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Sultan Qaboos University

Optical Properties of Photonic Crystal Fibers with Fluid Cores

Mohammed Salim Jasim Al-Taie

Gifted Guardianship Committee, Directorate of Education, Misan, Iraq
****Email: mohammed.altaie@iraqiggc.edu.iq.***

ABSTRACT: The objective of this research is to compare pulses travelling through different photonic crystal fiber cores (DPCFC) using both finite element method (FEM) /split step Fourier method (SSFM). A unique DCPCF design with exceptionally high non-linearity has been introduced to achieve ultra-high pulse amplitude. Via a generalized non-linear equation, we evaluate the refractive index ratio and dispersion, for each type which is used, as well as output amplitude for different cores in different photonic crystal fiber core by utilizing the solution for the nonlinear Schrodinger equation (NLSE). Lastly, the findings are compared to different photonic crystal fiber design parameters. This paper provides a photonic crystal fiber design consisting of multiple liquid cores and theoretically solved non-linear equations. It was discovered in this design that the refractive index of propylene glycol ($C_3H_8O_2$) is greater than ethylene glycol's (C_2H6O_2), and that both are far greater than silica's refractive index (SiO_2). Propylene (C_3H8O^2) has a lower dispersion than ethylene glycol (C_2H6O_2) and silica (SiO_2). The output amplitudes of ($C_3H_8O_2$) and (C_2H6O_2) were then shown to be substantially bigger than the output amplitudes of (SiO_2) with respect to distance and time. This emphasizes the need for using certain liquids as cores in holey fibers, dependent upon their use.

Keywords: Photonic crystal fiber; Split-Step fourier; Finite element method; Non-linear schrodinger equation; Solution pulse.

الخصائص البصرية للألياف المتبلورة الفوتونية ذات النوى السائلة

محمد سالم جاسم الطائي

الملخص: الهدف من البحث هو مقارنة النبضات المتنقلة عبر نوى ألياف بلورة فوتونية مختلفة بإستخدام طريقة العناصر المحدودة وطريقة فورييه ذات الخطوط المنقسمة , تم تقديم تصميم جديد من هذا النوع بوجود لا خطية عالية بشكل استثنائي لتحقيق سعة نبضة فائقة. من خلال معادلة لا خطية معممة ، تم حساب نسبة معامل الإنكسار و التشتت لنوى مختلفه ، اعتمادا على معادلة شرودنكر اللاخطية. أخيرًا ، تمت مقارنة النتائج بمعايير التصميم المختلفة. قدم هذا البحث تصميمًا من الياف بلورة فوتونية والمتكونة من نوى سوائل متعددة معتمدة على معادلات لا خطية تم حلها نظريًا. حيث تم اكتشاف في هذا التصميم أن معامل انكسار البروبيلين جليكول أكبر من الإيثيلين جليكول، وكلاهما أكبر بكثير من معامل انكسار السيليكا, كما يظهر أن البروبيلين جلايكول له تشتت أقل من الإيثيلين جلايكول والسليكا، كما تم عرض نسبة اتساع الخرج للنبضة في السوائل قيد الدراسة ومقارنتها مع السليكا حيث ظهر ان الأتساع للبروبيلين جلايكول و الإيثيلين جلايكول اكبر بكثير من السليكا مع المسافة والزمن . وهذه النتائج تؤكد الحاجة إلى استخدام سائل معين في قلب ليف البلورة الفوتونية لزيادة كفاءتها واداؤها لاستخدامها في التطبيقات المختلفة.

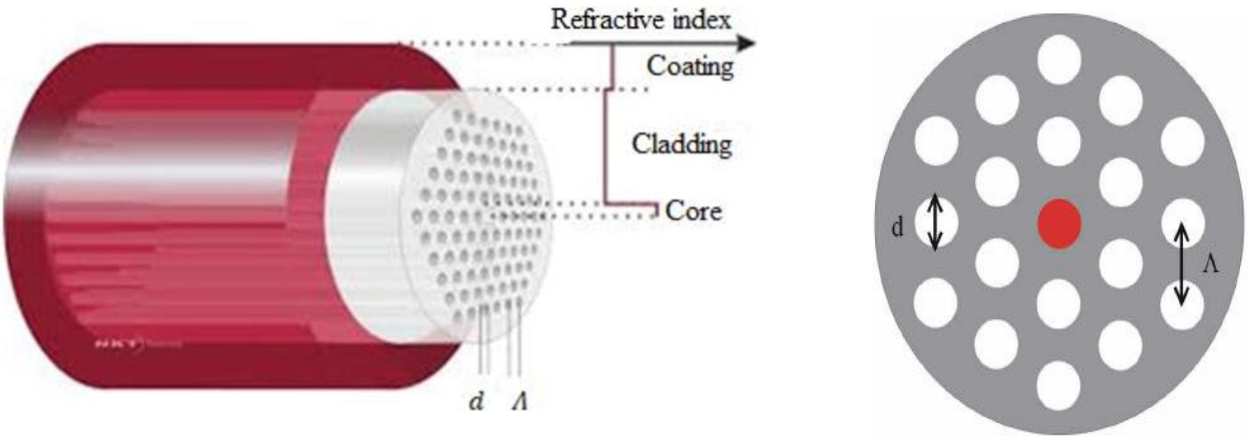
الكلمات المفتاحية: ألياف البلورة الفوتونية ،طريقة فورييه المنفصل ، طريقة العناصر المحدودة ، معادلة شرودنجر اللاخطية ، نبضة سوليتون.

1. Introduction

Fluid- filled core photonic crystal fibers (FCPCFs) have received a great deal of interest in recent years because of the wide range of uses they might have in a variety of industries [1-15]. Filling the core section of the PCF with fluids results in unique optical features such as wideband single-mode guiding, ultra- flattened dispersion, large birefringence, huge or ultra- tiny effective areas , should it be tailored mode area, significant nonlinearity, and so on [16]. Using various fluids to fill in the core of PCFs, should it be a multiple assessment refractive index may be obtained. By filling the core with different fluids, several characteristics of PCFs, including effective area, dispersion, and nonlinearity, may be adjusted [17-20]. The variation in refractive index between its core and the cladding in a FCPCF is significantly greater than in a silica core PCF[21-22]. The effective area of the modes of the FCPCF is inversely related to the fiber's nonlinearity [23-24]. It is generally understood that the size of the air hole, and therefore its effective area, is the control parameter in a PCF for adjusting nonlinearity and dispersion. Many academics are interested in the soliton pulse in PCFs with various structures, which is one of their applications [25-27]. PCFs have a higher dispersion than silica fibers, according to research. As a result, the dynamics of solution may be investigated on centimeter-length scales. The purpose of this study is to develop the proposed PCF design for ultra-high pulse amplitude. We use the finite element technique to compute the dispersion and nonlinear coefficients in this work. The technique of computation of the pulse amplitude in a PCF is investigated using the finite element technique, which solves the wave equations, and the Split-step method, which solves the NLSE with an exponentially decreasing dispersion profile for constant design parameters for various core fluids.

2. High Nonlinear Photonic Crystal Fiber Design

We computed the transmission constant of two distinct fluid photonic crystal fibers (PCFs) with propylene ($C_3H_8O_2$) and ethylene glycol ($C_2H_6O_2$) in the core region. The finite element method (FEM) is a commonly utilized mathematical technique for evaluating the field of electromagnetic radiation of PCF travel modes. PCF's effective refractive index was investigated using FEM. The PCF was determined by the diameter of the air hole (Figure 1, d), the distance between the air holes (Figure 1, Λ), and number of air holes (Figure 1, N). The investigated PCF had a lot of nonlinearity, and the parameters were $\Lambda = 3\mu m$, d = 1.68 μm, N = 6. Following up on these results, a new PCF was created by filling the core region with fluid.



(a) **(b)**

Figure 1. (a) Longitudinal section of the photonic crystal fiber, (b) Cross-section of the photonic crystal fiber.

By using finite element method (FEM), the effective refractive index of the fluid filled PCF is greater than that of the PCF with a solid core structure because the refractive index of propylene glycol and ethylene glycol is higher than that of silica, as shown in Figure 2.

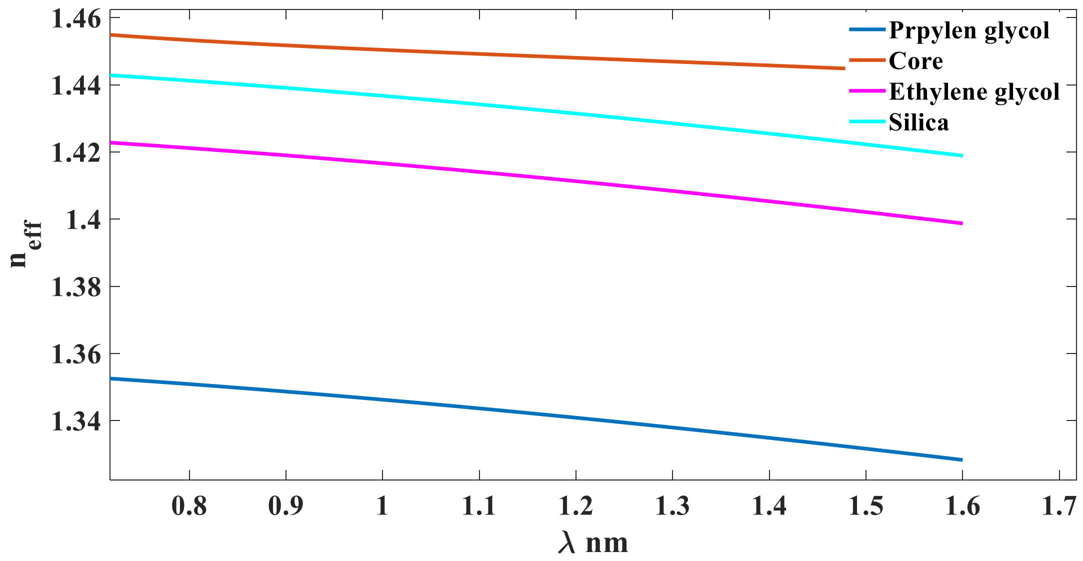


Figure 2. The relationship between the refractive indices of SiO_2, $C_3H_8O_2$ and $C_2H_6O_2$.

The group velocity dispersion (GVD) of propylene glycol and ethylene glycol was determined using the transfer function. Figure 3 illustrates the variance in GVD as a function of λ, for different fluids with d = 1.68m and Λ = 3m.

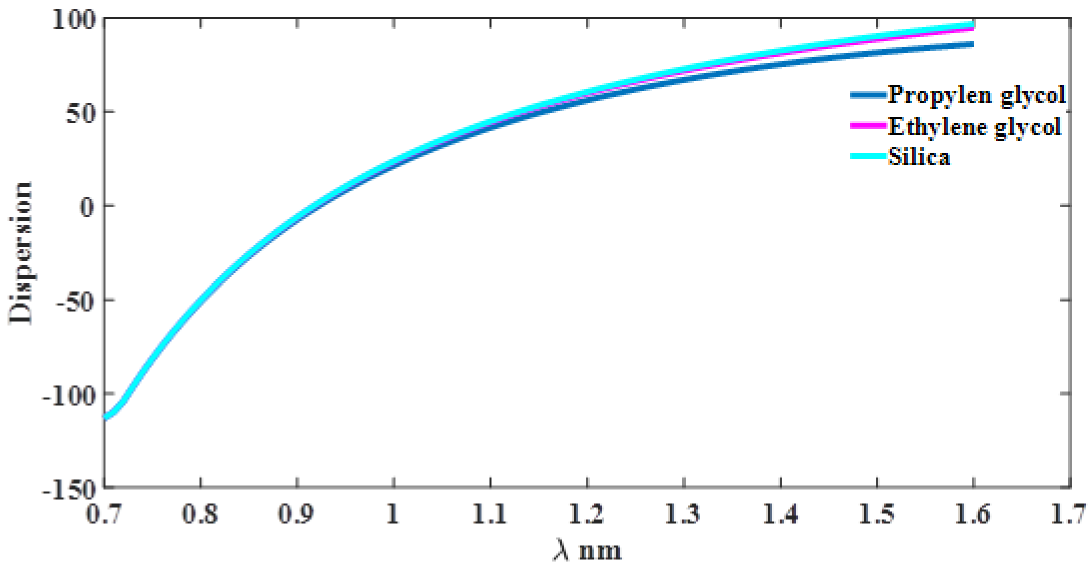


Figure 3. The dispersion of cores consisting of SiO_2, $C_3H_8O_2$, and $C_2H_6O_2$.

The computed wavelength dependency of the nonlinearity for various core regions in PCFs is shown in Figures 2 and 3, where the nonlinearity is calculated on a logarithmic scale due to the higher fluctuation in FCPCFs than that found in silica core PCFs. The greatest effective area a PCF can support is determined by the fluid in the core. The effects of the intensity dependent nonlinearity is shown to be minimized when the effective area is raised. The nonlinearity of the FCPCF is a few hundred times greater than that of the silica core PCF, as seen in Figure 3.

2. Pulse Amplitude in Photonic Crystal Fibers

Consider the following NLSE of the form in order to understand the mechanics of pulse amplitude in PCF[28-32].

$$\left(\partial A/_{\partial z}\right) \; - \; \Sigma_{n\geq 2}\left(i^{n+1}/_{n!}\right) \;\; \beta_n \left(\partial^n A/_{\partial T^n}\right) = i\gamma \; |A^2 \; |A \qquad (1)$$

and

$$A(0,T) = \sqrt{P_\circ \operatorname{sech}\left(T/_{T_\circ}\right) \exp(i\alpha\, T^2/_2)} \quad (2)$$

where A is the wave's slowly varying envelope intensity, z is the fiber's lengthwise position in meters, and T is the reference frame's duration in seconds. The parameter (γ) is used to indicate the Kerr nonlinear factor. Figure 4 illustrates the pulse amplitude of propylene glycol and ethylene glycol as a function of time at a wavelength of 835 nm, and Figure 5 depicts the impact of core fluids on pulse amplitude as a function of length in PCF, after solving Equation (1) theoretically using SSFM. Figure 4 shows a sequence of intensity pulses for each core material.

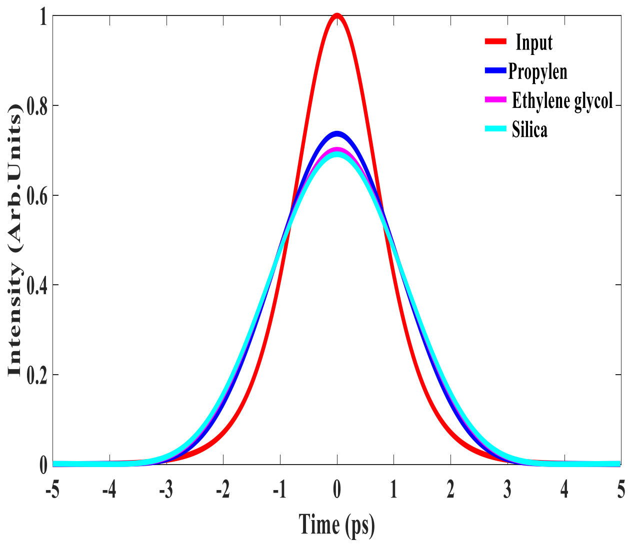


Figure 4. The difference in amplitude of different core materials with respect to time.

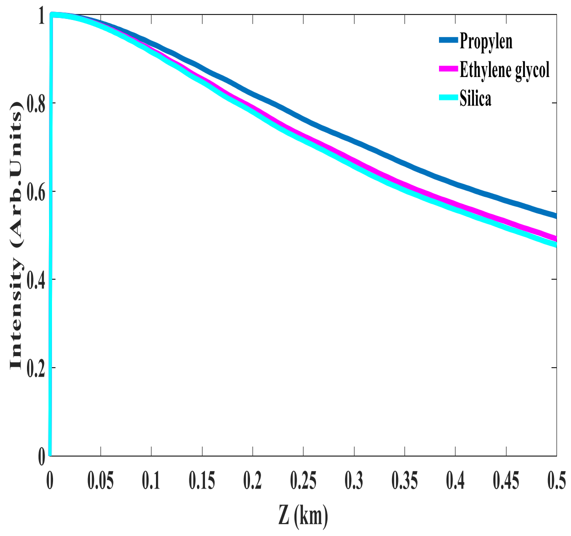


Figure 5. The difference in amplitude of different core materials with respect to length.

It is obvious from this graph that the amplitude of the pulses for propylene glycol and ethylene glycol are larger than that of silica, which is lower, and that it is higher for PCF with a fluid core than for PCF with a silica core. Because FCPCF can reach extremely high nonlinearity, very high pulse amplitude may be easily achieved by filling the core area with fluid, as illustrated in Figures 4 and 5. As a result, it is worth noting that our newly developed PCFs are very well suited for constructing nonlinear devices, in addition to increasing the amplitude of the pulses.

Conclusion

In conclusion, the pulse amplitude in FCPCF with $C_3H_8O_2$, $C_2H_6O_2$ and SiO_2 fluid cores was investigated using a FEM and an SSFM. In comparison with the amplitude ratio of silica-core PCF, we have successfully proven that the novel fluid core photonic crystal fiber we have developed can reach ultra-high pulse amplitude. In addition, the refractive index and dispersion for different liquid cores were studied. The objective of this research was to compare output pulse propagation through different cores of holey fiber (DCHF) using both finite element (FEM) and split step Fourier methods (SSFMs) to solve the nonlinear Schrodinger equation. In conclusion, it turns out that the pulse amplitude in different cores of holey fiber, which consist of $C_3H_8O_2$ and $C_2H_6O_2$, is much larger than the amplitude ratio of silica-core photonic crystal fiber. This gives great importance to using certain types of liquids as cores in holey fiber, depending upon the various uses and applications they will be put to, and according to the designers' needs.

Conflict of interest

The author declares no conflict of interest.

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References

1. Du, F., Lu, Y.Q., and Wu, S.T. Electrically tunable liquid-crystal photonic crystal fiber, *Applied Physics Letters*. 2004, **85**, 2181-2183.
2. Martelli, J. Canning, K. Lyytikainen. and Groothoff, N. Water-core Fresnel fiber, *Optics Express*, 2005, **13**, 3890-3895.
3. Zhang, R., Teipel, J. and Giessen, H. Theoretical design of a liquidcore photonic crystal fiber for supercontinuum generation. *Optics Express*. 2006, **14**, 6800.
4. Vasantha, R., Raja, J. and Porsezian, K. A fully vectorial effective index method to analyse the propagation properties of microstuctured fiber, *Photonics and Nanostructures*. 2007, **5**, 171-177.
5. Wang, J.Y., Jiang, C., Hu, W.S., Gao, M. Properties of index guided PCF with air-core, Optics and Laser Technology. 2007, **39**, 317-321.
6. Yu, C.P., Liou, J.H., Huang, S.S. and Chang, H.C. Tunable dual-core liquid-filled photonic crystal fibers for dispersion compensation. *Optics Express*. 2008, **16**, 4443.
7. Yu, C.P. and Liou, J.H. Selectively liquid-filled photonic crystal fibers for optical devices. *Optics Express*. 2009, **17**, 8729.
8. Zheng, X., Liu, Y., Wang, Z., Han, T., Wei, C. and Chen, J. Transmission and temperature sensing characteristics of a selectively liquid fliled photonic band gap fber. *Applied Physics Letters*. 2012, **100**, 141104.
9. Kedenburg, S., Vieweg, M., Gissib, T., Giessen, H. Linear refractive index and absorption measurements of nonlinear optical liquids in the visible and near-infrared spectral region. *Optical* Materials *Express*. 2012, **2**, 1588.
10. Vieweg, S., Pricking, T. Gissibl, Y.V. Kartashov, L. Torner, Giessen, H. Tunable ultrafast nonlinear optofuidic coupler. *European Physical Journal*. 2013, **41**, 12010.
11. Porsezian, K., Nithyanandan, K., Raja, R.V.J., Ganapathy, R. A theoretical investigation of soliton induced supercontinuum generation in liquid core photonic crystal fber and dual core optical fber. *European Physical Journal*. Special Topics. 2013, **222**, 625-640.
12. Herrera, O.D., Schneebeli, L., Kieu, K., Norwood, R. and Peyghambarian, N. Raman-induced frequency shift in CS2-filled integrated liquid-core optical fiber. *Optics Communications*. 2014, **318,** 83-87.
13. Chemnitz, M., Gaida, C., Gebhardt, M., Stutzki, F., Kobelke, J. Tnnermann, A., Limpert, J. and Schmidt, M.A. Carbon chloride-core fibers for soliton mediated supercontinuum generation. *Optics Express*. 2018, **26**, 322.
14. Monfareda, Y.E., Liangb, C.C., Khosravic, R., Kacerovskac,d, B. and Yang, S. Selectively toluene-filled photonic crystal fiber Sagnac interferometer with high sensitivity for temperature sensing applications, Results in *Physics Journal*. 2019, **13**, 102297.
15. Sharafali, A., Nithyanandan, K. A theoretical study on the supercontinuum generation in a novel suspended liquid core photonic crystal fiber, *Applied Physics B: laser and optics*. 2020, **57**, 18251.
16. Zhang, R., Teipel, J. and Giessen, H. Theoretical design of a liquid core photonic crystal fiber for supercontinuum generation, *Optics Express*. 2006, **14**, 6800-6812.
17. Mortensen, N.A. Effective area of photonic crystal fibers, Optics Express. 2002, **10**, 341-348.
18. Liao, J., Sun, J., Du, M. and Qin, Y. Highly Nonlinear DispersionFlattened Slotted Spiral Photonic Crystal Fibers, *IEEE Photonics Technology Letters*. 2014, **26**, 380-383.
19. Amin, M.N. and Faisal, M. Highly nonlinear polarizationmaintaining photonic crystal fiber with nanoscale GaP strips, *Applied Optics*. 2016, **55**, 10030.
20. Kumar, P., Fiaboe, K., Sekhar Roy, J. Design of nonlinear photonic crystal fibers with ultra-flattened zero dispersion for supercontinuum generation, *Electronics and Telecommunications Research Institute Journal*. 2020, **42(2)**, 282-291.
21. Algorri, J.F., Zografopoulos, D.C., Urruchi, V., and Sánchez-Pena, J.M. *Infiltrated Photonic Crystal Fibers for Sensing Applications, sensor Journal, Sensors*. 2018, **18**, 4263.
22. Shuai, B., Xia, L. and Liu, D. Coexistence of positive and negative refractive index sensitivity in the liquid-core photonic crystal fiber based plasmonic sensor, *Optics Express*. 2012, **20**, 25858-25866.
23. Afshar, V.S., Monro, T.M. and de Sterke, C.M. Understanding the contribution of mode area and slow light to the effective Kerr nonlinearity of waveguides, *Optics Express*. 2013, **21**, 18558-18571.
24. Ali, A., Nithyanandan, K. A theoretical study on the supercontinuum generation in a novel suspended liquid core photonic crystal fiber, *Applied Physics B*. 2020, **126**, 1-12.
25. Abedin, K. and Kubota, F. Widely tunable femtosecond soliton pulse generation at a 10-GHz repetition rate by use of the soliton self-frequency shift in photonic crystal fiber, *Optics Letters*. 2003, **28**, 1760-1762.
26. Agrawal, G.P. Nonlinear fiber optics, Fifth edition, *Elsevier/Academic Press*, Amsterdam, 2013, 142-149.
27. Turitsyn, S., Bogdanov, S. and Redyuk, A. Soliton-sinc optical pulses, *Optics Letters*. 2020, **45**, 5352-5355.
28. Hasegawa, A. and Tappert, F. Transmission of stationary nonlinear optical pulses in dispersive dielectric fibers. I. Anomalous dispersion. *Applied Physics Letters*, 1973, **23**, 142-144.
29. Senthilnathan, K., Li, Q., Nakkeeran, K. and Wai, P.K. A, Robust pedestal-free pulse compression in cubic-quintic nonlinear media. Physical Review A, 2008, **78(3)**, 033835.
30. Seadawy, A.R. Exact solutions of a two-dimensional nonlinear schr¨odinger equation. *Applied Mathematics Letters*. 2012, **25**, 687-691.

31. Duyckaerts, T. and Roudenko, S. Going beyond the threshold: scattering and blow-up in the focusing NLS equation. *Communications in Mathematical Physics*. 2015, **334,** 1573-1615.
32. Kevrekidis, P.G. and Frantzeskakis, D.J. Solitons in coupled nonlinear Schr¨odinger models: a survey of recent developments. *Reviews in Physics*. 2016, **1**, 140-153.

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