Structure Design of Refractive Index Sensor Based on LPFG with Double-layer Coatings

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***Abstract*—Based on the coupled-mode theory, the mode field distribution and mode transition of LP modes in an LPFG with double-layer coatings are studied theoretically. As a refractive index sensor, this LPFG structure is designed for high sensitivity by selecting a suitable thickness of the first coating. Date simulation indicates that the effective index of the LP cladding mode increases in steps with the first coating thickness, thus LP mode is guided to the overlay and the mode transition takes place, where the LP modes can be easily affected by the ambient. Thereby, the coated LPFG sensor should be designed to operate at the transition region. Further, for two types of LPFG with double-layer coatings, the transmittance spectrum, sensitivity and measurable dynamic range is analyzed. The sensitivity of the LPFG sensor is available to 10^3 with suitable overlay thickness.**

Keywords-Long-period fiber grating; LP mode; mode transiyion; effective index; sensitivity.

I. INTRODUCTION

The coupling of the long-period fiber gratings (LPFGs) happens between the forward-propagating core mode and the cladding modes. The effective index of the cladding modes of LPFGs is very sensitive to change of ambient refractive index (RI), so LPFGs have been wildly applied in fields of chemical and biological sensors. Ree et al. investigated firstly the behavior of an LPFG with Langmuir--Blodgett thin-film overlays[1]. It was found that the response of the LPFG with high refractive index overlays was sensitive to refractive indices higher than that of the cladding. Villar et al. studied the cladding mode transition and transmission spectrum of a coated LPFG based on the coupled-mode theory.[2] It is implied that a suitable overlay thickness can make some of the cladding modes transit into the overlay, and interact with the measurand. In view of the fact that the overlay index may be lower than that of the cladding, a novel LPFG with double-layer coatings is presented, which can be also acted as a refractive index sensor.

In this paper, a novel LPFG sensor is studied based on the coupled-mode theory described by Anemogiannis et al.[3] The transition of LP cladding modes is presented and the transmittance of this coated LPFG is discussed. Data simulation shows that the resonant wavelength shifts due to the minor variation of the overlay refractive index as the LPFG is located at the mode transition region. By selecting a suitable thickness of the first overlay, the high sensitivity of this LPFG sensor can be obtained. Thereby, the sensing property and structure design for two types of LPFG with double-layer coatings are discussed, which will be guidelines for the practical design of LPFG sensors.

II. ANANLYSIS OF LP MODE FIELD IN COATED LPFG

A. Coupled-mode theory for LP modes

LP_{0j} modes are calculated based on the coupled-mode theory and transfer-matrix formulation. The transverse electric-field component propagating along the *z*-axis is given by

$$U_{0j,i}(r,\varphi,z)=\exp(-j\beta_{0j}z)\,A_{0j,i}J_0(r\gamma_{0j,i})+B_{0j,i}Y_0(r\gamma_{0j,i}),\quad \beta_{0j}^2>n_2^2k_0^2,$$
$$U_{0j,i}(r,\varphi,z)=\exp(-j\beta_{0j}z)\,A_{0j,i}I_0(r\gamma_{0j,i})+B_{0j,i}K_0(r\gamma_{0j,i}),\quad \beta_{0j}^2<n_2^2k_0^2, \tag{1}$$

where i=1, 2, 3 and 4 stands for the core, cladding and double-layer coatings, respectively; β_{0j} is the propagation constant of the LP_{0j} mode, $\gamma_{0j,i}=\sqrt{k_0^2k_{n_i}^2-\beta_{0j}^2}$ is the magnitude of the transverse wave number. We have the transfer matrix equation

$$m_{22}^{1,N+1}(\beta_{0j})=0\,. \tag{2}$$

After resolving Eq.(2), the effective indexes n_{eff} (or $\beta_{0j}=n_{eff}k_0$) of the LP_{0j} modes can be calculated.

Supposing that the input field amplitude $A_{01}(0)=1$, based on the coupled-mode theory, we can obtain the transmittance T_{LPFG} of the gratings with length L,

$$T_{LPFG}(L)=10\times\log_{10}[\mathrm{Re}(A_{01}(L))^2+\mathrm{Im}(A_{01}(L))^2], \tag{3}$$

where $A_{01}(L)$ is the field amplitude at the end of the LPFG.

B. Mode transition regions of coated LPFG

Fig. 1 shows the effective refractive index of LP cladding modes versus the thickness of the first overlay thickness. As the thickness of the overlay increases to 0.5 µm, the LP_{02} mode is guided to the overlay. The effective refractive index is higher than 1.4447 as shown in Fig. 1. It means the cladding LP_{03} mode will become LP_{02}, and LP_{04} will become LP_{03}, and so forth. The phenomenon repeatedly emerges as the thickness increases to 2.0 μm, more modes are guided to the overlay and new re-organizations of the cladding modes takes place. The modes transit into the overlay, and they are more easily affected by the ambient. Thus a high sensitivity LPFG sensor can be designed by optimizing the overlay thickness.

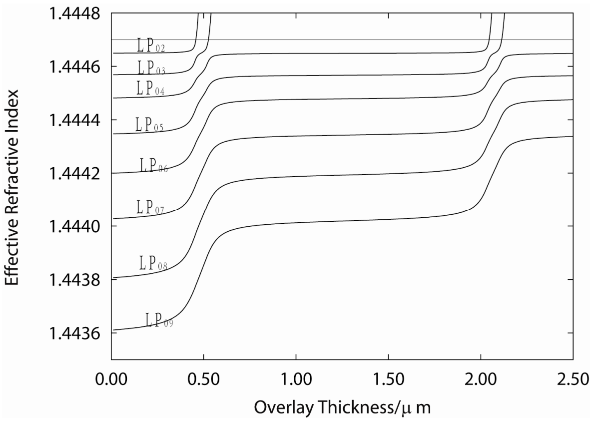

Fig.1 Relation of the effective refractive index with the overlay thickness

III. DESIGN STRUCTURE OF COATED LPFG SENSOR

A. First coating with higher refractive index

While the sensitive film index is lower than the cladding index, a coating with higher refractive index should be firstly coated on the cladding. For an LPFG sensor with double-layer coatings, the sensitive film index will be affected by the surrounding measurand. From Fig. 1, the thickness of the first coating must be located at the mode transition region. Fig. 2 shows the transmittance change of LPFG with the sensitive film index, in which the first coating thickness is selected to 0.5 μm according to Fig. 1. It is clear that the resonant wavelength shift obviously as a sensitive film index changes.

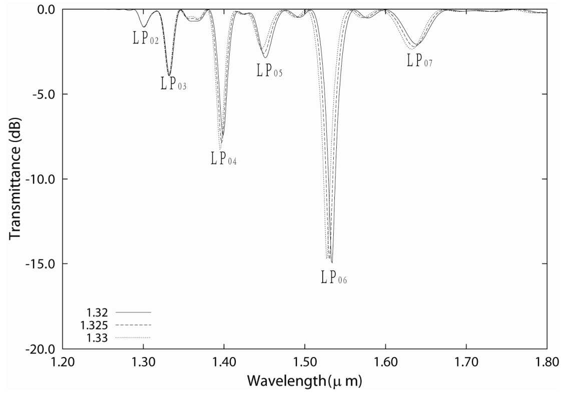

Fig.2 Transmittance of LPFG under different refractive index of the overlay

B. First coating with lower refractive index

For an LPFG coated with lower index overlay than the cladding, it can be also applied for a refractive index sensor by coating a sensitive film with higher index. Date simulation indicates the mode transits region shifts from lower index to higher index as the first coating thickness increases. Fig. 3 shows the dependence of transmittance on wavelength for sensitive film refractive index. Fig. 4 shows the sensitivity and measurable dynamic range for sensitive film refractive index. For two observed wavelength 1610.0nm and 1633.5nm, the sensitivity are 4.6×10^3 and 1.5×10^3, while the measurable dynamic range of overlay index are 2.0×10^{-4} and 9.3×10^{-4}.

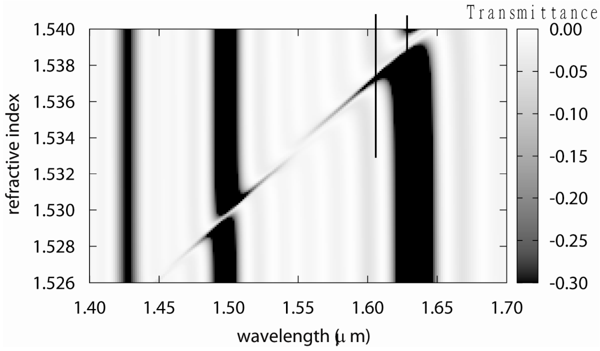

Fig.3 Dependence of *transmittance* on wavelength for overlay refractive index

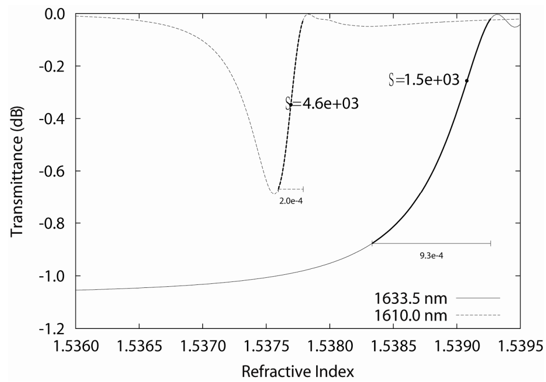

Fig.4 Sensitivity and measurable dynamic range for *overlay refractive index*

IV. CONCLUSION

An LPFG with double-layer coatings is presented and its sensing property and structure design is studied based on the coupled-mode theory. As the first coating thickness increases, the mode transition happens periodically. The transmittance of the LPFG located at the mode transition region shows that the resonant wavelength is very sensitive to the change of the refractive index of outside overlay. By selecting a suitable thickness of the first coating, the sensitivity of LPFG sensor is available to 10^3. This novel LPFG sensor with double-layer coatings overcomes the limitation of traditional coated LPFG in which the refractive index of sensitive coating must be higher than that of the cladding, and enlarges its scope of application, which allows it to be used far more widely.

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