Characteristics and Design of Coated LPFG Sensor Based on Mode Transition

Zhengtian Gu, Jinlong Lan, Haiyun Chen
Laboratory of Photo-electric Functional Films
College of Science, Uni. of Shanghai for Sci. and Tech.
Shanghai, China
E-mail: zhengtiangu@163.com

Kan Gao
Laboratory of Optical Fiber Sensors
No.23 Research Inst. of China Electronics Tech. Group,
Shanghai, China
E-mail: gaokan@siom.ac.cn

***Abstract*—The mode transition in a coated long-period fiber grating (LPFG) has been studied based on coupled-mode theory. The response of cladding mode effective index with increasing overlay thickness is analyzed. The lower order modes are transferred to the overlay, and the higher order modes replace the lower order modes order by order and continue to propagate in the cladding. Further, the transmission spectrum of the coated LPFG is investigated while the overlay thickness is located in mode transition and the surrounding region, the amplitude of attenuation peak of the cladding mode which will enter the overlay decreases rapidly and the peak position of adjacent higher cladding mode shift towards the former lower mode. To design high sensitivity LPFG sensor, the optimal overlay thickness is selected to ensure that the coated LPFG is located in the mode fast transition region. Finally, the response characteristics of film refractive index of coated LPFG were investigated for two typical cladding modes, and two kinds of the sensor sensitivity are defined and calculated. The results indicate that the resolution of film refractive index in mode transition can be available to 10^{-6} and 10^{-7} respectively, if the sensor is detected by transmittance change and wavelength shift.**

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

I. INTRODUCTION

Since N. D. Rees designed and investigated the structure of coated Long Period Fiber Grating (LPFG)[1], the jump of resonant wavelength with overlay thickness was first discovered. Then this jump pheromone was interpreted by the mode transition by I. Del Villar.[2]. In recent years, the investigation of the mode transition has been focused on non-absorption film coated LPFG sensor for surrounding refractive index (SRI) X. J. Yu[3] and P. Pilla [4] present that the coated LPFG has higher sensitivity for SRI in mode transition region. However, as a common gas, humidity or pH sensor, the sensitive film is always an absorptive film, so it is particularly important to study the mode transition and refractive index response characteristics for this kind of LPFG sensor. To our knowledge, the study of this aspect has not been reported.

Based on the coupled-mode theory, this paper firstly investigates the mode transition and the response characteristics of cladding mode efficient refractive index with overlay thickness. Further, the transmission spectrum of the coated LPFG is studied while the overlay thickness is located in mode transition and the surrounding region. By selecting a suitable overlay thickness, the high sensitivity of this LPFG sensor can be obtained. Finally the response characteristics of film refractive index of coated LPFG were investigated for two typical cladding modes, and two kinds of the sensor sensitivity are defined and calculated.

II. ANANLYSIS OF COATED LPFG MODE TRANSITIN

A. *Mode transition of coated LPFG*

Nelder-Mead which is the method of solving multiple variables function minimal value was used to solve the dispersion equation of the coated LPFG with absorption film. The LPFG transversal section is a four-layer cylindrical structure: core, cladding, overlay and ambient, their refractive index are n_1、n_2、n_3 and n_4 respectively, and they satisfy the relations of Real(n_3)>n_1>n_2>n_4. Considering that the cladding mode can be guided within the overlay, Fig. 1 shows the real efficient index of the first 14 cladding mode as a function of the overlay thickness. From Fig. 1, the cladding mode $HE_{1,2}$ becomes guided in the overlay at about 470 nm, and the mode higher than $HE_{1,2}$ successively transfers to the former lower mode, and the $EH_{1,3}$ mode becomes the lowest order cladding mode. As the overlay thickness further increases, the $EH_{1,3}$, $HE_{1,4}$, $EH_{1,5}$ modes become guided in the overlay at about 590, 1800, and 1960 nm. The change trend of real efficient index of the cladding modes in coated LPFG with absorption film is agreed with that in non-absorption film coated LPFG, but the values of efficient index have a few difference.

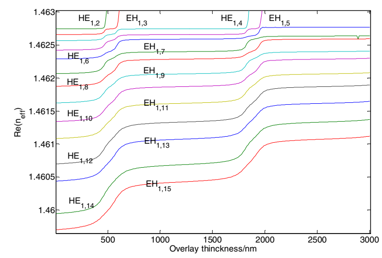

Fig. 1 Change of the first 14 cladding mode real effective refractive index in absorption film coated LPFG with the overlay thickness under the mode transition.

B. *Transimitance in mode transition regions*

In Fig. 2, the transmission spectrum of coated LPFG is given when overlay thickness is located in the first transition region and surrounding region. It can be seen that the position of attenuation band of each cladding mode will shift towards the lower wavelength with the increasing of the overlay

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thickness. For the attenuation band of the first cladding mode, as the overlay thickness increasing, its position shifts left and the amplitude decreases, and it reduces to zero when overlay thickness increase to a specific value (530nm), that is the attenuation band of the first cladding mode vanish, the reason is that the first cladding mode is guided within overlay in the value of overlay thickness. The position of attenuation band of the second cladding mode approach the first cladding mode, finally the attenuation band of the second cladding mode will cover the first cladding mode after vanishing of the attenuation band of the first cladding mode.

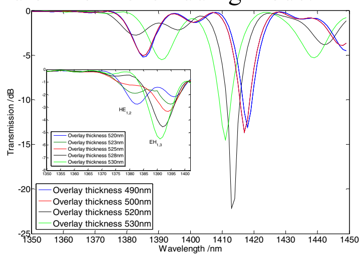

Fig. 2 Transmission spectra of coated LPFG for different values of the overlay thickness. Inset, the transmission spectra of coated LPFG for different values of the overlay thickness from 520 to 530 nm. The overlay refractive index is 1.57+ i× 0.01, and the ambient index is 1.

III. DESIGN OF COATED LPFG SENSOR

A. *Selection of the overlay thickness*

The amplitude of attenuation band of the $HE_{1,2}$ mode reduces from a value to zero, and that of $EH_{1,3}$ mode increases from small to big when overlay thickness increase from 520nm to 530nm, it was called the mode fast transition region (see Fig. 2). The inset of Fig. 2 more clearly reflects the change of the attenuation bands of $HE_{1,2}$ and $EH_{1,3}$ mode in the mode fast transition region, both the variation of the amplitude of $HE_{1,2}$ and position of $EH_{1,3}$ are great. It can be seen that the transmission spectra have a great variation, when overlay thickness is located in the vicinity of the critical point which the cladding mode is guided in the overlay. So a high sensitivity sensor can be designed to located in fast mode transition, The changes of overlay thickness and refractive index in mode fast transition region are given in Fig. 3.

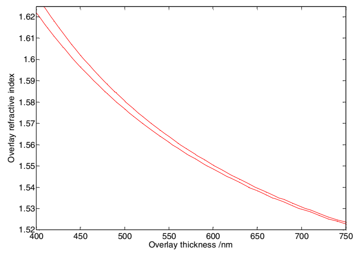

Fig. 3 Change of the mode fast transition region of coated LPFG with the overlay thickness and refractive index.

B. *Response of film refractive index*

For an LPFG sensor with coatings, the sensitive film index will be affected by the surrounding measurand. In Fig. 4, the response characteristics of film refractive index in transmission spectra of coated LPFG are given in the mode fast transition region. The wavelength shift of $HE_{1,2}$ mode can't be obtained when it is guided in the overlay, so we just investigate the change of its amplitude; the wavelength shift of $EH_{1,3}$ mode are great.

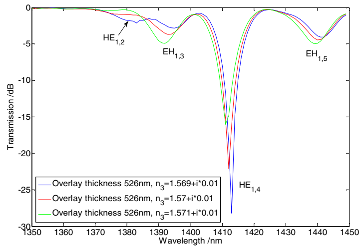

Fig. 4 Transmission spectra of coated LPFG for different values of the overlay refractive index in the mode fast transition region.

C. *The sensor sensitivity*

According to the different response characteristic of the above two mode of coated LPFG, the sensitivity S_T and S_λ of sensor is defined by transmittance change and wavelength shift respectively. Tab.1 lists the sensitivity and the film index resolution of $HE_{1,2}$ and $EH_{1,3}$ mode according to two sensitivity definition forms. For common spectrometer, the measurement accuracy of the transmittance is 10^{-3}, and the measurement accuracy of resonant wavelength is 0.01 nm. It can be seen that the resolution of $HE_{1,2}$ mode can be available to 10^{-6}, if the sensor is detected by transmittance change; and the resolution of $EH_{1,3}$ mode can be available to 10^{-7}, if the sensor is detected by wavelength shift from Table 1.

Table 1 the sensitivity and resolution of the cladding mode $HE_{1,2}$ and $EH_{1,3}$ in the mode fast transition region

Cladding mode	S_T	$\delta_n(T)$	S_λ	$\delta_n(\lambda)$	λ (nm)
$HE_{1,2}$	7.50×10^{2}	2.09×10^{-6}	–	–	1381
$EH_{1,3}$	–	–	2.25	6.98×10^{-7}	1395

IV. CONCLUSION

By analyzing the response of cladding mode effective index with increasing overlay thickness, it is concluded the mode transition in a coated LPFG happens periodically. Further, while the overlay thickness is located in mode fast transition the amplitude of attenuation peak of the cladding mode which will enter the overlay decreases rapidly, and the peak position of adjacent higher cladding mode shift towards the former lower mode. To obtain high sensitivity, the overlay thickness is selected to ensure that the coated LPFG is located in the mode fast transition region. The response characteristics of film refractive index of coated LPFG for two typical cladding modes indicate that the resolution of film refractive index in mode transition can be available to 10^{-6} and 10^{-7}.

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