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Sensitivity Enhancement of Methane Detection Based On Hollow Core Photonic Crystal Fiber

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Abstract: Monitoring methane (CH4) concentration is essential in many industrial and environmental applications. Emission of such gases is indeed important to detect for health, safety and environmental reasons. The major risk in all these areas is an explosion hazard, which may occur if methane reaches its Lower Explosive Limit (LEL) of5% concentration in air. For that reason, it is necessary to develop gas sensors to monitor that methane levels below this value. Due to a weak absorption of methane, this gas is difficult to detect using conventional methods.Hollow core photonic crystal fibers (HC-PBF) have emerged as a promising technology in the field of gas sensing. The strong interaction achievable with these fibers are especially advantageous for the detection of weakly absorbing regions of methane. In this paper, we investigated, by full vectorial finite element method (FV-FEM) in Rsoft CAD environment, the dependency of relative sensitivity on the fiber parameters and wavelength. Consequently, we introduced the optimal structureof an index guiding hollow core photonic crystal fiber capable of measuring methane concentrations down to 0.1%in air. The simulations showed that the sensing sensitivity increased with an increase in the core diameter and a decrease in the distance between centers of two adjacent holes.

Key Words: Photonic crystal fiber, Methane, Finite element method,Rsoft CAD.

1. INTRODUCTION

Sensing of gas species and their concentrations is widely used for process control, environmental and safety monitoring. Methane detection is extremely important for safety monitoring in chemical facilities, gas plants, landfill sites, mines and domestic environments. The major risk in all these areas is an explosion hazard, which may occur if methane reaches its Lower Explosive Limit (LEL) of5% concentration in air. For that reason, it is necessary to develop gas sensors to monitor that methane levels below this value.

Methane shows molecular absorption lines at different regions of the infrared spectrum. In particular, weak absorption lines are present in the near infrared $v_2 + 2v_3$ band at 1.3 μm [1]. Gas sensors operating at this wavelength range benefit from the low cost light sources and detectors fully developed for telecommunication applications. However, conventional spectroscopic gas cells typically show interaction Pathlengths of few centimeters, which makes difficult the detection of methane in this region [2].

Optical gas spectroscopic systems are attractive for gas detection since they provide high spectral resolution, precise gas species identification and possibility of remote and distributed measurements [3].

Optical fibers used for gas sensing offer clear advantages such as immunity to electromagnetic interference, small size, low cost and the possibility for distributed measurements. Different fiber designs including fibers with a small hole in the center of the core [4] and D-shaped optical fibers [5] have previously been employed in gas sensing. However, such fiber sensors suffer from a poor overlap between the gas volume and the mode field of the propagating light, which results in weak absorption and therefore long length of fibers, are required.

Hollow optical waveguides have also been used but they are usually multi-mode and their losses are high, which limits the practical waveguide length to a few meters [6].

To overcome the limitation of the low sensing sensitivity, more research work needs to be done. Parameters such as sensitivity and fiber length need to be considered in detail in order to optimize a gas sensor. The Beer-Lambert law [7] gives the relationship between absorption length (fiber length), gas concentration and light intensity. In addition, in order to minimize the response time of the sensor, the fiber should be as short as possible while still long enough to provide a sufficient signal. The optimum length depends on the molecular species to be monitored and the amount of gas present in the environment.

For gases with weak absorption lines or in low concentration, an increased sensitivity can be obtained by using longer fiber length. However, the attenuation increases with the length of the fiber.

Effects limiting the sensitivity of the detection are mainly fiber loss and background noise, which is expected to result from the polarization properties and the aligning of the fiber**.**

An effective way to increase the sensing sensitivity is to design new structures, in which a significant fraction of the total modal power can be made to overlap with the gas.

Photonic crystal fibers (PCFs) [8] is a breakthrough in fiber optic technology, leading to unprecedented properties that overcome many limitations. In contrast with traditional optical fibers, PCFs are made of single material and have several geometric parameters that can be manipulated for larger flexibility of design.

With the modulation of the size and location of the cladding air holes, the characteristics of PCFs, such as mode shape, transmission spectrum, nonlinearity, dispersion and birefringence, could be tunable to manage the anticipated values [9].

Additionally, the existence of air holes, running along the length of the fiber, create new abilities for the appropriate interaction between light and sample through evanescent fields in the holes [10]. This enables further dynamic modification of the waveguide properties and provides perspectives for various all-in-fiber tunable or sensing devices.

In this paper, an evanescent field sensor for methane detection based on the photonic crystal fiber is introduced, in which the core consists of an air hole with dimensions smaller than the dimensions of the cladding holes to satisfy the effective index guiding criterion.

Due to the central hole, the difference between the refractive indices of the core and cladding dropped, more light would penetrate into the cladding, and thus the sensitivity increased.

The larger central hole diameter (d)showed the higher evanescent field fraction, nevertheless, the central hole diameter should be less than the cladding hole diameter(d_{cl}), to satisfy the effective index guiding Criterion.

Although due to the smaller air hole in the center, the evanescent field interaction was enhanced, but this type of PCFs had a huge confinement loss [11].

In this work we have carried out consequently, an optimal structure for simultaneously achieving more sensitivity and less confinement losses.

2. SIMULATED METHOD

Among the full vectorial methods used in modeling PCFs, the finite element method (FEM) [12] is particularly effective for handling curved interfaces with high accuracy, and it is obviously a good choice for the analysis of combined circular and elliptical shape.

In the modal solution approach based on the FV-FEM, the intricate cross section of the PCF can be accurately represented using many triangles of different shapes and sizes. This flexibility makes the FV-FEM preferable to other approaches.

In this study, we have adopted an efficient FV-FEM with PMLs to predict all the propagation characteristics of the waveguide with high accuracy.

The fiber cross-section representation is very accurate as the domain is divided into subdomains with triangular or quadrilateral shape, where any refractive index profiles can be properly represented.

Applying the variational FV-FEM procedure to Maxwell's equations, the following vector wave equation is derived [13].

$$\nabla \times \left([s]^{-1}\nabla \times \vec{E}\right) - {k_0}^2 n^2 [s]\vec{E} = 0 \qquad (1)$$

Where $k_0 = 2\pi/\lambda$ the free-space wavenumber, $\lambda$is the wavelength, $\vec{E}$denotes the electric field, $n$is the refractive index, $[s]$ is the PML matrix, and $[s]^{-1}$is the inverse of the PML matrix.

When applying an FV-FEM to PCFs, a curvilinear hybrid edge/nodal element [14] is very useful for avoiding spurious solutions and for accurately modeling curved boundaries of air holes. Dividing the fiber cross section into a number of the curvilinear hybrid elements, from Eq. (1) we can obtain the following eigenvalue equations:

$$[k]\{E\} = {k_0}^2 {n_{eff}}^2 [M]\{E\} \qquad (2)$$

Where $[k]$ and $[M]$ are the finite element matrices, $\{E\}$ is the discretized electric field vector consisting of the edge and nodal variables, and n_{eff} is the effective index.
For an efficient calculation, we take advantage of the symmetries of the first modes in the structure by simulating only a quarter of the PCF cross section, on which we apply a suitable combination of short circuits. Moreover, with these electromagnetic short circuits, it is possible to select a family of modes with a given polarization.

3. NUMERICAL ANALYSIS

The cross-section of the analyzed fiber is shown in Fig.1. It consists of triangular lattice formed by five rings of periodic arrangement air holes.

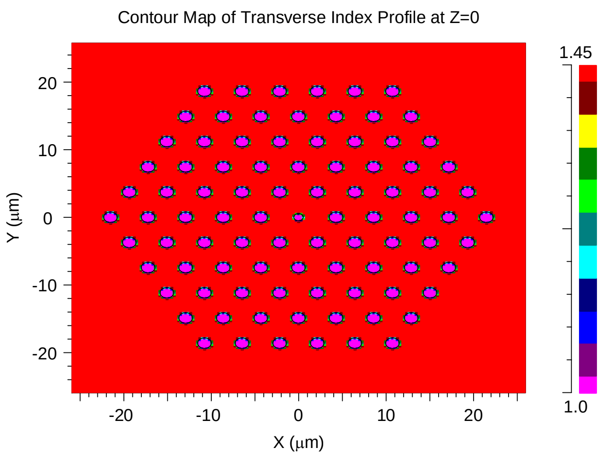

Fig.1 Cross section of the design PCF.

A small air hole is introduced in the center of PCF structure, and the diameter $(d)$of the defected core is smaller than the diameters of the cladding air holes. We choose two degree of freedom $(d,)$ respectively the core diameter and the distance between adjacent holes.
In the design procedure, we set the outer ring to have the same air-hole diameter(d_{cl}), to reduce fabrication complexity. Parameters $(d)$and () areadjusted and their influence on the sensitivity curve is investigated.
To review the proposed PCF optical properties, the finite element method (FEM) for solving Maxwell's equations was applied due to its proven reliability and high accuracy for analysing the PCF [12].
The structure of the design influences the field distribution significantly. According to the theory of the effective index [15], introduction of the air-core decreases the effective index of the fiber core. The air-core decreases the effective index of the fiber core, which leads to the weakness of the confinement effect of the cladding. As a result, the field limited in the core extends to the cladding gradually. Consequently, the modes of such fibers are inherently leaky. Moreover, we must consider that the imaginary part of its complex propagation constant represents the leakage loss of a mode.
For having an appropriate model of the leakage, an open boundary condition is required, which doesn't create reflection at the boundary. Perfectly matched layers (PMLs) are so far the most efficient absorption boundary condition for this purpose.
The confinement lossL_c, in decibels per meter is given by[16, 17]:

$$L_c = 8.686 K_0 I_m[n_{eff}] \quad (3)$$

Where $I_m[n_{eff}]$ is the imaginary part of the effective index.
The evanescent field in the air holes is absorbed by the methane species, and the gas concentration can be obtained from the intensity through the Beer-Lambert law [18,20]:

$$I(\lambda) = I_0(\lambda) exp[-r\alpha_m(\lambda) lC] \quad (4)$$

Where I is the output light intensity in the presence of gas and I_0 refers the output light intensity without the presence of the gas.
In addition, α_m which is a function of the wavelength, is the methane absorption coefficient, *l* and *C*, respectively, denote the length of the PCF used for detection (interaction length) and *C* the methane concentration, and finally, *r* is a relative sensitivity coefficient defined as [21,22]:

$$r = \frac{n_r}{n_e} \cdot f \quad (5)$$

Where n_r refers to the refractive index of the methane, the effective refractive index of the guided mode is presented by n_e, and f is the fraction of the total power located in the holes; in the meantime, in the typical fiber, f can be calculated by [21,22]:

$$f = \frac{\int_{holes}(E_x H_y - E_y H_x) d_x d_y}{\int_{totale}(E_x H_y - E_y H_x) d_x d_y} \quad (6)$$

The transverse electric and magnetic fields of the mode are introduced by E_x, E_y and H_x ,H_y respectively.
Now, with solving Maxwell's equations by utilizing a finite element method, the effective refractive index n_e and the mode field pattern, E_x, E_y and H_x ,H_y can be acquired.

4. RESULTS and DISCUSSION

First, we have simulated the structure of the design PCF, the confinement loss was calculated at different wavelengths using the FEM based software(FemSim).Here we interested in the wavelength range from0.8 μm to $2\mu m$. This range is within the low loss window of silica fiber and covers the absorption lines of the methane in the near infrared region.
Figure 2 shows the calculated confinement loss versus wavelength by changing the dimensions of the central hole. By decreasing, the diameter of the central hole from 2 μm to 1.2 μm, the confinement loss will reduce because the difference of core and cladding indices is high, and consequently, more light power can be confined in the core region.

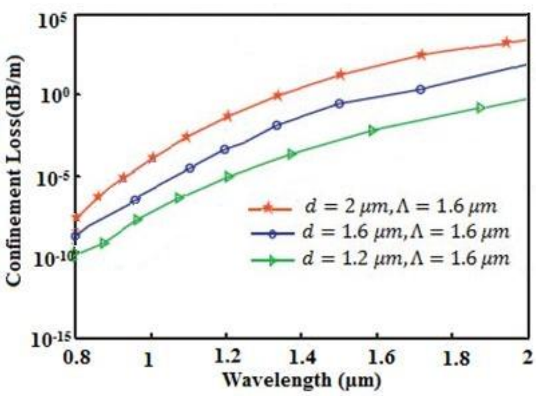

Fig.2 Confinement loss versus wavelength for different core diameters.

Generally, overlaps are quite poor for small holes. Better penetration into the holes is obtained for longer wavelengths and larger core size.
The loss plotted is for a five-ring cladding, and can naturally be reduced by adding more holes. There is huge flexibility in adjusting the sizes, shapes and positions of the microstructure holes to optimize performance. So far, we have looked at five ring structures for all designs. This allows for fast calculation, and puts all designs on an equal footing for fair comparisons of confinement loss. Once a suitable five-ring design is obtained, one can easily achieve a desirable confinement loss level (with negligible change in the basic mode structure) by adding more holes to the cladding. These results demonstrate a nearly ideal single mode waveguide for methane detection: The fiber combines almost complete overlap of light with the gas with acceptable loss over long interaction lengths.

The well-shaped mode fields, robust confinement mechanism and relatively large core size present further advantages for achieving more sensitivity.

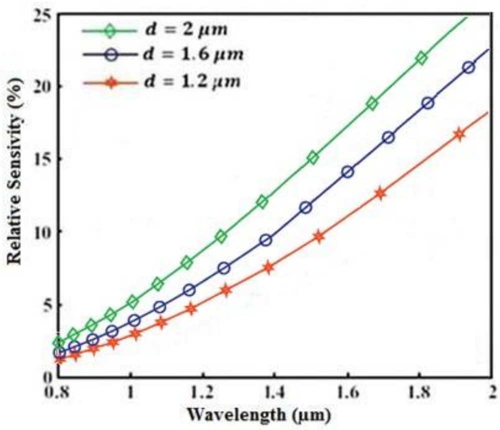

Fig.3 Relative sensitivity versus wavelength for different core diameter.

Figure 3 shows the calculated relative sensitivity for the proposed PCF with varying the core diameter.
The relative sensitivity increases with increasing the core diameter because more evanescent field fraction spreads to the cladding holes and interacts with samples.
The sensitivity increases with an increase in the wavelength because the light can penetrate into the cladding holes by increasing the wavelength.
Figure 4 reviews the same basic trends, the calculated relative sensitivity for the proposed PCF with varying the distance (□) between adjacent holes, with a reduction in (□) from 2.4 μm to 1.6 μm, the relative sensitivity increases because the cladding index reduces by a reduction in (□), and so more light enters the cladding.

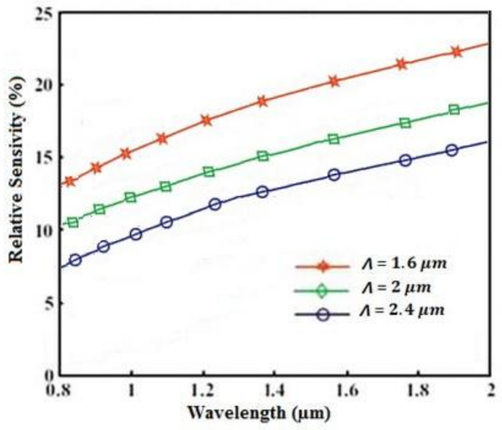

Fig.4 Relative sensitivity versus wavelength for different pitch.

5. CONCLUSION

We have analyzed and demonstrated an evanescent wave absorption sensor for methane detection using a short length of pure silica hollow core PCF.
The proposed sensor architecture is significantly simpler than other structures for controlling the sensitivity.
The design procedure for this proposed sensor structure could be more efficient and easier because relatively fewer geometrical parameters are need to be optimized. Thus, we can choose the appropriate geometric parameters to achieve the desirable sensitivity.
The relationship between the sensing properties of index guided PCF with air core and the fiber parameters, as well as the fiber length and operating wavelength, has been numerically investigated.
The sensitivity of the modified fibers depends on the penetration of the transmitted power into the fiber holes and can be controlled by controlling core and holes dimensions.
The relative sensitivity at wavelength of $\lambda = 1.33\ \mu m$ that is in the Methane absorption line is enhanced. The confinement loss is also improved.

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