Sensing characteristics of a metal film coated long-period fiber grating

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Abstract: To obtain the influence rules of the coating parameters of a long-period fiber grating (LPFG) with respect to temperature, strain and refractive index sensing properties, based on the mode coupling theory, a strict four-layer theorietical model of a metal film coated LPFG is established, and these parameters that affect the spectral characteristics of the metal film coated LPFG are studied. The simulation results show that there is an optimal metal film thickness on the surface of the LPFG that will induce the surface-plasmon resonance (SPR) effect, which results in higher sensitivity to the environmental temperature and refractive index but has little influence on the strain. There is theoretical evidence that when the silver thickness is between 0.8 and 1.2 nm, the refractive index sensitivity will reach the peak point of 42.402 6, at which the refractive index sensor sensitivity is increased by 4.5%. The theoretical results of coating a long-period fiber grating provide a good theoretical basis and guidance for LPFG design and parameters optimization.

Key words: metal film coated long-period fiber grating (LPFG); surface plasmon resonance (SPR); transmission spectrum; sensing characteristics

CLD number: TN201 **Document code**: A

Article ID: 1674-8042(2017)01-0089-08 **doi**: 10.3969/j.issn.1674-8042.2017.01.014

0 Introduction

The use of an optical fiber grating, which is a new optical device that uses the photosensitive properties of fiber material, leads to the change of the fiber core refractive index cycle along the axial direction, forming a spatial phase grating, which essentially changes the way the light propagates in the fiber core. A fiber Bragg grating is a type of device based on wavelength selection. Examples of such devices mainly include Bragg gratings, long-period gratings and chirp gratings, and they are very convenient in a broad range of applications, such as optical lasers, optical fiber sensors and optical communication, due to the grating inside the fiber core. A Fabry-Perot cavity (F-P cavity) could be fabricated by writing two same-wavelength fiber gratings on an erbium-doped optical fiber, which can be used as an optical fiber laser. A Michelson interferometer could be constructed, which can be used as an optical filter. In addition, a chirp grating can be used to construct an optical fiber dispersion compensator. After nearly 30 years of development, optical fiber gratings are now widely applied in optical fiber sensors, such as temperature sensors[1], strain sensors[2] and refractive index sensors[3]. Compared to conventional optical fiber sensors, an optical fiber grating has many advantages, such as ease of fabrication, resistance to electromagnetic interference, small size, high sensitivity, long-distance transmission, real-time monitoring of multi-parameters[4], and other unique advantages. A long-period fiber grating is a type of transmission fiber

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Received date: 2016-11-15

Foundation items: National Natural Science Foundation of China (No. 51309001); Scientific Research Key Project of Anhui Province (No. KJ2017A041)

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grating for which the resonant wavelength and amplitude are sensitive to changes in the external environment, which is a good sensing property. GUAN Shou-hua et al.[5] obtained the fitting curve of the long-period fiber grating (LPFG) resonance wavelength with changes in temperature through experimental measurements. Sakata H et al.[6] provided a convenient temperature measurement method using an optical fiber grating, which involves an experimental measurement that includes the relationship between light intensity and temperature. ZHANG Zijia et al.[2] obtained experimental results that the best strain sensitivity of the cladding mode occurs for the medium mode sequence.

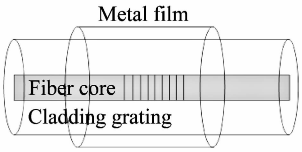
Surface-plasmon resonance (SPR) will be generated between a metal film and a medium interface when the LPFG cladding, which has high sensitivity to the environment, is coated with a thin layer of metal film. SPR is a type of physical optics phenomenon. It is the result of electron density oscillations propagating as transverse-magnetic (TM) polarized highly attenuated evanescent waves at the interface between a metal and a dielectric medium. To match the effective refractive index (ERI) of an incident optical wave with such a SPW along the interface, grating structures on the metal surface or total internal reflection in a high refractive index substrate are widely applied[7]. Now, the phenomenon of SPR is widely used in biosensing in medical[8], pharmaceutical[9] and environmental applications[10]. It can be directly used in biological detection applications for which the process does not need to be marked. It can also be used in the detection of water pollution to judge the degree of water pollution according to changes in the refractive indices of water samples.

The characteristics and applications of coating a long-period fiber grating have become a research hotspot in recent years. Schuster T et al.[11], in his invited papers in 2012 in J. Lightwave Technology, proposed coating metal film formations on the surface of LPFGs to produce the SPR effect and found that the sensitivity increased 10 fold when the refractive index was between 1.332 and 1.335, and the precision reached 1.0×10^{-5}. GU Zheng-xian et al.[12] proposed using the bimodal resonance effect of a metal film LPFG liquid concentration sensor, coated with a 103 nm-thick silver film with an SPR-effect LPFG, to monitor the refractive index of NaCl solution and found that the precision could reach 1.8×10^{-5}. WANG Jian-neng et al.[13] proposed using an 8.4 nm-thick gold film coated LPFG to measure chloride ion concentrations in NaCl solution and found that the sensitivity increased from 0.058 6 nm to 0.071 nm one percent. JIANG Ming-shun et al.[14] proposed a tunable erbium-doped fiber laser (EDFL) with a temperature-controlled Cu-coated LPFG, which was used as a band-prevented filter. The coated LPFG, which was inserted into the fiber ring cave, would tune the highest gain point of the fiber laser ring. An optical fiber laser wavelength tunable range of 20.72 nm was achieved. However, relative to the interest in coated LPFGs abroad, there are few domestic studies of metal film coated LPFGs; this is especially true for theoretical studies and production manufacturing. At the same time, due to the lack of accurate simulation models, there have been few coated film theoretical research studies on LPFGs. Only studies concerned with testing the structures using optimal coating parameters have been performed. To a certain extent, these tests limit the practical applications of coated LPFGs.

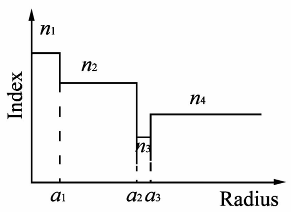
This paper is based on a four-layer cladding LPFG model and discusses the influence of metal film coated LPFG parameters, including coating materials, thickness and other coating parameters, on the temperature, strain and refractive index sensing characteristics of coated LPFGs. A series of qualitative and quantitative results are obtained. This paper also provides a theoretical idea about how to improve the spectrum sensing characteristics of metal film coated LPFGs.

1 Coated-LPFG theoretical model and SPR effect

An LPFG sensor coated with a thin metal film outside the cladding can be considered as a four-layer model of an LPFG. Fig. 1(a) and (b), respectively, present the structure and refractive index distribution of the metal-coated LPFG sensors[11], where n_1 is the core layer refractive index; a_1 is the core layer radius; n_2 is the inner cladding refractive index; a_2 is the inner cladding radius; $n_3=n+ik$ is the third cladding metal film refractive index, which is plural; a_3 is the third cladding metal film radius; $h=a_3-a_2$ is the film thickness; and n_4 is the fourth cladding environmental refractive index.



(a) Structure chart



(b) Refractive index profile

Fig. 1 Theorietical model of long-period fiber grating

Gold and silver are inert metals, meaning that they are resistant to reaction with other substances; hence, using these metals can ensure the sensitivity and stability of the LPFG sensors. There are many methods for applying metal film coatings on the surfaces of LPFGs, such as the ion beam sputtering deposition method, which involves stripping off the coating layer of the fiber, cleaning it up, placing the LPFG parallel to the target material, and, finally, using a small sputtering apparatus to apply the metal film coating o the LPFG.

The transmission constant changes to a plural refractive index because of the metal film layer. Actually, the real component offset leads to changes in the resonant wavelength and the loss peak amplitude, and the imaginary component produces the loss characteristics of the transfer mode, for which $\beta_{\mathrm{cl}}=\beta_{\mathrm{r,cl}}+i\beta_{\mathrm{i,cl}}$ is the metal film layer transfer constant. Coated LPFG mode coupling occurs prior to the transmission of the fiber core mode coupling to the synthetic n-order cladding mode of transmission. They will attenuate after a distance transmission, and the corresponding LPFG coating phase condition is

$$\frac{2\pi}{\Lambda}=\beta_{\mathrm{co}}-\beta_{\mathrm{cl}}=(n_{\mathrm{eff,co}}-n_{\mathrm{eff,cl}})\frac{2\pi}{\lambda_{\mathrm{L}}}. \tag{1}$$

Hence,

$$\lambda_{\mathrm{L}}=(n_{\mathrm{eff,co}}-n_{\mathrm{eff,cl}})\Lambda, \tag{2}$$

where Λ is the grating period; β_{co} is the fiber core mode transmission constant; β_{cl} is the real part of the transmission constant for the cladding mode ($\beta_{\mathrm{r,cl}}$); $n_{\mathrm{eff,co}}$ and $n_{\mathrm{eff,cl}}$ are the fiber core mode and cladding mode effective refractive indices, respectively; and λ_{L} is the resonance wavelength. Changes in the environment, such as temperature, strain and environmental refractive index, due to the series of reactions resulting from the thermal expansion effect and elastic-optic effect, will lead to changes in the grating periods, lengths and refractive indices of the fiber core and cladding layers. Then, these changes will transform the LPFG mode coupling, finally inducing changes in the grating transmission spectrum. From Eq. (1), which describes the LPFG sensing property, the resonant wavelength and loss peak amplitude will change eventually, and we can use this property to make all types of sensors with different functions.

2 Influence of deposition parameters on LPFG spectral characteristics

The parameters of the LPFG are as follows: $a=4.2$ μm is the fiber core radius, $b=58.35$ μm is the cladding radius, and the environmental layer radius is infinite. The refractive indices are $n_1=1.449\,21$, $n_2=1.444\,03$ and $n_4=1$. $L=50\,000$ μm is the grating length, $\Lambda=460$ μm is the grating period, $IM=0.000\,1$ is the refractive variable, and the center wavelength is 1 550 nm. In the experiment, the loss of the largest resonance peak is studied and the material dispersion is ignored. The silver film refractive index $n_{\mathrm{Ag}}=0.469+\mathrm{i}9.32$.

2.1 Influence of temperature characteristics of coated LPFG

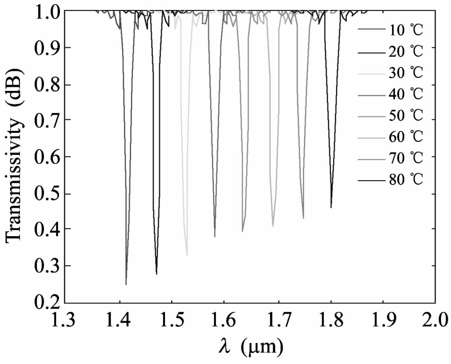
The parameters will vary with the environmental temperature due to the thermal expansion effect, namely,

$$\frac{\mathrm{d}\lambda}{\lambda}=(\alpha+\Gamma_T^m)\mathrm{d}T, \tag{3}$$

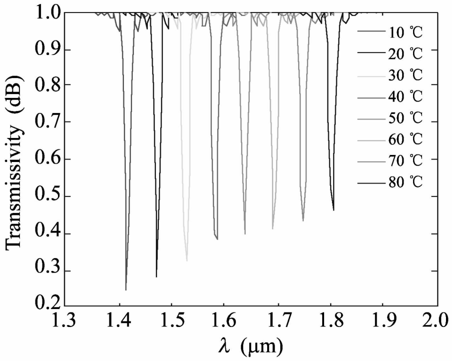
where α is thermal coefficient of expansion, and $\Gamma_T^n = \dfrac{\xi_{\mathrm{co}} n_{\mathrm{eff,co}} - \xi_{\mathrm{cl}} n_{\mathrm{eff,cl}}^m}{n_{\mathrm{eff,co}} - n_{\mathrm{eff,cl}}^m}$ is temperature sensitivity factor.

Obviously, the environmental temperature could be calculated by measuring the difference in the loss peak of the LPFG.

Regardless of whether a 60 nm gold or 60 nm silver film is used, the resonance wavelength of the LPFG transmission spectrum will shift to the right as the temperature increases, but the loss peak amplitude will gradually decrease, as shown in Fig. 2.



(a) 60 nm gold film



(b) 60 nm silver film

Fig. 2 Transmission spectra for a 60 mm metal film under different temperatures

Fig. 3 shows the relationship between the resonance wavelength of the LPFG and the temperature before coating, revealing a linear relationship. The light wavelength and temperature fitting curve is $\lambda_1 = 5.52T + 1\ 361.5$. Fig. 4 shows the relationship between the wavelength and the temperature for different silver thicknesses ranging from 20 nm to 100 nm, revealing a linear relationship. The highest sensitivity of the wavelength to temperature is 5.526 4. In this case, the LPFG has a 60 nm silver film coating. Otherwise, it is obvious that a thinner silver coating induces higher sensitivity. For example, an LPFG with a 20 nm metal film coating will have lower sensitivity than an uncoated LPFG. There exists a proper silver thickness at which the temperature sensitivity reaches its highest point. Therefore, we must strictly control and optimize the thickness of the thin film to fabricate metal film coated LPFG sensors, for which the SPR effect increases the sensor sensitivity.

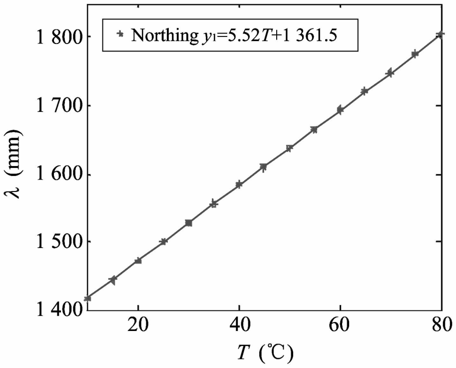


Fig. 3 Relationship between wavelength and temperature before coating

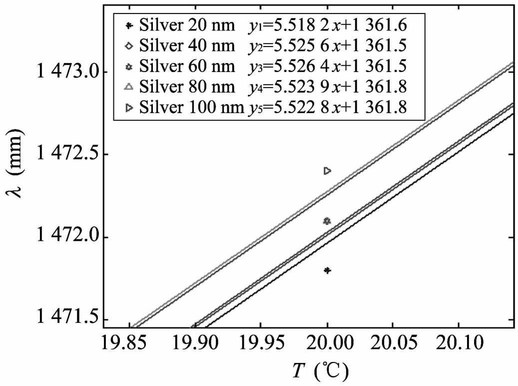


Fig. 4 Relationship between wavelength and temperature for different thicknesses of silver film

Fig. 5 shows the relationship between the light intensity and the temperature before coating. It is obvious that the light intensity gradually linearly increases with the temperature. The fitting curve is $y_1 = 0.037\ 8T - 6.230\ 9$. Fig. 6 shows the relationship between the light intensity and the temperature for different thicknesses of the silver film. The metal film thicknesse ranges from 20 nm to 100 nm, and these thicknesses result in almost the same sensitivity. By comparison of the fitting curves in Figs. 5 and 6, we can determine that, after coating, the intensity of the temperature sensitivity is increased by 1.05%, which is higher than that prior to coating. This is because the SPR effect will occur when a thin metal film is plated on the LPFG, which can improve its sensitivity.

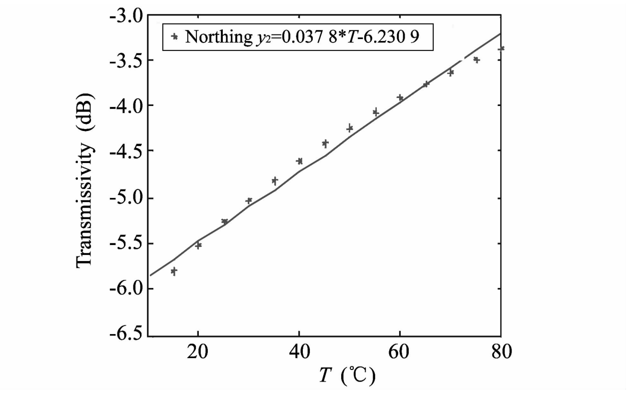


Fig. 5 Relationship between intensity and temperature before coating

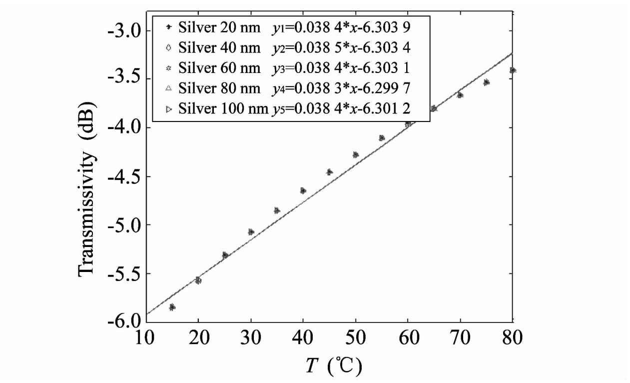


Fig. 6 Relationship between intensity and temperature for different thicknesses of silver film

2.2 Influence of film strain characteristics of coated LPFG

A series of parameters will vary with axial strain due to the elastic-optic effect, namely,

$$\frac{d\lambda}{\lambda} = (1+\Gamma_{\varepsilon}^{m})d\varepsilon, \tag{4}$$

where Γ_{ε}^{m} is the strain sensitivity factor.

Figs. 7 and 8 show the fitted data of the wavelength of the LPFG and the strain, respectively, for uncoated and plated 0.1—7 000 nm silver film. Both indicate that the resonance wavelength is blue shifted with increases in the strain, and the data are used to obtain good linear fitting equations, as shown in Fig. 8.

It is clear from the data and the testing results that the silver thicknesses can be classified into five groups. The group of thicknesses ranging from 0.1 nm to 7 nm has the highest sensitivity to strain (0.107 3 nm/με). It shows that the silver film thickness has little influence on the strain characteristics of metal-coated LPFG.

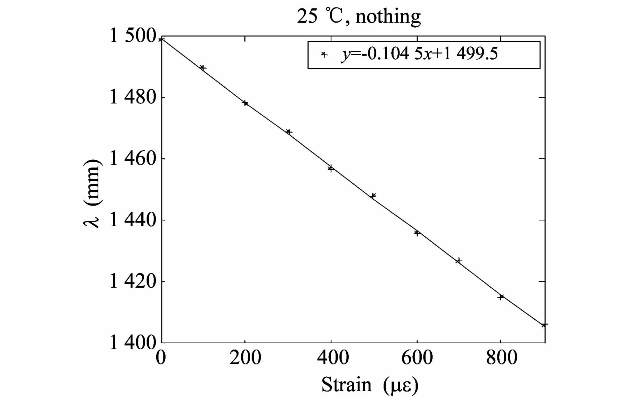


Fig. 7 Wavelength-strain fitting data for uncoated LPFG

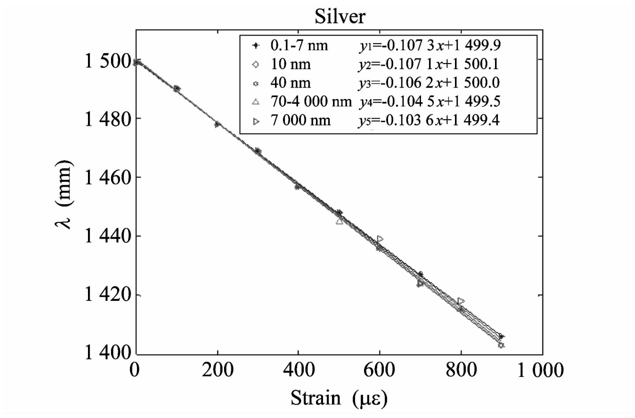


Fig. 8 Wavelength-strain fitting data for silver coated LPFG

2.3 Influence of refractive index sensing properties of coated LPFG

When the refractive index of the surrounding environment changes, the cladding mode field distribution and transmission constant will change, and then, the cladding effective index will also change. Finally, the resonance wavelength will change accordingly, as shown in Eq. (2). This means that we can measure the environmental refractive index by monitoring the shift in the LPFG resonance wavelength. When the environmental refractive index increases to the cladding refractive index, the LPFG resonance peak will gradually disappear. When the environmental refractive index exceeds the cladding refractive index, there will be no discrete cladding mode[3], which is why only the refractive indices of the surrounding environment that are less than the cladding refractive index are analyzed.

The SPR effect is very sensitive to the refractive index of the LPFG surface after metal film coating. The resonance wavelength of the LPFG will shift when the environmental refractive index changes. Fig. 9 shows the spectrum of a 0.8 nm silver film coated LPFG for different environmental refractive indices, ranging from 1.1 to 1.4. The resonant wavelength shifts 0.9 nm when the refractive index changes from 1.1 to 1.2; the resonance wavelength shifts 1.8 nm when the refractive index changes from 1.2 to 1.3; and the resonant wavelength shifts 4.2 nm when the refractive index changes from 1.3 to 1.4. From the results, it is concluded that as the environmental refractive index increases by 0.1, the shift in the resonant wavelength increases gradually, that is, LPFG has better refractive index sensitive features when the environmental refractive index is closer to the cladding mode refractive index.

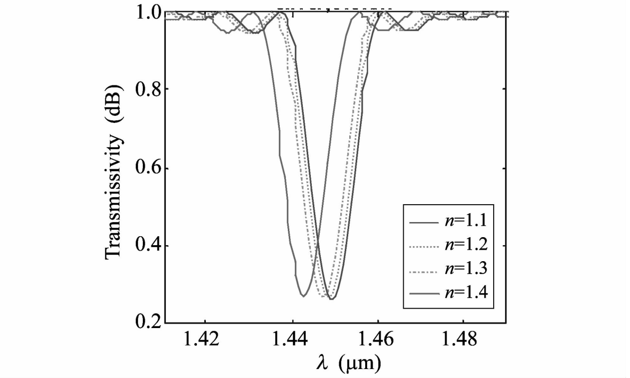


Fig. 9 Transmission spectra for different environmental refractive indices

The refractive index of the NaCl solution LPFG sensor with a 0.8 nm silver film is studied. The NaCl concentrations and corresponding refractive index values are given in Table 1.

Table 1 Quality volume concentrations of NaCl solutions corresponding to different refractive indices ($\frac{1}{300}$ g/mL)

Quality NaCl (g/300 ml)	Refractive index of NaCl solution
0	1.333 0
12	1.339 5
24	1.346 0
36	1.352 0
48	1.357 1
60	1.362 1
72	1.367 5
84	1.372 0
96	1.376 0

Fig. 10 shows the LPFG transmission spectra for each concentration of NaCl. The LPFG resonant wavelength in air is 1 446.6 nm; in NaCl solution, with the increase of the concentration, the resonant wavelength is gradually blue shifted. As seen in Fig. 10, the total wavelength shift is approximately 1.8 nm when the concentration of the NaCl solution is increased from $0\times\frac{1}{300}$ g/ml to $96\times\frac{1}{300}$ g/ml, and the linear fitting curve is $y=-42.402\,6x+1\,503.2$. Namely, as the refractive index of the NaCl solution increases by 0.01, the resonant wavelength shifts 0.4 nm. Using this feature, we can construct all types of sensors to detect the refractive index and the concentration of a solution or gas.

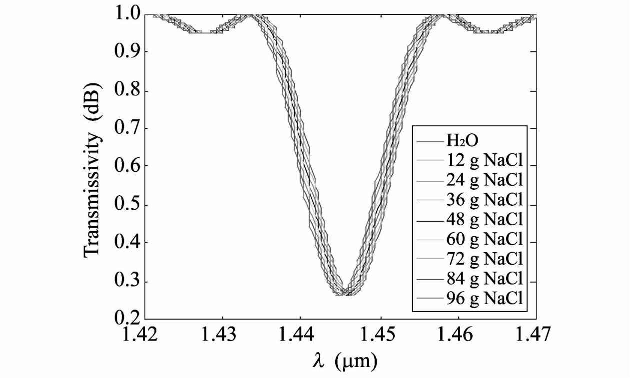
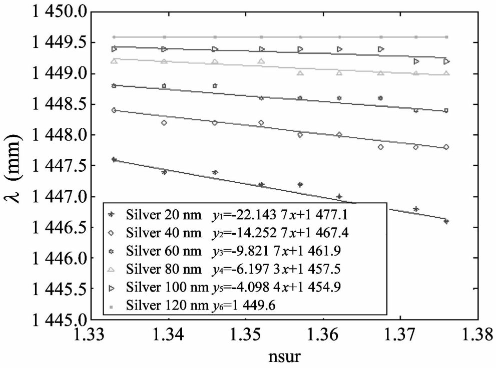


Fig. 10 Transmission spectra for different NaCl concentrations

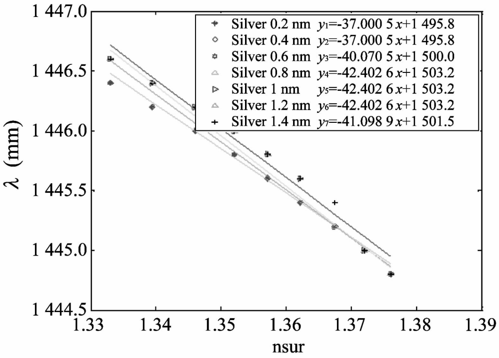
Fig. 11(a) shows fitted data of the resonance wavelengths of the LPFG and the refractive indices for different coating thicknesses of the metal film. It is evident that with the decrease of the thin film thickness, the sensitivity of the LPFG refractive index increases after silver film coating. It is found that for silver coating thicknesses of up to 120 nm, the LPFG resonant wavelength will remain constant, even if the environmental refractive index changes, that is, at this point, the refractive index sensitivity of the LPFG will vanish. Furthermore, when the coating film thickness is between 20 and 160 nm, the refractive index sensitivity of coated LPFG is lower than that of uncoated LPFG.

To find the optimal value of the coating film thickness, silver coating film thicknesses between 0.2 and 1.4 nm are studied. In this range, the refractive index sensitivity of the LPFG reaches its peak value.

Fig. 11(b) shows the fitted data of the resonance wavelength of the LPFG and the refractive index when the coating thickness of the silver film changes from 0. 2 to 1. 4 nm. It is found that when the coating film thickness is between 0. 8 and 1. 4 nm, the refractive index sensitivities of the coated LPFGs are higher than that of the uncoated LPFG. However, it is not as we expect when the coating film thickness is between 0. 2 and 0. 6 nm, the refractive index sensitivities of the coated LPFGs are lower than that of the uncoated LPFG. This means that the refractive indices are higher for thinner coated metal films. There should exist an optimal thickness parameter that would allow the LPFG to reach its highest possible refractive index sensitivity. From the fitted data in Fig. 11(b), it is evident that when the silver thickness is between 0. 8 and 1. 2 nm, the refractive index sensitivity will reach the peak point of 42. 402 6. The refractive index sensitivity of uncoated LPFG is 40. 517 8. Therefore, the refractive index sensitivity of the sensor is increased by 4. 5%.



(a) Silver thickness from 20-120 nm



(b) Silver thickness from 0.2-1.4 nm

Fig. 11 Fitted data of resonance wavelengths and refractive indices for different coating thicknesses of metal film

3 Conclusion

This paper introduced a theoretical model and determined the sensing characteristics of a metal film coated LPFG through the simulation analysis of the transmission spectrum of the LPFG. In addition, detailed conclusions were drawn on the coated and uncoated LPFGs with regard to temperature, strain and refractive index sensing properties. The results show that the resonance wavelength will red shift as temperature increases; the resonant wavelength will blue shift as strain increases; and the resonant wavelength will blue shift as the environmental refractive index increases. Furthermore, coating an LPFG surface with a metal film of suitable thickness will induce the SPR effect. After coating, both wavelength and light intensity have higher sensitivity to temperature than in the case of the uncoated LPFG. Specifically, the sensitivities of light intensity and temperature could each reach 1. 05%. Meanwhile, there is an optimal thickness of the thin film that results in the best SPR effect for increasing the sensor sensitivity. The results of the theoretical analyses indicate that the metal film coating has little influence on the strain characteristics of the LPFG. With regard to the refractive index, the sensitivity is higher after metal film coating of the LPFG, and the LPFG has better refractive index sensitive features when the environmental refractive index is closer to the cladding mode refractive index. It is not true that a thinner metal film coating will lead to a higher refractive index sensitivity. There should be an optimal thickness parameter that would allow the LPFG to reach its highest possible refractive index sensitivity. There is theoretical evidence that when the silver thickness is between 0. 8 and 1. 2 nm, the refractive index sensitivity will reach the peak point of 42. 402 6, at which the refractive index sensor sensitivity is increased by 4. 5%. In summary, the theoretical analysis of a coated LPFG provides a good theoretical basis and guiding significance for LPFG design and parameters optimization.

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镀金属膜长周期光纤光栅的传感特性

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摘 要： 本文基于耦合模理论，建立了严格的四层金属膜理论模型，探讨了镀金属膜长周期光纤光栅(Long-period fiber grating，LPFG)的温度、应变及折射率特性，以及镀膜参数对镀金属膜长周期光纤光栅光谱特性的影响。仿真结果表明，长周期光纤光栅表面最优的金属膜厚度将引起表现等离子共振(Surface-plasmon resonance，SPR)特性，这一特性将使得LPFG对稳定及折射率都有较高的敏感性，而对应变影响较小。理论分析表明，银膜厚度在0.8－1.2 nm范围内时，折射率敏感度达到最大值为42.402 6，敏感度增加4.5%。仿真结果为镀膜长周期光纤光栅的设计及参数优化提供了理论指导。

关键词： 镀金属膜长周期光纤光栅；表面等离子共振；传输光谱；传感特性

引用格式： WANG Yan，LIU Jia-ping，LIU Ji-hong，et al. Sensing characteristics of a metal film coated long-period fiber grating. Journal of Measurement Science and Instrumentation，2017，8(1)：89-96. [doi：10.3969/j.issn.1674-8042.2017.01.014]