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Design and Simulation of Exhaust Pollution Monitoring Sensor Based on Photonic Crystal Fiber

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Abstract

Many critical issues appear due to the exhaust gases from transportations facilities, electric generators, industries, and so on. This lead to air pollution, which could be define as an introduction of biological materials or chemicals that's causes harm to all living organism including humans. Also damaging the environment of earth. The principal gases that cause air pollution from these sources are nitrogen oxides (NO, NO2 and N2O) and carbon oxides (CO and CO2). There is a need to develop sensors that are characterized by highly-sensitive and miniaturize that capable of real-time analyses detection; optical fiber sensors agree with these needs. In this work, Large Mode Area- Polarization Maintaining Photonic Crystal Fiber (LMA-PM-PCF) for exhaust gases monitoring have been proposed to detect air-polluted gases over a wide transmission band covering (1μm) to (2μm) wavelength. Different guiding properties had been studied for the infiltrated PCFs. According to simulated results, the high relative sensitivity is obtained for sample infiltrated with CO gas; The higher sensitivity makes this fiber a potential candidate to detect CO that is commonly known as silent killer.

Keywords: Exhaust air pollution, Nitrogen oxides, Carbon oxides PCF sensors, FEM.

الخلاصة

العديد من القضايا الحرجة تظهر بسبب الغازات السامة المنبعثة من عربات النقل ، والمولدات الكهربائية ، والصناعات ، وما إلى ذلك. وهذا يؤدي إلى تلوث الهواء ، والذي يمكن تعريفه على أنه إدخال للمواد البيولوجية أو المواد الكيميائية التي تسبب الضرر لجميع الكائنات الحية بما في ذلك البشر الى الهواء. كما تضر ببيئة الأرض. الغازات الرئيسية التي تسبب تلوث الهواء من هذه المصادر هي أكاسيد النيتروجين (NO، NO2 و N2O) وأكاسيد الكربون (CO و CO2). لذلك ظهرت الحاجة لتطوير أجهزة تحسس تتميز بدرجة حساسية عالية وتكون صغيرة الحجم والتي من شأنها أن تكون قادرة على الكشف والتحليل في الوقت الحقيقي ؛ أجهزة تحسس المكونة من الألياف البصرية تتفق مع هذه الاحتياجات. في هذا العمل تم اقتراح ألياف الكريستال الضوئية (LMA-PM-PCF) للكشف عن الغازات الملوثة للهواء على نطاق إرسال واسع يغطي (μm1) إلى (μm2). وقد تمت دراسة خصائص إنتشار الضوء فيالـPCF. ووفقاً لنتائج المحاكاة ، تم الحصول على الحساسية النسبية العالية للعينة التي تحتوي على غاز أول أكسيد الكربون ؛ إن الحساسية الأعلى تجعل هذا الألياف مرشحًا محتملاً لاكتشاف CO الذي يعرف باسم القاتل الصامت.

Introduction

Air pollution could be defined as the increasing in toxic compounds or chemicals includes those generate from biological origin in air in such a level that is influence on life in general and health risks in special. The chemical compounds that make the air quality low are referred to air pollutants. These compounds may be found in the air in two major forms either, gaseous form (as gases), or solid form (as particulate matter suspended in the air). The gaseous like Nitrogen Oxides (NOX)(Toxic gases), Carbon Monoxide (CO) (Extremely toxic, produced by incomplete combustion and vehicle exhaust) and Carbon Dioxide (CO2) (Not toxic, but may dislocate oxygen and produce death through asphyxiation and it is a greenhouse gas, emitted by combustion processes, microbial activity, plant respiration) [1].The physical sensing based on optical fibers used to sense and monitor complex environment and its surrounding such as temperature, humidity, etc. having important applications in wearable sensors, robotics, health and safety monitoring [2]. Due to its advantages of low cost, less noise/interference, higher sensitivity, fast response, reliability, and compactness optical sensors found to be very suitable for the gas, chemical and biological sensing applications [3]. Now a day, Photonic Crystal Fiber (PCF) has been shown great development in optical sensing [4]. Photonic crystal fibers (PCFs) is a period arrange of microscopic cylindrical air holes that run along the entire length of fiber [5]. PCFs received a big attention in developing optical devices and sensors. Because the existing of air holes give freedom in design by changing the structure, number or shape of air hole around the core which lead to light controlling capabilities and then faster detection response and miniaturized structure [6]. The PCF sensing mechanism depends on the absorption lines of the corresponding gases. PCF based liquid and gas sensors have been shown excellent performance in terms of sensitivity response [7]. Different structures of PCFs had been introduced by many research groups as follows. An index-guiding PCF (IG-PCF) based gas sensor was proposed which show a relative sensitivity of 13.23% and confinement loss of 3.77 × 10−6 [8]. Morshed *et al.* [9] present a PCF contains microstructure core instead of hollow core (of prior PCF) which improves the relative sensitivity of 42.27% with a lower confinement loss of 4.78 × 10−6 for gas sensing. Asaduzzaman *et al.* detected colorless or toxic gasses and monitoring air pollution with a micro-cored PCF based gas sensor. They obtain high relative sensitivity of 53.07% is obtained at 1.33µm wavelength [10]. Ibadul Islam *et al.* designed a gas sensor based on hexagonal shape PCF The investigated results reveal the relative sensitivity of 56.65% and confinement loss of 2.31×10-5 dB/m at the 1.33-µm wavelength [11]. In this research paper, we have suggested a Single-mode 5 µm core polarization-maintaining fiber where four-layer hexagonal cladding (LMA-PM-5).

Geometry of the Proposed PCF

Large Mode Area- Polarization Maintaining PCF (LMA-PM-PCF) have been designed in this work, and simulated for gas sensing application. Maxwell's equation was used to simulate the guiding properties of the proposed PCF by Finite Element Method (FEM) through the simulation software COMSOL MULTIPHYSICS. The LMA-PM-PCF is optimized to exhibit low loss from (1µm) to (2µm) while keeping an almost constant mode field diameter. The cladding region was hexagonal with four rings of holes in the edges of the outermost cladding. The diameters of core is (5µm), the dimeter of air holes (1.43µm) and pitch is equal (3.25µm). Figure (1) shows Transverse cross section of the proposed PCF.

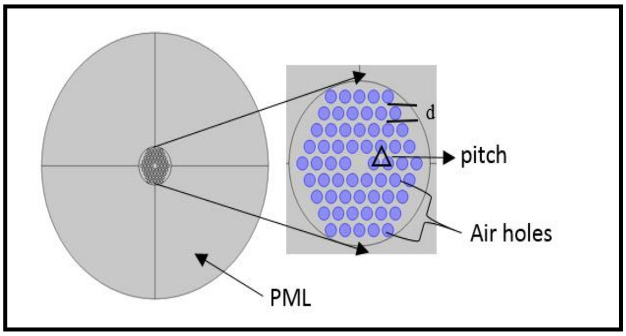


Figure 1: Transverse cross section of the proposed LMA-PM-PCF.

Numerical Analysis andEquations

Finite Element Method is a method to solve differential or partial equations numerically involve depending on the physical systems by dividing the system into small sub regions or elements. Each element is an, simple unit. The elgebric equations solved by computer [12].

The PCF has been infiltrated display in this research with (Air, CO, CO2, and N2O) the last three gases consider as an origin of the air pollution caused by exhaust gases from automobiles and electric generators. The better optical guiding properties to ensure the application of PCFs as gas/chemical sensors through the following properties:

A. *Effective Area*

Effective mode area is represent the distribution of the electric -field (E) of fundamental mode occurs inside the fiber core, as a result, effective mode area (EMA) of a PCF can be determined by the following equation [11]:

$$A_{eff} = \frac{\left(\iint_s |E_t|^2 dxdy\right)^2}{\iint_s |E_t|^4 dxdy} \quad (1)$$

B. Non Linear Coefficient (γ)

The small effective area of PCF leads to nonlinear effects due to high optical power density. The nonlinearity is related with the effective area of the PCF background material in associated with the operating wavelength λ. The nonlinear coefficient can be examined by the following equation [12]:

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

Where (n_2) is the nonlinear-index coefficient in the nonlinear part of the refractive index$\delta n = n_2|E|^2$and for pure silica its equal to $2.2*10^{-20}$ m^2/watt, c speed of light, ωangular frequency of the signal, and λits wavelength.

C. Confinement loss

Confinement loss or leakage loss occurs due to leaky nature of the mode and irregular arrangement of air holes. Those air holes are playing the role of dielectric medium. This loss depends on many parameters like transmitted wavelength, shape, size, number of air holes, and rings. The confinement loss or leakage loss can be calculated by the imaginary part of the effective refractive index. The confinement loss or leakage loss can find by the following equation [8]

$$L_c = -20 log_{10} e^{-\frac{k_o}{m[n_{eff}]}} = 8.686 k_o Im[n_{eff}] \quad (3)$$

Where, (k_o) is the propagation constant in free space, and Im[n_{eff}] is the imaginary part of the complex effective refractive index (n_{eff}).

D. Birefringence

Birefringence is one of the crucial properties of PCFs. It is highly influential for polarization maintaining fiber (PMF). The birefringence could be found by the difference between refractive index of x-polarization and y-polarization as follow [10]:

$$B(\lambda) = |n_{eff}^x - n_{eff}^y| \quad (4)$$

E. Relative Sensitivity

The relative sensitivity is an important parameter had to be found for PCF sensors. Relative sensitivity could be defined as the response of a PCF to physical, chemical, or biological quantity under measurement. Relative sensitivity (r) found through the following equation [10]:

$$r = \frac{n_s}{Re[n_{eff}]} f \quad (5)$$

Where (n_s) is the refractive index of target gas species, typically consider as 1 and Re[n_{eff}] is the real part of the effective mode index,f is the fraction of holes power by total optical power which can be defined as [10]:

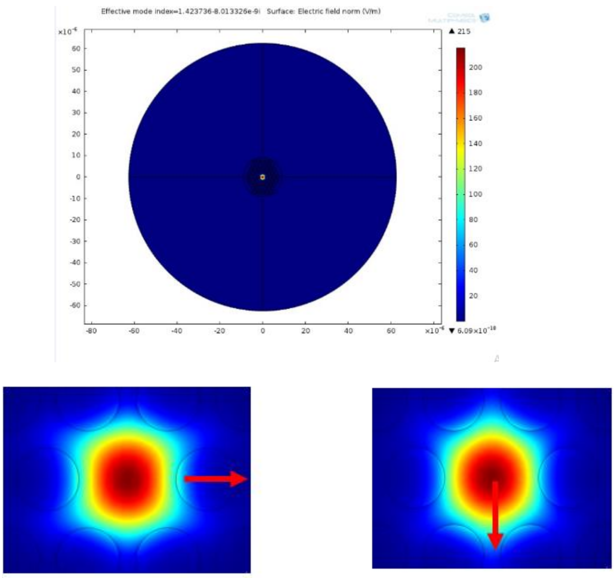
$$f = \frac{\int_{holes} Re(E_x H_y - E_y H_x) dxdy}{\int_{total} Re(E_x H_y - E_y H_x) dxdy} \quad (6)$$

Where E_x, E_y, H_x, and H_y are the transverse electric and magnetic field of the guided mode, respectively.

Results and Discussions

The x-polarization and y-polarization of the mode field pattern along proposed LMA-PM-PCF had been shown in Figure (2). From the figure that the leakage loss was very low , therefore the mode field is tightly confined to the core region.

The effective refractive index neff for operating wavelength range (1μm) to (2μm) with step (0.05μm) had been found for the fundamental mode. Figure (3) reveals that neff linearly decreases with respect to increase in wavelength for different analyte: air, CO, CO2, and N2O. The decreasing due the spreading of light into cladding region due to the existence of air hole at higher wavelength. Effective area and nonlinearity proprieties of proposed PCF are leading parameters of the optical devices.



X-polarization Y-polarization

Figure 2: Single mode Gaussian distribution output of fundamental core mode for different analyte.

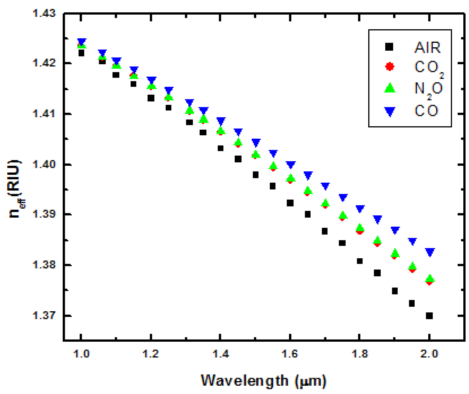


Figure 3: Effective refractive index versus wavelength for different analyte.

Figures (4 and 5) exhibits the effective area and nonlinear coefficient variations with respect to wavelength changes for different analyte air, CO, CO_2, and N_2O. The curves demonstrate the effective area increases by increasing the applied wavelength. This fiber reaches to (6μm2) effective area at (2μm) for sample infiltrated with CO gas. Nonlinearity plays a vital role in the field of nonlinear optics and supercontinuum generation. Investigation of the nonlinear property has reflected in figure (5).

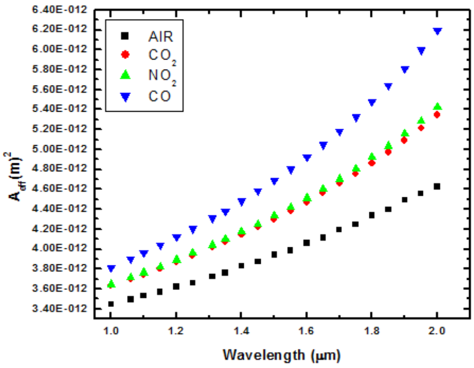


Figure 4: Effective mode area of propagating mode versus wavelength for different analysis

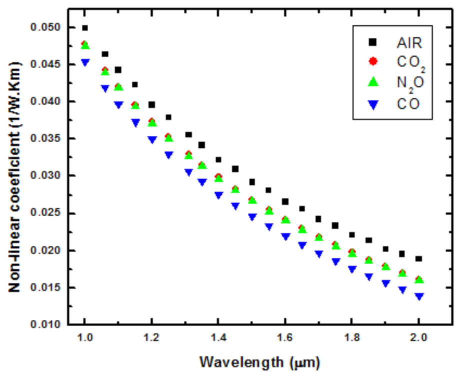


Figure 5: Nonlinear coefficient versus wavelength for different analyte.

The confinement loss have been calculated from the imaginary part of effective refractive index for wavelength range (1-2) μm with different analyte. Figure (6) shows the confinement loss just for CO2, CO, and N2O because in case of air there is no leakage outside the core so no imaginary part of effective refractive index. From the figure we notice that the leakage loss is highest (5.15dB/cm) at (2μm) for samples infiltrated with CO gas. In addition, for all samples at higher wavelength light spread into cladding hole and confinement loss appear as clearly in figure (6).

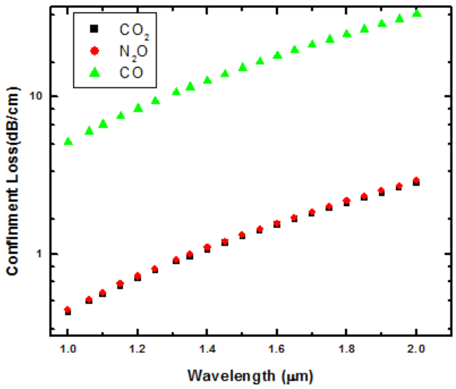


Figure 6 : Confinement loss versus wavelength for different analyses.

From the figure (7) it is clearly reported that better guiding properties are gained for samples infiltrated with CO. while figure (8) shows the relative sensitivity for the proposed sensor it's clear that its increased with increasing of operated wavelength and it was higher for samples infelt rated with CO gas about 65%.

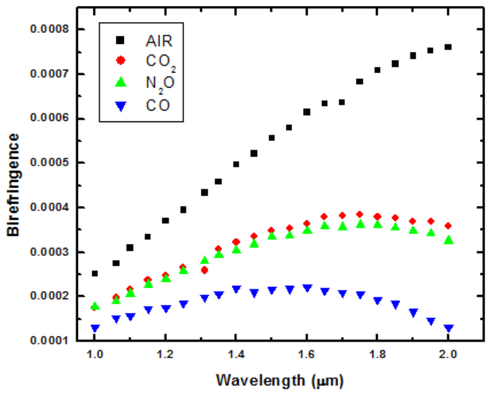


Figure 7 : The change of birefringence as a function of wavelength for different analyte

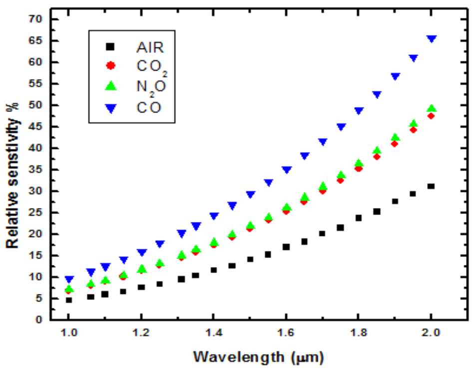


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Figure 8: .Effective refractive index versus wavelength for different analyte.

Conclusion

The LMA–PM–PCF was gas sensor have been presented. This PCF was infiltrated with different gases; air, CO2, CO, and N2O for wavelength range (1-2) µm. To study the sensor parameter numerical investigation had been done by applying finite element method and with boundary condition perfectly matched layer of circular shape. From the results, the higher relative sensitivity obtained for samples infiltrated with CO gas which makes this fiber a potential candidate to detect CO that's considered as silent killer gas.

References

[1] A. Faiz, Ch. Weaver, and M. Walsh, "Air Pollution from Motor Vehicles Standards and Technologies for Controlling Emissions," report submitted to United Nation, 1996.

[2] J. C. Yeo and C. T. Lim, "Emerging flexible and wearable physical sensing platforms for healthcare and biomedical applications," *Microsystems & Nano-engineering*, **vol. 2**, pp.1-16, 2016.

[3] W. Ding, Y. Jiang, R. Gao, and Y. Liu, "High-Temperature Fiber-Optic Fabry-Perot Interferometric Sensors," Review of Scientific Instruments, vol. 86, Issue 5, 2015.

[4] S. Asaduzzaman, B. K. Paul, and K. Ahmed, "Enhancement of Sensitivity and Birefringence of a Gas Sensor On Micro-Core Based Photonic Crystal Fiber," in *3rd International Conference in Electrical Engineering and Information Communication Technology* , 2016.

[5] P. Russell, "Photonic Crystal Fibers," *Science*, vol.24, no. Issue 12, pp. 4729-4749, 2005.

[6] B. Temelkuran, S. D. Hart, G. Benoit, J. D. Joannopoulos, and Y. Fink, "Wavelength-Scalable Hollow Optical Fibers With Large Photonic Band Gaps For Co2 Laser Transmission," *Nature*, vol.

420, p. 650–653, 2002.

[7] M. N. Petrovich, A. Brakel, F. Poletti, K. Mukasa, E. Austin, and V. Finazzi, "Microstructured Fibers For Sensing Applications," in *The International Society for Optical Engineering*, 2005.

[8] S. Olyaee, and A. Naraghi, "Design and Optimization Of The Index-Guiding Photonic Crystal Fiber Gas Sensor," *Photonic Sensors*, vol. 3, p. 131–136, 2013.

[9] M. Morshed, M.I. Hassan, T.K. Roy, M.S. Uddin, and S.A. Razzak, "Microstructure Core Photonic Crystal Fiber For Gas Sensing Applications," *Appl. Opt.* , vol. 54, p. 8637–8643, 2015.

[10] S. Asaduzzaman, and K. Ahmed, "Proposal of a Gas Sensor with High Sensitivity, Birefringence And Nonlinearity For Air Pollution Monitoring," *Sensing and Bio-Sensing Research*, vol. 10, pp. 1-7, 2016.

[11] Md. Ibadul Islam, K. Ahmed, Sh. Sen, S. Chowdhury, B. Kumar Paul, Md. Shadidul Islam, M. Badrul Alam Miah, and S. Asaduzzaman, "Design and Optimization of Photonic Crystal Fiber Based Sensor for Gas Condensate and Air Pollution Monitoring," *Photonic Sensors , vol. 7, no. 3, pp.234–245, 2017.*, vol. 7, no. 3, pp. 234-245, 2017.

[12] G. Renversez, and B. Kuhlmey, "Dispersion Management with Microstructured Optical Fibers: Ultra flattened Chromatic Dispersion with Low Losses," *Optics Letters*, vol. 28, pp. 989-991, 2003.