Characteristics of Plasmon Coupling Mode in SPR Based LPFG

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***Abstract*—Based on mode coupled theory, this paper investigates the coupled characteristics and the excitation conditions of the surface plasmon mode in the structure of SPR based LPFG coated with metal film, and analyzes the strain sensing properties of this LPFG. Firstly, according to the properties of surface plasmon wave (SPW) in a cylindrical waveguide, SPW electromagnetic field distribution in the LPFG coated with metal film can be obtained by solving the electromagnetic wave equation. Using the coupled-mode theory, the coupled-mode equations of SPR based LPFG is derived and set up, and the coupled conditions between the core mode and SPW are given. Further, transmission spectra of LPFG coated with metal film can be obtained by solving coupled-mode equation, the results show that the SPR peak is generated by the coupling of core mode and SPW. By analyzing the influence of grating period on the SPR peak, it can be known the tiny change of the grating period will cause obvious deviation of the SPR peak. So this structure of SPR based LPFG is very suitable for strain sensor. Further calculation shows the strain sensitivity can reach 2.04 pm/με, superior to the traditional LPFG sensors.**

Keywords-Coated Long-period fiber grating; mode transition; transmission spectrum; sensitivity.

I. INTRODUCTION

Long Period Fiber Grating (LPFG) has a highly sensitive for the tiny varying of the surrounding refractive index [1], and the optical chemical biosensors based surface plasmon resonance (SPR) have been widely used due to high sensitivity[2]. LPFG [3] is a device which can couple the core mode into cladding modes. LPFG can be used to couple the core mode into cladding modes and the surface plasmon wave (SPW), so the SPR phenomenon may be shown in the transmission spectra. It can be imagined, if the structure of LPFG is combined with the effect of SPR to build the sensor of SPR based LPFG coated with metal film, it would have a higher sensitivity. Further, it is important to note that the SPR theory of flat structure is not appropriate for the cylindrical waveguide structure of LPFG coated with metal film, therefore, a suitable SPR theory for cylindrical waveguide needs to be put forward.

This paper proposes a theoretical model of SPR based LPFG coated with the metal film. Firstly, the field distribution of SPW mode is got by analyzing the characteristics of the electromagnetic field distribution in a cylindrical waveguide and the properties of the SPW. Further, based on the coupled-mode theory, the resonant conditions of coated LPFG based SPR is obtained. Then, the transmission spectra of LPFG coated with metal film is got by solving coupled-mode equations. Finally, the changes of amplitude and position of SPR spectra with the grating period is investigated, and the dependence of the resonant wavelength shift on the strain is analyzed.

II. THEORETICAL ANANLYSIS OF SPR BASED LPFG

A. Resonance conditions

When a gold film is coated on the surface of cladding of LPFG, it can be regard as the triple-cladding structure. In this structure, the radii of the core, cladding and gold film are a_1, a_2 and a_3, respectively; the film thickness is $h_3=a_3-a_2$; the refractive indices of the core, cladding, gold film and environment are n_1, n_2, N_3 and n_4, respectively. The selected parameters of the optical fiber are as follows: n_1=1.4681, n_2=1.4628, N_3=0.559+9.81i (λ=1550nm), n_4=1.445, a_1=4.15μm, a_2=62.5μm. The parameters of grating are as follows: σ=4×10^{-4}, L=4cm, Λ=450μm, where σ is the amplitude of the modulation of the core refractive index, L is the length of the grating, and Λ is the period of the grating.

SPW field distribution in the triple-cladding structure of LPFG is obtained by solving wave equation based on the theory of the traditional SPR. In LFPG, the cladding modes will couple with SPW to excite SPR, and the energy of these cladding modes is changed, which results in the coupling with the core mode, and an appearance of the SPR peak in the core transmission spectra. Based on it, new coupled-mode equations of triple-cladding structure of LPFG coated with metal film are derived. Therefore, the resonance conditions are got by new coupled-mode equations.

$$\begin{cases} \beta_{1v}^{cl} = \beta^{spw} \\ \beta_{11}^{co} - \beta_{1v}^{cl} = \dfrac{2\pi}{\Lambda} \\ \beta_{11}^{co} - \beta^{spw} = \dfrac{2\pi}{\Lambda} \end{cases} \tag{1}$$

where β_{1v}^{cl}, β^{spw}, β_{11}^{co} are represent the propagation constants of cladding modes, SPW and core mode, respectively.

B. Transmission spectra

The transmittances of coated LPFG can be achieved by numerical solving the coupled-mode equations. Suppose the center of the grating is the origin of the z-axis, the boundary conditions for a long-period grating L in length are $A^{co}(z=-L/2)=1$, $A_v^{cl}(z=-L/2)=0$ and $A^{spw}(z=-L/2)=0$.

The transmittance through the grating is defined as

$$T = \left| \frac{A^{co}(z = L/2)}{A^{co}(z = -L/2)} \right|^2 \quad (2)$$

where $A^{co}(z = L/2)$ and $A^{co}(z = -L/2)$ are the amplitude of the core mode at the exit end and the entrance end, respectively. The intensity of SPW mode through the grating is defined as

$$I = \left| A^{spw}(z = L/2) \right|^2 \quad (3)$$

where $A^{spw}(z = L/2)$ is the amplitude of the SPW mode at the exit end.

Figure 1 shows the transmission spectra of the core and SPW intensity in the triple-cladding structure of LPFG coated with a gold film. The black solid line represents for the transmission spectra of the core mode, and the red dashed line represents for the intensity of SPW when the core coupled to cladding mode and SPW. From Fig. 1, it can be seen that the small attenuation peak position of long wavelength in black solid lines corresponds to intensity peak of SPW, so the attenuation peak is believed to be the SPR peak.

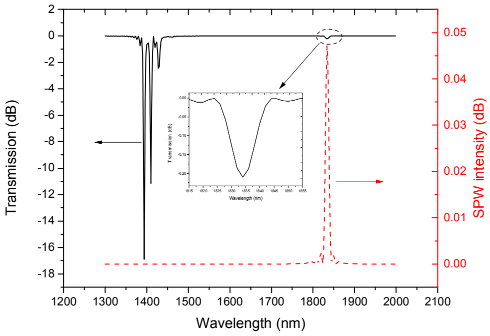

Fig. 1 Transmission and SPW intensity of a triple-clad LPFG coated with gold film

The illustration in Fig. 1 is the partial enlargement for the SPR peak. We can see that, the amplitude of SPR peak is much smaller compared with the attenuation peaks when the core coupled to cladding mode. This is because the SPW field of the core is much smaller than that of the cladding mode, which results in that the energy in the core mode coupling to the SPW is less than that to the cladding mode.

III. STRAIN SENSING OF COATED LPFG BASED SPR

For an LPFG, the changes of the fiber structure or grating parameters will affect the amplitude and positions of the attenuation peaks in transmission spectra. To study the sensing properties of the triple-cladding structure of LPFG coated with a metal film, the transmission spectra are given with different grating periods.

Figure 2 shows the transmission spectra of the triple-cladding structure of LPFG coated with gold film with the different grating periods. It can be seen that, the amplitude of SPR peak increases and its position shifts to the long wavelength, and the wavelength shift is available to 102 nm when the grating period increases from 450 to 500 μm. While imposing strain to LPFG, the influence of the elasto-optical effect to attenuation peak is less than that of the grating period[4]. So the strain can be indirectly detected by the change of grating period to a great extent.

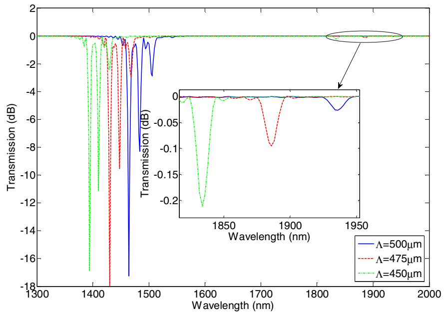

Fig. 2 Transmission spectra of LPFG coated with gold film when the grating periods are different

Figure 3 shows the dependence of the resonant wavelength shift of LPFG coated with gold film on the strain. It can be seen that the resonant wavelength shift displays a linear relationship with the strain. The strain sensitivity can reach 2.04 pm/με, which is an order of magnitude higher than that of the non-coated LPFG[5]. With the changing of strain, the wavelength shift of the SPR peak in this structure is great which shows this structure is very suitable for strain sensor.

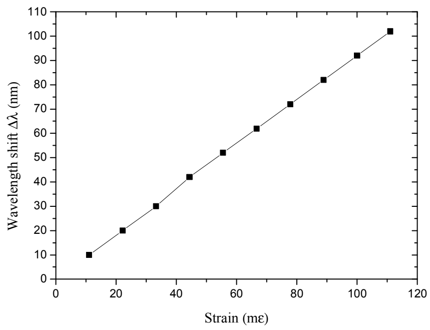

Fig. 3 Changes of resonant wavelength of LPFG coated with gold film with grating periods

IV. CONCLUSION

Based on the coupled-mode theory, the coupled conditions between the core mode and SPW are given. Transmission spectra of LPFG coated with metal film show that the SPR peak generated by coupling of core mode and SPW. The grating period has great influence on the SPR peak, so this SPR based LPFG is very suitable for strain sensor. The stain sensitivity of the sensor can reach 2.04 pm/με.

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