattice photonic crystal fibers. The variable Q is used here so that we can scan over the wavelength in steps equal to a power of ten. Q is defined by, Q = log(Λ/λ). From fig. 6 we see, all modes lie above the line drawn at V=2.405. So, square-lattice Ge photonic crystal fiber is a multimode fiber. Fig. 7 shows the fundamental mode, ie. the lowest order mode of the fiber. Fig. 8 shows the first two modes of this fiber are tightly confined in the core, obtained with pitch Λ=2.3 μm and d/Λ=0.3. So, we had two bound modes for this fiber. This square lattice has a large core width. That is why the magnetic fields are strongly confined in the first air hole ring.

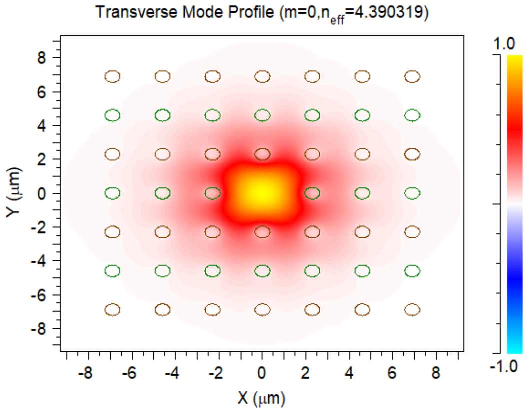

Figure 7: Fundamental mode of the square-lattice Ge photonic crystal fiber

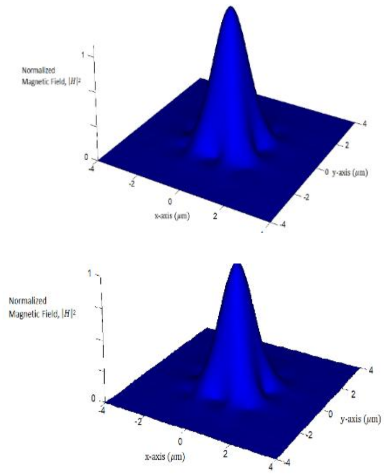

Figure 8: Normalized magnetic field of the fundamental mode (left) and second mode (right) at 1550 nm with pitch Λ=2.3 μm and d/Λ=0.3 for the Ge-Based square-lattice photonic crystal fiber.

Conclusion

We have made an in-depth analysis of the properties of the Ge composed PCF. The variation of the effective index and chromatic dispersion with different hole-to-hole spacing and air-hole diameter were investigated. We found that with the increase of the air-hole diameter, dispersion D(λ) increases. However, our Ge made fiber is much less dispersive than that of Silica fiber. The dispersion value of the square-lattice Silica PCF with d/Λ = 0.5 and Λ = 2 μm is around 53 ps/km.nm, at 1.55 μm [7]. Our proposed Ge fiber has a dispersion of only 26 ps/km.nm at 1.55 μm with the same air filling fraction and Λ = 2.3 μm. Thus, we suggest that, Ge composed PCFs are more appropriate than silica PCFs and a good candidate for using in optical telecommunication networks.

Disclosure: There is no conflict of interest among the authors.

Acknowledgements

The authors thank the Information and Communication Technology Division (ICT- Division), Department of the Ministry of Posts, Telecommunications and Information Technology of the Government of Bangladesh, for providing the prestigious ICT fellowship 2020-21 (3rd round) and supporting this.

References

[1] D. M. A. J. C. Knight, T. A. Birks, P. St. J. Russell, "All-silica single-mode optical fiber with photonic crystal cladding," Opt. Lett., vol. 21, pp. 1547–1549, 1996.
[2] J. Broeng, D. Mogilevstev, S. E. Barkou, and A. Bjarklev, "Photonic Crystal Fibers: A New Class of Optical Waveguides," Opt. Fiber Technol., vol. 5, no. 3, pp. 305–330, 1999, doi: 10.1006/ofte.1998.0279.
[3] R. P, "Photonic crystal fibers," Science (80)., vol. 17, no. 299, pp. 358–62, 2003, doi: 10.1126/science.1079280. PMID: 12532007.
[4] J. J. D. Joannopoulos, S. Johnson, J. N. J. Winn, and R. R. D. Meade, Photonic crystals: molding the flow of light. 2008. doi: 10.1063/1.1586781.
[5] K. Saitoh and M. Koshiba, "Highly nonlinear dispersion-flattened photonic crystal fibers for supercontinuum generation in a telecommunication window," vol. 12, no. 10, pp. 2027–2032, 2004.
[6] K. Hansen, "Dispersion flattened hybrid-core nonlinear photonic crystal fiber," Opt. Express, vol. 11, no. 13, p. 1503, 2003, doi: 10.1364/oe.11.001503.
[7] N. Karasawa, "Dispersion properties of liquid-core photonic crystal fibers," Appl. Opt., vol. 51, no. 21, pp. 5259–5265, 2012, doi: 10.1364/AO.51.005259.
[8] A. Suzuki and M. Yoshida, "Design of dispersion-flattened photonic crystal fiber with 800 nm wide low-dispersion band," Results Opt., vol. 12, no. April, p. 100474, 2023, doi: 10.1016/j.rio.2023.100474.
[9] M. R. Hasan, M. S. Anower, M. M. Rashid, and S. Ali, "A polarization maintaining hexagonal photonic crystal fiber for residual dispersion compensation," 2016 3rd Int. Conf. Electr. Eng. Inf. Commun. Technol. iCEEiCT 2016, vol. 28, no. 16, pp. 1782–1785, 2017, doi: 10.1109/CEEICT.2016.7873107.
[10] F. Esposito, R. Ranjan, S. Campopiano, and A. Iadicicco, "Arc-induced long period gratings from standard to polarization-maintaining and photonic crystal fibers," Sensors (Switzerland), vol. 18, no. 3, 2018, doi: 10.3390/s18030918.
[11] Z. Wu et al., "Low-loss polarization-maintaining THz photonic crystal fiber with a triple-hole core," Appl. Opt., vol. 56, no. 8, p. 2288, 2017, doi: 10.1364/ao.56.002288.
[12] M. Chen and Y. Zhang, "Improved design of polarization-maintaining photonic crystal fibers," vol. 33, no. 21, pp. 2542–2544, 2008.
[13] Y. B. and H. H. M. Bennoune, A. Smaoui, "Optical Components Based on PCF Fibers," in Canadian Conference on Electrical and Computer Engineering, 2007, pp. 74–77. doi: 10.1109/CCECE.2007.26.
[14] B. P. P. and S. K. V. S. Chaudhary, D. Kumar, "Advances in Photonic Crystal Fiber-Based Sensor for Detection of Physical and Biochemical Parameters—A Review," IEEE Sens. J., vol. 23, no. 2, pp. 1012–1023, 2023, doi: 10.1109/JSEN.2022.3222969.
[15] S. O. Konorov, A. M. Zheltikov, and M. Scalora, "Photonic-crystal fiber as a multifunctional optical sensor and sample collector," Opt. Express, vol. 13, no. 9, p. 3454, 2005, doi: 10.1364/opex.13.003454.
[16] J. C. Knight, "Photonic crystal fibers and fiber lasers (Invited)," J. Opt. Soc. Am. B, vol. 24, no. 8, p. 1661, 2007, doi: 10.1364/josab.24.001661.
[17] V. Elgamri, A., Rawat, B., Trivedi, A., Manhas, S., Karwal, "Photonic Crystal Fiber (PCF) Raman Amplifier," in Advances in Signal Processing and Communication,Springer, 2019. doi: 10.1007/978-981-13-2553-3_1.
[18] K. Hougaard and F. D. Nielsen, "Amplifiers and lasers in PCF configurations," J. Opt. Fiber Commun. Reports, vol. 1, no. 1, pp. 63–83, 2004, doi: 10.1007/s10297-004-0018-9.
[19] F. Begum and Y. Namihir, "Photonic Crystal Fiber for Medical Applications," Recent Prog. Opt. Fiber Res., no. March, 2012, doi: 10.5772/27739.
[20] S. M. A. Razzak et al., "Dispersion-flattened modified hexagonal photonic crystal fibers with low confinement loss," Opt. Rev., vol. 14, no. 4, pp. 165–168, 2007, doi: 10.1007/s10043-007-0165-3.
[21] and A. J. S. Jinendra K. Ranka, Robert S. Windeler, "Visible continuum generation in air–silica microstructure optical fibers with anomalous dispersion at 800 nm," Opt. Lett., vol. 25, no. 25–27, 2000, [Online]. Available: https://opg.optica.org/ol/abstract.cfm?URI=ol-25-1-25
[22] K. Saitoh, M. Koshiba, T. Hasegawa, and E. Sasaoka, "Chromatic dispersion control in photonic crystal fibers: application to ultra-flattened dispersion," Opt. Express, vol. 11, no. 8, p. 843, 2003, doi: 10.1364/oe.11.000843.
[23] S. K. Pandey, J. B. Maurya, and Y. K. Prajapati, "Photonic crystal fiber with high nonlinearity and extremely negative dispersion," Opt. Quantum Electron., vol. 53, no. 12, pp. 1–13, 2021, doi: 10.1007/s11082-021-03376-y.
[24] J. P. Silva, D. S. Bezerra, I. E. Fonseca, and H. E. Hernandez-figueroa, "Photonic Crystal Fiber Design with Ge-Doped Core," pp. 787–791, 2009.
[25] RSoft, "RSoft BandSolve," Synopsys, Inc., Opt. Sol. Gr., [Online]. Available: optics.synopsys.com
[26] M. D. Feit and J. A. Fleck, "Computation of mode eigenfunctions in graded-index optical fibers by the propagating beam method," Appl. Opt., vol. 19, no. 13, p. 2240, 1980, doi: 10.1364/ao.19.002240.
[27] M. Marciniak, "Beam propagation method modelling of light propagation in optical waveguides," in International Conference on Mathematical Methods in Electromagnetic Theory, 1998, pp. 106–111.
[28] C. M. and E. Van Keuren, "A simple three dimensional wide-angle beam propagation method," Opt. Express, vol. 14, pp. 4668–4674, 2006.
[29] G. H. Song, "Transparent boundary conditions for beam-propagation analysis from the Green's function method," J. Opt. Soc. Am. A, vol. 10, pp. 896–904, 1993.
[30] L. Thylén, "The beam propagation method: an analysis of its applicability," Opt Quant Electron, vol. 15, no. 433–439, 1983, doi: 10.1007/BF00619865.
[31] and S. H. Scarmozzino, A. Gopinath, R. Pregla, "Numerical Techniques for Modeling Guided-Wave Photonic Devices," J. Sel. Top. Quantum Electron., vol. 6, no. 150, 2000.
[32] "optical-fibre-chromatic-dispersion." [Online]. Available: https://vividcomm.com/2018/12/23/optical-fibre-chromatic-dispersion