Highly sensitive pressure-induced plasmon resonance birefringence in a silver-coated photonic crystal fiber

S Zhang\textsuperscript{1,2}, X Yu\textsuperscript{1,5}, P Shum\textsuperscript{3}, Y Zhang\textsuperscript{1}, H P Ho\textsuperscript{3} and D Liu\textsuperscript{4}

\textsuperscript{1}Singapore Institute of Manufacturing Technology, 71 Nanyang Drive, S638075, Singapore
\textsuperscript{2}School of Electrical and Electronic Engineering, Nanyang Technological University, Block S2, 50 Nanyang Avenue, S639798, Singapore
\textsuperscript{3}Department of Electronic Engineering, The Chinese University of Hong Kong, Ho Sin Hang Engineering Building, CUHK Shatin, N.T. Hong Kong
\textsuperscript{4}Department of Optical Communication and Optical Network Engineering, Huazhong University of Science and Technology, 1037 Luoyang Road, Wuhan, China

Email: xyu@simtech.a-star.edu.sg

Abstract. Using the finite element method, we have reported simulation and analysis results on the pressure-induced plasmonic loss in a photonic crystal fiber structure containing hexagonal silver-coated holes. We have also demonstrated that this configuration may offer highly sensitive pressure sensing capabilities. By measuring the resonance wavelength difference between two orthogonally polarized fundamental modes, a high sensitivity value of 32.89 nm/N has been achieved in the visible wavelength range. The effect of pitch size and hole diameter variation on the resonance wavelength have been studied in detail as well.

1. Introduction
A plasmon describes the quantized nature of energy of the surface electrons in the metal [1]. Surface plasmon resonance (SPR) refers to the excitation of surface plasmon polaritons, which are plasmons coupled with photons along the interface of the metal and dielectric materials. There are several methods for SPR to occur including prism coupling, waveguide coupling, fiber-optic coupling and grating coupling. Among all fiber-based plasmonics devices, there is a special class of optical fibers named photonic crystal fibers (PCFs) which possesses a periodic dielectric structure [2]. When metal inclusions are introduced into PCFs, new features which incorporate plasmonics effect have been the research highlight for the past decade, especially in the sensing technology field. PCF-based SPR sensors provide numerous advantages, such as miniaturization, a high degree of integration and remote sensing capabilities. Other applications such as optical circuitry, fiber-integrated optoelectronic components, electrochemistry, glass poling, liquid crystal devices and imaging on the sub-wavelength scale have also been proposed [3].

\textsuperscript{5} To whom any correspondence should be addressed.
This paper mainly focuses on the pressure sensing application, which has also attracted many research groups worldwide. Bock et al have experimentally measured the pressure and temperature sensitivities of two PCFs and successfully developed a temperature-insensitive pressure sensor using a commercial polarization-maintaining PCF [4]. Subsequently, Gahir and Khanna have improved the model with simpler design configuration. They have theoretically and experimentally presented a temperature-compensated pressure sensor on PCFs operating at 1550 nm [5]. Similarly Fu et al have reported a large wavelength-pressure coefficient sensitivity using the Sagnac interferometer design with a polarization-maintaining PCF. The demonstrated measurement range was 0.3 MPa [6]. But until recently, the SPR effect in metal-based PCF with pressure sensing application has only been reported. Pone et al have demonstrated a metal-coated elliptical holey fiber based pressure sensor by measuring the splitting of the resonance wavelength of two orthogonally polarized fundamental modes in the infra-red wavelength region. The splitting value increases with the ellipticity of the air holes [7]. However, they only considered the deformation of holes while assuming that the pitch size, i.e. the distance between two adjacent holes remain the same. In fact, this does not reflect the actual situation when the fiber is exposed to an external force or pressure.

In the present paper, we report simulation results on pressure-induced plasmonic loss in a PCF structure containing hexagonal silver-coated holes taking into consideration of the mechanical deformation of both the pitch size (Λ) and the hole diameter (d) due to the external force applied on the fiber structure. Previously published results reveal that the plasmonic peak in the visible wavelength range exhibits higher sensitivity to changes in waveguide structural parameters and the analyte refractive index [8]. Thus our effort has been focused on the wavelength region of 400-800 nm, in order to achieve a high sensitivity and facilitate easy operation and detection. To our knowledge, the investigation on the PCF-based pressure sensor incorporating the SPR effect in the visible wavelength range has not been widely explored so far. We have numerically studied the polarization-dependent SPR condition by computing the difference between the resonance wavelengths of two degenerate fundamental modes in the x- and y-polarization direction. In our PCF device, both the Drude model and the Sellmeier equation have been adopted in the optical simulations to increase the accuracy. We report a large wavelength–force detection coefficient of 32.89 nm/N, which demonstrates the potential application of our device in highly sensitive pressure measurement.

2. Simulation structure

![Figure 1](https://example.com/figure1.png)

**Figure 1.** A PCF structure with silver-coated holes. "dₓ" and "dᵧ" are the hole diameter in the x- and y-direction respectively. "Λ" is the pitch size indicating the distance between the center of two adjacent holes. The holes are numbered 1-6 clockwise with "1" indicated in the figure (not drawn on scale).

The simulation model used in this paper is a PCF structure with six silver-coated holes as illustrated in figure 1. The hole pitch size is 1.5 µm and the diameter is 0.8 µm. The silver layer thickness shown in red is 50 nm. By compressing the fiber in the y-direction with an external force, the structure experiences stress and undergoes deformation. The simulation study is carried out in two parts. Firstly, the mechanical deformation due to the external force is studied using the finite element method based commercial software ANSYS (ANSYS, Inc. version 12.1). The mechanical property constants of the
PCF materials are set as in table 1. The pressure-induced hole ellipticity \( \delta \) is calculated according to the formula given in reference 6:

\[
\delta = \frac{2 \left( d_x - d_y \right)}{d_x + d_y} \times 100\%
\]

(1)

Table 1. Mechanical properties of silica glass and silver.

|                | Young’s Modulus (GPa) | Poisson’s Ratio | Yield Strength (MPa) | Ultimate Strength (MPa) |
|----------------|-----------------------|----------------|----------------------|------------------------|
| Silica glass\(^a\) | 73                    | 0.17           | -                    | 69                     |
| Silver\(^b\)   | 76                    | 0.37           | 55                   | 140                    |

\(^a\) Data are extracted from reference 9.
\(^b\) Data are extracted from reference 10.

The second part of study is on the simulation of optical properties of the fiber device. FemSIM (RSoft Design Group, version 3.1), another finite element method based simulation tool with perfectly matched layer boundaries is adopted to find the complex propagation constants of coupled fundamental modes over a wide wavelength range based on the deformed fiber structure. The frequency-dependent dielectric constant of silver \( \varepsilon_{Ag} \) is approximated by the Drude model, together with the standard Sellmeier expansion for silica. In order to facilitate phase matching between a core-guided mode and a plasmonic mode in the visible wavelength range, the holes are assumed to be filled with analyte with a refractive index of \( n=1.41 \). The measurement parameter of interest is the resonance wavelength birefringence expressed as:

\[
\Delta \lambda_r = \lambda_r^y - \lambda_r^x
\]

(2)

where \( \lambda_r^x \) and \( \lambda_r^y \) are the resonance wavelength of the x- and y-polarized fundamental mode respectively.

It should be noted that several assumptions have been made in this paper to simplify the simulation model: (1) only the anamorphic effect caused by the external force is studied, the stress-optical effect is not considered at the current stage; (2) the silver layer thickness remains the same throughout the compression process; (3) the effect of the ambient temperature change on the structure deformation of the fiber is not considered.

3. Results and Discussion

The simulation experiment is first carried out with the ANSYS software to examine the mechanical deformation parameters, i.e. the \( \Lambda \) and \( d \) change. Then the results are fed to the FemSIM simulation to study the effect of the external force on the optical properties, i.e. fiber core confinement loss and \( \Delta \lambda_r \) variation.

3.1. Mechanical deformation
An external force is applied uniformly in the y-direction on the surface of the PCF structure. The whole fiber becomes elliptical, with the x-direction as the major axis or transverse diameter as shown in figure 1. The deformation along the fiber length direction, i.e. the z-direction is ignored. Both the pitch size and hole diameter change in the x- and y-direction have been studied. The investigation range of the force value is 0-5 N, which is within the elastic deformation range for both silica glass and silver. It has been found in the simulation that the degree of hole diameter change is more significant than that of the pitch size change. The reason is that the Young’s Modulus (E), or the slope of the linear deformation region of the stress-strain curve for silver is larger than that for silica glass as indicated in table 1, which means that under the same pressure condition, silver will deform more than materials made of silica glass. In addition, a video clip offering a zoom in view of the hole
3.2. Optical properties

The aforementioned FemSIM tool is used to find the complex effective mode index of the coupled fundamental mode, i.e. $n_{\text{eff}} = \Re(n_{\text{eff}}) + j\Im(n_{\text{eff}})$. The real part of the effective refractive index reflects the propagation constant while the imaginary part is proportional to the confinement loss.

The resonance wavelength $\lambda_r$ for both x- and y-polarization state fundamental mode at different force values have been plotted in figure 2 (a) and (b) respectively. The peak in the loss spectrum signifies the coupling between a confined core mode and a plasmonic mode. The sharp increase in loss in the transmission corresponds to the matching of the frequency and momentum of the incident light with that of the surface plasmons, causing the plasmons to absorb the light energy and not reflected back. This core confinement loss is proportional to the imaginary part of the effective index by equation (3) below [11]. Thus the plasmon resonance wavelength can be identified by locating the peak of a loss spectrum against a wavelength plot [12].

$$\alpha(dB/cm) = \frac{40\pi}{\ln(10)} \frac{\Im(n_{\text{eff}})}{\lambda(cm)}$$  (3)

**Figure 2.** Confinement loss at different wavelengths for the (a) x-polarized and (b) y-polarized fundamental mode when an external force is applied ranging from 0 to 5 N.

From figure 2, it is observed that the resonance wavelength for the x-polarization state ($\lambda_r^x$) is generally blue-shifted as the force increases whereas $\lambda_r^y$ is red-shifted. The amount of shift of $\lambda_r^y$ is larger than that of $\lambda_r^x$ since the force is applied in the y-direction. The splitting of the resonance wavelength $\Delta\lambda_r$ defined in equation (2) increases monotonically with the increase in force as represented in the blue curve in figure 3 below. Moreover, when there is no force applied and the holes are circular, the two fundamental modes are degenerate and $\lambda_r^x = \lambda_r^y$ or $\Delta\lambda_r = 0$. A cubic polynomial fitting result is obtained and indicated beside the curve with a close to 1 R-square value of 0.9882 and root mean square error (RMSE)=8.029. The highest resolution is calculated to be 32.89 nm/N when the force value is equal to 3.5 N. In addition, the green curve in figure 3 plots the average hole ellipticity $\delta$ variation defined in equation (1) with respect to the force. The ellipticity value of holes (1, 2, 4, 5) and (3, 6) as numbered according to figure 1 are different because they undergo different degree of deformation, i.e. the calculated $\delta_{1245}$ is smaller than $\delta_{36}$ because of the fact that the center two
holes are further apart than the rest four. However, it is interesting to note that \( \delta \) in average increases linearly with the external force. If we assume that 0.1 nm shift between two plasmonic peaks can be resolved, the ellipticity detection limit is estimated to be \( 2.89 \times 10^{-4} \), which shows a remarkable improvement than the results published previously. Our results also confirm the merits of a thinner metal coating layer (from 100 nm to 50 nm) and a visible wavelength investigation range (compared to the infra-red wavelength range) [7].

![Figure 3](image)

Figure 3. The resonance wavelength birefringence \( \Delta \lambda_r \) and the average hole ellipticity \( \delta \) variation with respect to the external force.

| Force: \( F \) (N) | \( \Lambda \) change, \( d \) fixed: \( \Delta \lambda_r^\Lambda \) (nm) | \( \Lambda \) fixed, \( d \) change: \( \Delta \lambda_r^d \) (nm) | \( \Lambda \) & \( d \) change (actual): \( \Delta \lambda_r \) (nm) |
|------------------|----------------|----------------|----------------|
| 0                | -0.95          | -0.95          | -0.95          |
| 1                | 2.10           | 6.45           | 3.70           |
| 2                | -1.30          | 34.30          | 17.40          |
| 3                | 2.75           | 70.70          | 61.20          |
| 4                | 2.40           | 88.45          | 80.20          |
| 5                | 0.30           | 137.35         | 114.50         |

Table 2. Effect of \( \Lambda \) and \( d \) change on \( \Delta \lambda_r \).

In order to examine in detail the parameters that contribute to the change of resonance wavelength birefringence \( \Delta \lambda_r \) due to the external force, the effect of \( \Lambda \) and \( d \) change have been studied separately as named \( \Delta \lambda_r^\Lambda \) and \( \Delta \lambda_r^d \) respectively in table 2. It is evident that \( \Delta \lambda_r \) change is more dependent on the hole diameter change which is in line with our previous discussion in section 3.1. As the force increases, \( d_x \) increases and \( d_y \) decreases. In the x-direction, the silver coating layer is closer to the core. Thus more energy in the core region is available to excite surface plasmons on the silver-silica interface, which results in stronger SPR coupling efficiency. The energy loss in the core is higher which translates to a larger value of the resonance wavelength in the x-direction for the y-polarized fundamental mode [13]. Similarly the change of \( d_y \) leads to a blue-shifted \( \lambda_r^\zeta \) value. The results obtained agree well with our previously published conclusion [14]. In addition, it has been found that \( \Delta \lambda_r \) variance of the pressure sensor, i.e. the last column in table 2, is actually the net effect of \( \Delta \lambda_r^\Lambda \) and \( \Delta \lambda_r^d \) change and can be estimated quantitatively using a polynomial equation below:
\[
\Delta \lambda_r(\Lambda, d) = a + b(\Delta \lambda^A_r)^1 + c(\Delta \lambda^d_r)^1 + d(\Delta \lambda^A_r)^1(\Delta \lambda^d_r)^1 + e(\Delta \lambda^A_r)^2 + f(\Delta \lambda^A_r)^2(\Delta \lambda^d_r)^1
\]

(4)

where \(a=1.201, b=0.595, c=0.785, d=0.142, e=-1.102, f=-0.030\) with fitting parameters: R-square=1 and RMSE=4.11×10^{-14}. In fact, this curve fitting result is not unique and should be system specific. However, we have proven that such a correlation exists and can be expressed in a simple polynomial form depending on the number of data points available and the individual accuracy requirement. Further investigation shows that the last three nonlinear terms in equation (4) contributes a much more significant percentage to the final value than the first three linear terms. This indicates that the actual pressure sensor mechanism by measuring the resonance wavelength birefringence is not just a simple linear superposition of the individual effect of \(\Lambda\) and \(d\) change. However, the physical interpretations of the remaining nonlinear terms still require further exploration.

4. Conclusion
In this paper, we have analytically investigated the confinement loss and surface plasmon resonance condition of two orthogonally polarized fundamental modes in the context of a photonic crystal fiber with silver-coated elliptical holes. The relationship between the resonance wavelength birefringence \(\Delta \lambda\) and the external force is studied in detail. The highest sensitivity demonstrated in the simulation is 32.89 nm/N, indicating that the device is capable for applications such as high sensitivity pressure measurement. In addition, a hole ellipticity detection limit value as low as 2.89×10^{-4} also shows a significant improvement over the current statistics reported. A polynomial equation which relates the effect of the pitch size and hole diameter change on the resonance wavelength birefringence is established. In addition, it should be highlighted that although the investigation is carried out for an external force applied in the y-direction, the results can be generalized to a force applied in any other directions. The stress-optical effect and the ambient temperature variance could be considered for further investigations on metal-based PCF pressure sensor devices.

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