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DESIGN AND SIMULATION OF H2 GAS SENSOR FOR USE IN COAL MINES USING PHOTONIC CRYSTAL WAVEGUIDE

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Masoud Jabbari
Department of Electrical Engineering, Marvdasht Branch, Islamic Azad University, Marvdasht, Iran
Jabbari.mas2000@gmail.com

Amin Nouri
South Pars Gas complex Co.(S.P.G.C),Assaluyeh, Boushehr, Iran.
nouriinst@gmail.com

Resumen: Los gases explosivos más comunes en las minas de carbón son el metano CH2, el sulfuro de hidrógeno (H2S), el hidrógeno (H2) y los gases de monóxido de carbono (CO) (Floren 2003). La mayoría de las minas de carbón de Irán son bajas en gases, ya que operan en profundidades bajas a moderadas. Esto lleva a clasificar estas minas en las clases más peligrosas. Si la mina es muy gaseosa o está en estado gaseoso siempre, entonces las personas que trabajan en la mina considerarán los problemas con precisión y realizarán las operaciones de extracción con cautela, pero si la cantidad de gasificación es baja, ignorarán el riesgo. En nuestro país, debido a la alta previsión diaria y costo de mantenimiento de los sensores químicos, no se ha utilizado ningún sensor en minas pequeñas con una profundidad máxima de tres kilómetros y se clasifican como minas no gaseosas. Este trabajo tiene como objetivo proponer un sensor en tiempo real de bajo costo sin ningún material consumible que pueda ser utilizado por todas las minas. Los sensores de guías de ondas de cristal fotónico tienen dimensiones muy pequeñas. Además, dado que estas estructuras trabajan con la luz, alertarán a los sistemas centrales de automatización en tiempo real. Además, estas estructuras no tienen materiales consumibles y pueden utilizarse sin interrupción durante largos períodos sin mantenimiento (Lourtioz, Benisty, Berger, Gerard, Maystre, Tchelnokov (2008).

Palabras Clave: Cristal Fotónico, Banda Fotónica Prohibida, Sensor de Gas Hidrógeno, Sensor Aplicado en Minas

Abstract: The most common explosive gases in coal mines include methane CH2, hydrogen sulfide (H2S), hydrogen (H2), and carbon monoxide (CO) gases (Floren 2003). Most of Iran's coal mines are low gaseous since they operate in low to moderate depths. This leads to classify these mines in the most dangerous classes. If the mine is highly gaseous or be in gassy condition always, then people working in the mine will consider the problems accurately and carry out extraction operations cautiously, but if the amount of gasification is low, they will ignore the risk. In our country, due to the high daily providence and maintenance cost of chemical sensors, is has not been used any sensor in small mines with a maximum depth of three kilometers and they are classified as non-gassy mines. This paper aims to propose a real-time sensor having low cost without any consumable materials that can be used by all mines. Photonic crystal waveguide sensors have very small dimensions. Also, since these structures work with the light, they will alert the central automation systems as real time. Also, these structures do not have any consumable materials and can be used without interruption for long periods without maintenance (Lourtioz, Benisty, Berger, Gerard, Maystre, Tchelnokov (2008).

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Keywords: Photonic Crystal, Prohibited Photon Band, Hydrogen Gas Sensor, Applied Sensor in Mines

1. INTRODUCTION

The Bin Shiho mine blast in China (1942) is the largest coal mine incident in the world had 1,549 casualties. Hydrogen gas was the main cause of this huge explosion in the coal mine. There is no efficient sensor at a reasonable price to detect hydrogen unlike sensors for methane and hydrogen sulfide explosions. Hydrogen cannot be measured by portable devices. The only tool that can determine the percentage of this gas is the gas chromatograph device. It is a great and expensive device and needs an experienced technician. Today, the air of the mine is sampled if the possibility for the presence of hydrogen exists and then it will be sent to a laboratory having a gas chromatograph device, which is a timely process.

Photonic crystals are one of the most suitable frames for use in optical and real-time sensors (Busch, Lölkes, Wehrspohn, Föll 2004), (Wim bogaerts 2004). Photonic crystal sensors are very small and have a short response time and can be used in very small environments. Many physical quantities, such as refractive index, temperature, humidity, and chemical sensors can be measured by combining light into a photonic crystal structure and, therefore, reflecting and transmitting light through the structure and analysis of this spectrum by external analyzers. In coal, copper and cobalt mines, there are usually stone reservoirs of hydrogen and methane gas. These stone reservoirs are created by the trapping of some gas in the interlayers of the rocks. The main problem in mines is sudden release of the gas and as a result the fire, momentary explosion and disruption in transmission of the fresh air and power systems (Quimby 2006).

Photonic crystals have periodic or quasi-periodic arrays of dielectric materials (there may be metallic and nonmetallic defects) that are designed and constructed in one dimensional, two-dimensional, and three-dimensional structure. The one dimensional photonic crystals are only periodic in one direction. Planar Bragg and fiber Bragg gratings are two types of the most widely used one-dimensional periodic structures. The two-dimensional photonic crystals are periodic in two directions while they are homogeneous and constant along the third axis. Theoretically, the length of homogeneous dimension is considered to be infinite in these structures. But in reality, when the length of homogeneous dimension is considered finite (contrary to photonic crystal fibers), these two-dimensional crystal structures are called Slab blades. The photonic crystal blade structures have enabled to integrate and construct optical processing devices due to their limited length. Photonic crystal blades are usually used for sensor applications. 3D photon crystals are periodic in all directions (Benisty, Weisbuch, Labilloy, Rattier, Smith, Krauss, De La Rue, Houdre, Oesterle, Jouanin and Cassagne 1999).
Construction of such structures is very difficult and so they have very limited applications. In general, photonic crystal blades are divided into three groups. In the first type, there are air cavities in the dielectric bed. In the second type, the bed is of air and the periodic rods are of dielectric. In the third type, both the bed and rods are of dielectric. Todays, metal crystals are also considered but in this article we don’t pay attention to them. Photonic crystals have certain frequency constraints known as Frequency Prohibited Bands (PBGs) in which, no wavelengths can propagate within the photonic crystal structure. Failure to propagate in the prohibited band means non-damping of transmitted wave through photonic crystals. The prohibited band can be changed and controlled by changing the characteristics, such as the number of structure cells, the layout (square, triangular or hexagonal arrays), network constant and dielectric constant. Also, certain deficient modes can be created in the prohibited band by introducing a point defect in the periodic structure making it possible to control the photonic crystal behavior, more (Joannopoulos, Johnson, Winn, Meade 2007).

The performance process for the proposed sensor is so that at first, the sensor should be calibrated in a safe environment based on the percentage of hydrogen gas. Generally, the percentage of hydrogen gas in the shallow mines is negligible in normal conditions. In simulation, we consider the amount of calibrated bias for hydrogen gas equal to zero. The sensor system is made up of a diode laser having 2 nm wavelength and a light meter (single-pixel) detector. In normal mode, the laser coupled beam reaches the detector without any loss after passing through the photon crystalline waveguide and illuminates it. In this case, the detector will send analog signals from 0 to 1023, and it will be digitized by a digital-analog converter and then it will be sent to the central computer. The signal level is reduced if the hydrogen gas is released, and the central computer is informed the emission of hydrogen gas. Decrease in the signal level should be calibrated based on allowable and unallowable concentrations in mining conditions.

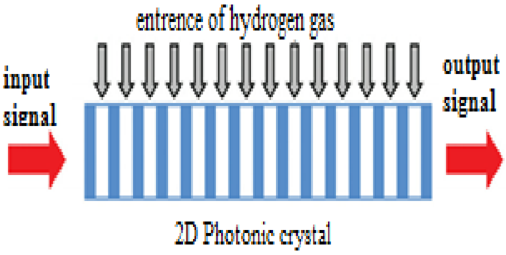

Figure 1. Photonic crystal sensor for hydrogen gas. Hydrogen gas enters the sensor through the transverse section.

The essential point allowing the design of the sensor is the difference in the refractive indices of the hydrogen and air molecules. The refractive index of hydrogen - air molecules' mixture varies from 1.000145 to 1.013depending on the concentration of hydrogen in the air. By modeling and analyzing the difference in refractive index, we can figure out whether the hydrogen gas is added to the air or not. It should be noted that maybe the change in the air refractive index is due to methane and hydrogen sulfide.

If the portable and inexpensive sensors for methane and hydrogen sulfide do not signal the increase in these gases, the increase in hydrogen gas would undoubtedly lead to a change in the refractive index of the air.

2. SIMULATION

At first, we simulate the structure of the photonic crystal blade, and then present the results of photonic band gap analysis. It has been attempted to simulate the photonic crystal blade with minimal variations respect to the original structure or it will be simulated by removing dielectric rods. The structure of the interested photonic crystal blade is such that its homogeneous axis is in the direction of the y axis and is outward. The outward direction is the direction in which the hydrogen gas is applied to the blade. The designed photonic crystal blade is of a kind in the air and the rods are of Si material having a refractive index of 3.4. Silicon material has been chosen since firstly, it is inexpensive and highly available, and secondly, it is easy to couple with the other elements, such as fiber optics due to same matter. The filling ratio for rods is 0.29. This ratio represents the ratio of the rod radius to the network structure constant. In the RSoft Photonics CAD software, Band SOLVE tool is used to simulate the structure of the photonic crystal blade and to obtain a photonic band gap. The photonic crystal is of Hexagonal type in 20 × 20 dimension. The cross-section of the rods is circle and the material is considered without nonlinearity effect.

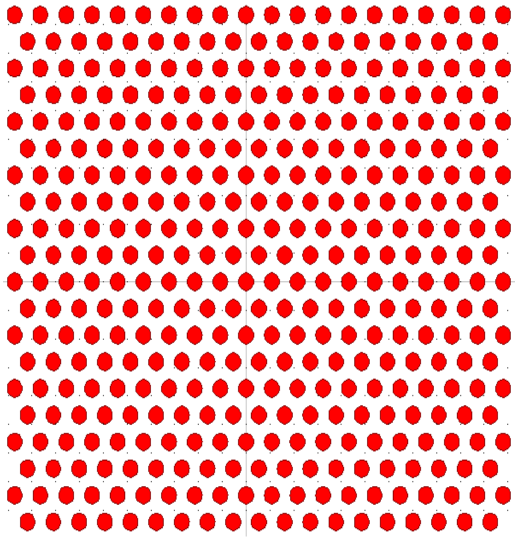

Figure. 2. The basic photonic crystal used in simulation

The first step in analyzing the photonic crystal behavior is to obtain the photonic band of the structure. For this purpose, the band gap is displayed in two modes of TM and TE after specifying the unit cell.

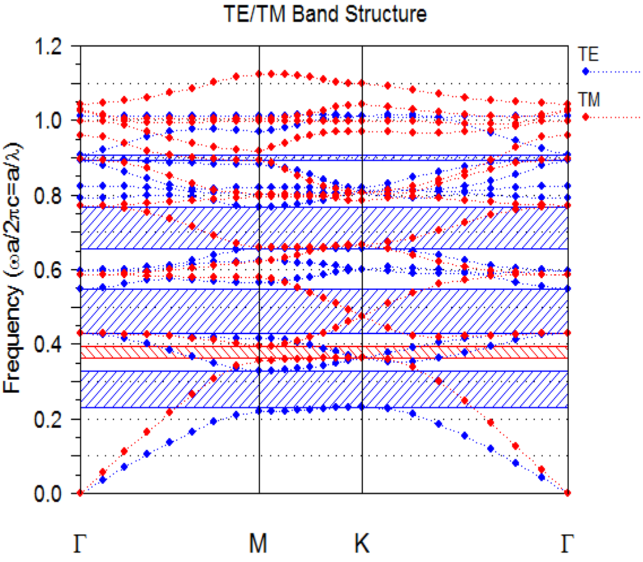

Figure. 3. Band gap structure in TM and TE modes

The first point that can be derived from the band gap diagram is that there is no shared band gap for the two modes of TE and TM. Hence, the used laser diode should be polarized to a large percentage in arbitrary polarization. It is evident that the photonic crystal designed in TE mode has wide band gaps. We aim to generate a very thin channel in the band gap using quantum dot defects to propagate desired wavelengths. This is important with regard to necessity to select a wavelength range of 100 nm for functioning of sensors.

The sensor structure consists of four main parts. Input waveguide is created by removing 4 rods. The output waveguide is simulated like the input waveguide through removing four rods. 7 rods are located in the certain crystalline locations between the input waveguide and the bending waveguide and only their radius has been changed. The radii for the primary and middle rods are 0.9 and 1, respectively. The change in the dimensions of the rods leads to a defect and, therefore, the change in the propagation mode within the band gap. A bending waveguide is placed in a way that it has the highest scattering for wavelengths around the main wavelength.

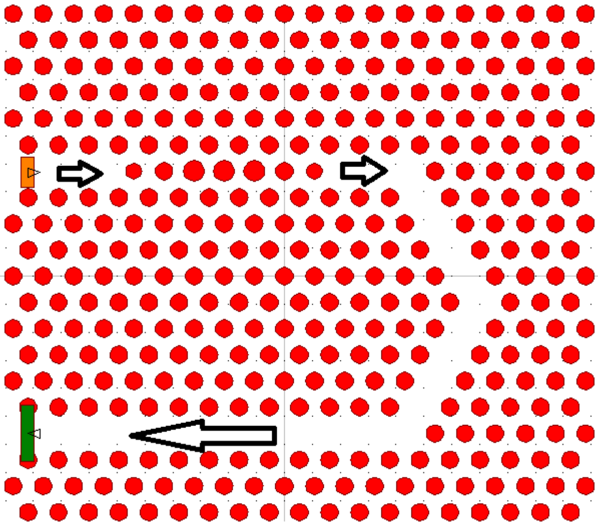

Figure. 4. Band gap structure in TM and TE modes

The spectral behavior of the proposed structure in the base mode has been shown in Fig. 5 at wavelength range of 1650 nm to 1750 nm. As is clear from the figure, there is only a very thin passage in the wavelength of 100 nm. When the hydrogen gas is released, there is a decrease in the peak power of the passing spectrum at a wavelength of 1688 nm due to the difference in the refractive index. As the percentage of hydrogen increases, the peak level of the passing signal decreases and as a result the received intensity by the detector decreases indicating the emission of hydrogen gas.

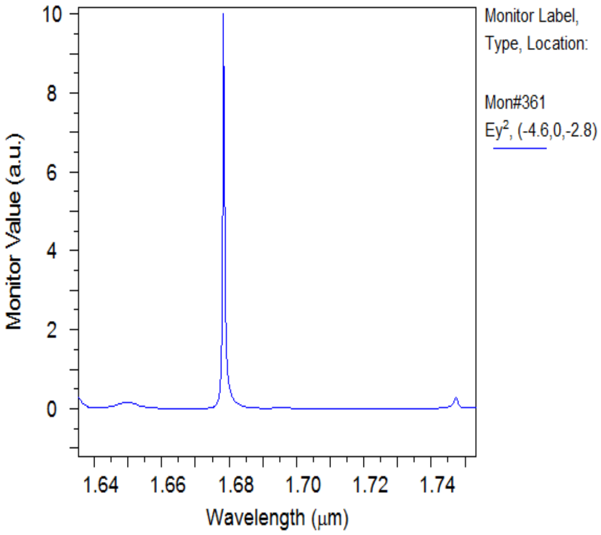

Figure. 5. Schematic output of sensor simulation at 100 nm spectrum width

In the functional state, the sensor has a full passing at the wavelength of 1688 nm. It means that the PIN photodiode receives the maximum signal. When the hydrogen gas is emitted and it is replaced instead of the air, the output spectrum for the structure will change instantly. When hydrogen gas reaches the 3000 ppm concentration, a potential for the fire can be possible. Based on the relationship proposed by Lourtioz et al. (Lourtioz, Benisty, Berger, Gerard, Maystre, Tchelnokov (2008) for the measurement of the refractive index in gas mixture and its relationship with the concentration, a concentration of 3000 ppm can be considered equivalent to a refractive index of 0.00015. With this change, the refractive index for the output spectrum of the simulation shown in Fig. 6 is obtained.

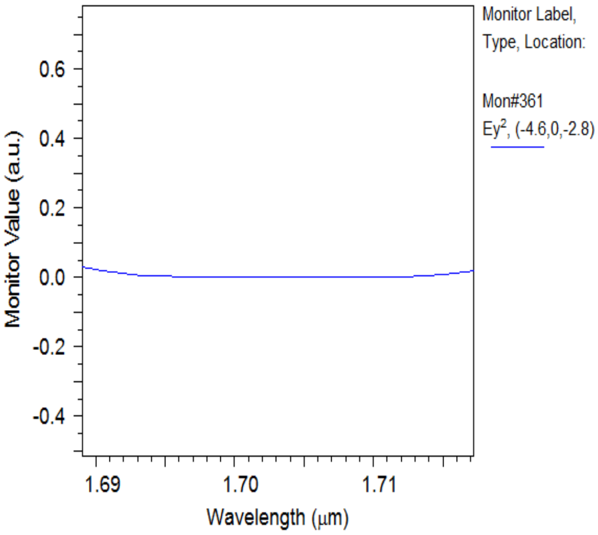

Figure. 6. Schematic output of sensor simulation in the presence of hydrogen.

As it is clear, there is no signal at 30 nm spectrum width.

3. CONCLUSION

The purpose of this simulation is to provide a simple way for instantaneous detection for presence of hydrogen gas in the mines' environment. The proposed structure has small dimensions as well as a wide performance range. In the basic mode, the photodiode receives an optical signal indicating the absence of hydrogen. When the photodiode undergoes the decrease in the received signal level (decrease in intensity), it will imply the release of hydrogen gas in the environment.

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