Vol 16 No 6, June 2007
1009-1963/2007/16(06)/1694-06
Chinese Physics
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Temperature or strain induced adjustable-chirp characteristics of uniform fibre grating with tapered metal coating*

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(Received 19 August 2006; revised manuscript received 25 January 2007)

Temperature and strain characteristics of uniform fibre grating with tapered metal coatings have been analysed theoretically, by which adjustable chirp characteristics of such gratings are shown. Electroplating is adopted to fabricate such gratings, and the tapered metal coating is obtained by gradually drawing the fibre grating out of the solution during the process of electroplating. The gradually changing cross-sectional area of the metal coating is calculated by a newly suggested numerical method. By combining the theoretical and numerical simulation analyses, the gratings' characteristics are given at various temperatures and strains. The results obtained using such a method are also testified by experiments.

Keywords: fibre grating, chirp, dispersion compensation
PACC: 4280S, 4280F, 4281D, 4230Q

1. Introduction

As an effective solution for dispersion compensation in high speed and long haul optical communication systems, chirped fibre Bragg gratings have attracted more and more attention because of the compact design, high dispersion figure of merit, capability to compensate higher order dispersion and especially the absence of nonlinear effects, etc.[1−3] Compared with the dispersion compensation fibre, another merit of the fibre Bragg grating is its great agility to change the dispersion characteristics. So fibre gratings are widely used as tunable dispersion compensators to compensate the residual dispersion and dispersion slope.[4,5] And many efforts have been devoted to the development of a more flexible method to fabricate chirp gratings, in which special attention is paid to the method of chirping the uniform fibre grating. Because the reflective characteristics of fibre grating are determined by the effective index and the period of index modulation fringe, chirp can be achieved by varying the fringe period, the effective index or both along the fibre axis. On the whole, the methods can be divided into two categories. One is introducing a period or index change during the process of the grating fabrication, writing grating in a core-tapered fibre is a representation,[6] while the fabrication of fibre with nonlinearly-changed core diameter is somewhat difficult. The other is introducing an index or period change after the grating is written, and the realization of such methods often relies on some assistant material.[7] The representation is the method based on cantilevers.[8] However, the applications of such methods are greatly constrained by the large volume of cantilever.

In this paper, we propose a method which can make the uniform grating change to the one with desired chirp characteristics by a metal coating around the grating with gradually changing thickness. Electroplating is adopted to obtain the coatings. To use such a coating method, a numerical simulation method is put forward. And the gratings' characteristics can be given numerically for various temperatures and strains. Experiments are also carried out to confirm the analysis results.

2. Device design and theoretical analysis

The basic concept of forming the device is given in Fig.1, from which we can see that the metal coat-

*Project supported by the Paper Fund of Beijing Jiaotong University, China (Grant No 2005RC033) and the National Natural Science Foundation of China (Grant No 60477017).
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ing with gradually changing thickness around the fibre grating is the main feature. Before analysis, we assume that the metal coating can cling to the fibre grating tightly and the applied stretching force or the change of ambient temperature is not too large so as to ensure external force-induced change of the grating and that of the metal coating are the same.

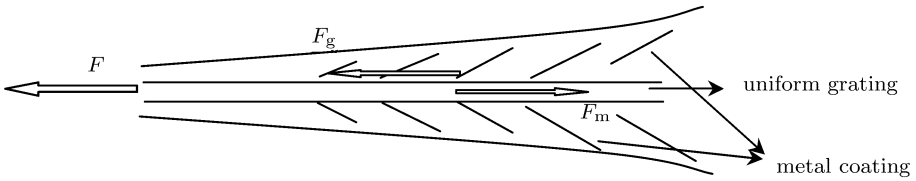


Fig.1. Schematic diagram of applying stretching force to the fibre grating with metal coating.

After the grating is coated with a metal coating, its cross-sectional area can be expressed as $A(x) = A_m(x) + A_g$, where x is the position along the fibre axis, $A_m(x)$ denotes the cross-sectional area of the tapered metal coating, and A_g denotes the cross-sectional area of the fibre grating. According to the theory in mechanics of materials, if the cross-sectional area varies slowly or $dA(x)/dx$ is far smaller than the dimensions of the device, the stress can be represented by the following relation when a longitudinal stretching force F is applied along the grating axis:[9]

$$\sigma_x = F/A(x). \tag{1}$$

And according to the definition of stress σ_x and strain ε_x, the change of the period of such grating can be given by

$$\Delta\Lambda/\Lambda = \Delta L/L = \varepsilon_x = \sigma_x/E = F/E/A(x), \tag{2}$$

where E is the Young modulus of the material.

When the ambient temperature of such grating is changed, the different expansion coefficients of the metal coating and the fibre grating will induce a interlaminar strain at their interface.[10] With further consideration of the thermo-optic effect the period Λ and the effective index n_{eff} of the grating will experience changes as

$$\frac{\Delta\Lambda}{\Lambda} = \alpha_g\Delta T + \varepsilon_{xg}, \quad \frac{\Delta n_{\text{eff}}}{n_{\text{eff}}} = \xi\Delta T - P_e\varepsilon_{xg}, \tag{3}$$

where α_g is the thermal expansion coefficient and $P_e \approx 0.22$ is the effective photoelastic coefficient of the fibre grating.

Considering the assumption and Eqs.(2) and (3), the same change of the coating and the fibre grating will have relations

$$\frac{F_t}{A_g E_g} + \alpha_g\Delta T = -\frac{F_t}{A_m(x)E_m} + \alpha_m\Delta T, \tag{4}$$

where F_t is the force caused by the thermal interlaminar stress ε_{xg}, and variables with subscripts m and g respectively denotes those for metal coating and grating.

Then ε_{xg} can be obtained as

$$\varepsilon_{xg} = F_t/(A_g E_g) = [(\alpha_m - \alpha_g)\Delta T] \times \frac{A_m(x)E_m}{A_g E_g + A_m(x)E_m}. \tag{5}$$

So according to Eqs.(3)–(5), the wavelength change of such a grating experiences temperature as (λ_B is the designed reflective wavelength of grating)

$$\frac{\Delta\lambda}{\lambda_B} = \frac{\Delta\Lambda}{\Lambda} + \frac{\Delta n_{\text{eff}}}{n_{\text{eff}}} = (\alpha_g + \xi)\Delta T + (1 - P_e)[(\alpha_m - \alpha_g)\Delta T] \times \left[1 - \frac{A_g E_g}{A_g E_g + A_m(x)E_m}\right] \tag{6}$$

and the chirp profile along the grating axis is

$$\lambda(x) = \lambda_B\left\{1 + (\alpha_g + \xi)\Delta T + (1 - P_e)[(\alpha_m - \alpha_g)\Delta T] \times \left[1 - \frac{A_g E_g}{A_g E_g + A_m(x)E_m}\right]\right\}. \tag{7}$$

From Eq.(7), it can be seen that the reflective wavelength varies with the cross-sectional area of the metal coating along the fibre grating. This is the reason why temperature change of the grating can induce chirp.

The above analysis focuses on the effect of temperature change on the characteristics of the metal coated grating. In the following, the effect of tensile force on the grating will be shown.

Suppose a kind of metal coating with a larger Young's modulus than the fibre's is adopted, such as copper, then according to the definition of the Young's modulus, the metal is more difficult to be elongated

than the fibre. When a tensile force F is applied, the fibre grating will stretch while the metal coating tends to hold it back with a force $F_{\rm m}$ as shown in Fig.1. And accordingly, the fibre grating also exerts a force $F_{\rm g}$ on the metal coating. Because the two forces are a pair of counterforces, $F_{\rm g}$ is equal to $F_{\rm m}$. Thus, for the fibre grating, the total force applied on it is $F - F_{\rm m}$. Since the same change of the coating and the fibre grating will result in the same stress i.e. $\varepsilon_{x{\rm g}} = \varepsilon_{x{\rm m}}$, we have

$$\varepsilon_{x{\rm g}} = \frac{F - F_{\rm m}}{E_{\rm g}A_{\rm g}} = \varepsilon_{x{\rm m}} = \frac{F_{\rm g}}{E_{\rm m}A_{\rm m}(x)} = \frac{F_{\rm m}}{E_{\rm m}A_{\rm m}(x)}. \quad (8)$$

So the force $F_{\rm m}$ can be given as

$$F_{\rm m} = \frac{FE_{\rm m}A_{\rm m}(x)}{E_{\rm m}A_{\rm m}(x) + E_{\rm g}A_{\rm g}}. \quad (9)$$

Then the change of grating period can be obtained

$$\frac{\Delta\Lambda}{\Lambda} = \varepsilon_x = \frac{F - F_{\rm m}}{E_{\rm g}A_{\rm g}} = \frac{F}{E_{\rm m}A_{\rm m}(x) + E_{\rm g}A_{\rm g}}. \quad (10)$$

Furthermore, because of the photoelastic effect, the effective index will also change in this case. So the grating with wavelength change experiences a force

$$\frac{\Delta\lambda}{\lambda_{\rm B}} = \frac{\Delta\Lambda}{\Lambda} + \frac{\Delta n_{\rm eff}}{n_{\rm eff}} = \frac{(1 - P_{\rm e})F}{E_{\rm m}A_{\rm m}(x) + E_{\rm g}A_{\rm g}}. \quad (11)$$

And the chirp profile can be given by

$$\lambda(x) = \lambda_{\rm B}\Big(1 + \frac{(1 - P_{\rm e})F}{E_{\rm m}A_{\rm m}(x) + E_{\rm g}A_{\rm g}}\Big). \quad (12)$$

Equation (11) shows that the grating's Bragg reflective wavelength and the chirp profile also depend on the cross-sectional area of the metal coating $A_{\rm m}(x)$ when a force F is applied on it. Thus the tensile force will also induce chirp in the grating.

If further comparison is made between Eqs.(6) and (10), it can be safely concluded that the signs of the chirp induced by temperature change and tensile force are opposite.

3. Numerical method to characterize the grating with metal coating obtained by electroplating

Because of the small volume of fibre, many traditional methods of coating are not suitable for it any more. Electroplating is adopted because of its low requirement to the volume and shape of the component under electroplating. But because the fibre grating is non-electric, pre-disposal must be made on it. One of the choices is vacuum evaporation coating method, which is a widely adopted method to change the chemical and physical characteristics of industrial element. A thin layer of metal coating with uniform thickness about several μm can be coated around the grating by such a method. In this way, the electric grating can be taken as a cathode, and when the grating is immersed in the electroplating solution and suitable low current flows through it, a metallic coating will be deposited on it. Thus, a gradual change of the coating's thickness can be obtained by gradually pulling the grating out of the solution during the electroplating process, because in this case the different sections of the grating will experience different electroplating time. The above is the simple explanation of the realization of a tapered metal coating. In the following, it will be shown how to calculate the cross-sectional area of the coating obtained by this method and how to obtain the characteristics of such grating numerically.

According to the Faraday's Law of electrolysis,[11] the mass of substance produced at an electrode during electrolysis is proportional to the number of moles of electrons transferred there, so the mass of the substance produced can be calculated as

$$m = ItM/(zF_{\rm c}), \quad (13)$$

where M is the molecular weight of the metal as an anode, z is the number of transferred elementary charges, I is current, t denotes time and $F_{\rm c}$ is Faraday constant (96500 C/mol).

When the metal used as the anode is given, the parameters in the above equation except I and t will be fixed. So by adjustment of the magnitude of current and electroplating time, the mass of the deposited metal can be controlled and thereby the thickness of the metal coating can be controlled.

The widely used transfer matrix method is adopted in numerical simulations of the fibre grating, which divides the grating into a number of small sections and proceeds to sum up the electric fields as they propagate along the gratings. Obviously, it is a piecewise-uniform approach, so the main problem lies in seeking the special parameters for each small grating section. Considering the case of grating being pulled out with a uniform velocity, the numerical simulation method can be illustrated as follows.

1) Enlightened by the piecewise-uniform method, the total metal coating can be regarded as the addi-

tion of multiple layers; each layer is deposited during a time interval Δt, as is shown in Fig.2. And the cross-sectional area of each layer can be determined by the mass of the metal that deposits during the time interval. According to Eq.(11), when the current is kept unchanged, the mass of each metal layer will be equal due to the same time spent, which is denoted by ΔW.

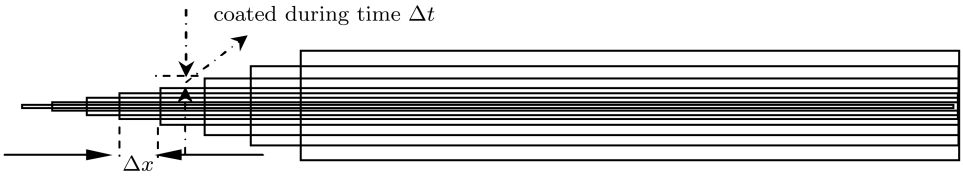


Fig.2. Schematic diagram of the calculation method by layer addition.

2) Because of the uniform velocity of v, during the time interval Δt a section of grating will be pulled out of the electroplating solution, the length of which is Δx. And the process that the grating is fully pulled out of the solution can be divided into N sections, $N = \mathrm{abs}(L/\Delta x)$. Because of the decrease of length, the cross-sectional area of each layer is not equal, though the mass of each layer is the same. The volume of each layer can be obtained by the $\Delta W/\rho$ where ρ is the density of the anode metal, and considering the decreasing length of each layer, the cross-sectional area of each layer can be obtained.

3) The cross-sectional area around the No. n section grating can be calculated by the summation of the n layers of metal coatings deposited on the grating during the former n time intervals and can be expressed as the following equation (the thickness of the uniform metal coating made by the vacuum evaporation coating method is very small so it is neglected)

$$A_{\mathrm{m}}(n\Delta x) = \sum_{i=1}^{n} \Delta W/[\rho(L - \Delta x(i-1))],$$
$$0 < n < N + 1. \tag{14}$$

After the acquisition of the gradually changing cross-sectional area $A_{\mathrm{m}}(x)$, the change of the reflective wavelength along the grating axis can be calculated according to Eqs.(6) and (11) at every diverse position, by which the grating characteristics can be finally obtained.

Table 1. Simulation parameters.

n_{eff}	$\delta_{n\,\mathrm{eff}}$	L/nm	N	ΔW/g	Apodization ratio	$E_{\mathrm{SiO_2}}$/GPa
1.447	0.3×10^{-4}	140	140	8.9×10^{-6}	0.618	94
Density of Cu/(kg/m^3)			Molecular weight of Cu/(kg/mol)		Apodization function	E_{Cu}/GPa
8.9×10^3			63.5×10^{-3}		Hamming ($H = 0.885$)	124

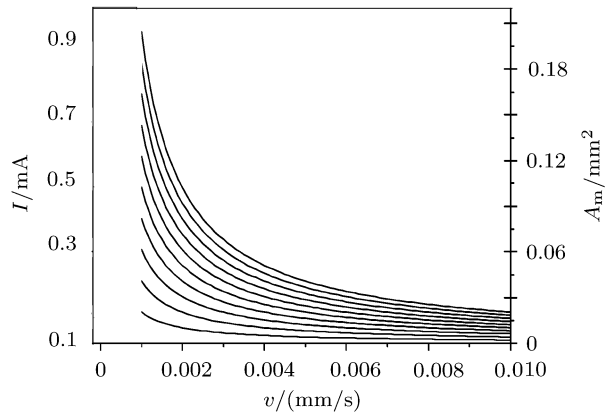


Fig.3. Relations between the cross-sectional area of metal coating and the pulling velocity during electroplating (for different electrical currents).

With the method described above, numerical simulation is carried out. The simulation parameters are listed in Table 1. Curves of the cross-sectional area of metal coating versus the pulling velocity v at different electrical currents are shown in Fig.3, from which the parameters of electroplating for coatings with desired cross-sectional area can be chosen. And the parameters ranges are chosen by considering the feasibility of experiments. Further numerical simulations of metal-coated grating characteristics show that fibre gratings exhibit dispersion tunability at different strains or different temperatures. The reflectivity and group delay characteristics of a grating experience three different temperature changes as shown in Fig.4, and the char-

acteristics of the grating under three different forces are shown in Fig.5. The grating end with thinner coating is taken as the input end in the two cases. From Figs.4 and 5, we can see that as the temperature or force is increased, the bandwidth of the grating is enlarged and the dispersion is decreased, and the sign of dispersion in the two cases are different as expected.

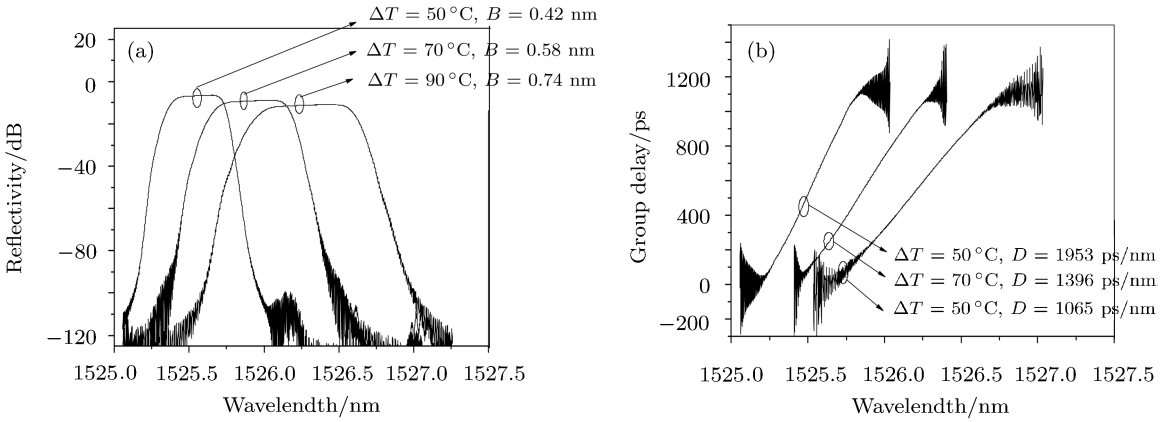


Fig.4. Reflectivity spectra (a) and group delay (b) versus λ when the grating experiences different temperature changes.

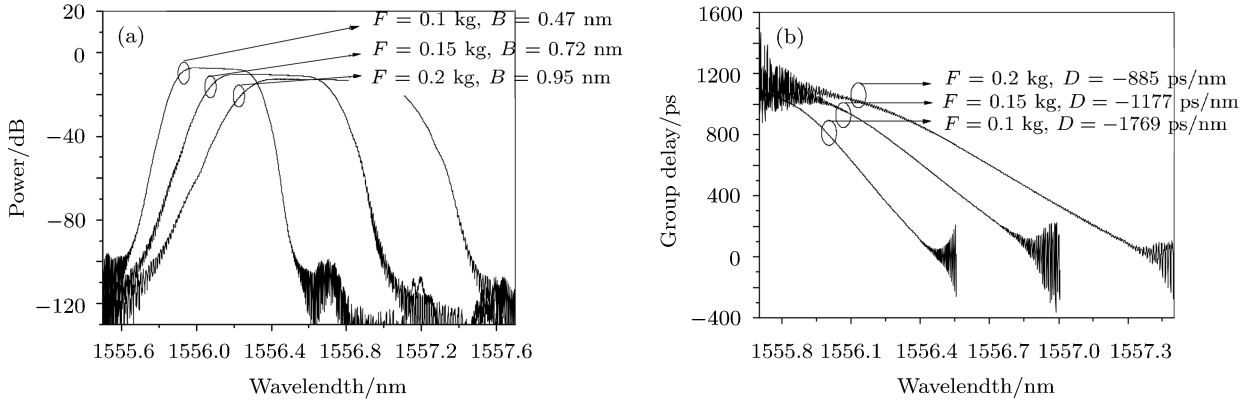


Fig.5. Reflectivity spectra (a) and group delay (b) versus λ when the grating is under different tensile forces.

Table 2. Grating characteristics comparison between experiments and numerical simulation.

	Temperature effect: $\Delta T = 70\,^{\circ}\mathrm{C}$		Strain effect: $F = 80$ g	
	Bandwidth/nm	Dispersion/(ps/nm)	Bandwidth/nm	Dispersion/(ps/nm)
Experiments	0.4	−1955	0.23	3193
Simulation	0.37	−1843	0.267	3004

4. Experiments

Based on the above analysis, experiments are carried out as in the following steps,

1) A grating is first written in hydrogen-loaded standard single-mode fibre with a uniform period phase mask. Its reflectivity spectrum is shown in Fig.6, with the central wavelength being about 1524.673 nm, and the bandwidth about 0.06 nm.

2) A thin layer of metal is coated around the grating by vacuum evaporation coating method.

3) The grating as a cathode is connected with a DC (Direct Current) source with constant currents. $CuSO_4$ solution is chosen because of the good ductility of copper. And copper is adopted as an anode. The drawing velocity should be adjusted according to the value of current to obtain a suitable thickness of the metal coating. For the experiment, $I = 1$ mA and $v = 0.008$ mm/s is adopted. A metal-coated grating is finally obtained with the maximum diameter at one end being about 0.29 mm.

4) The coated fibre grating is first put into a temperature controllable machine, and heated to 90 °C. The measured delay spectrum of the grating is shown in Fig.7.

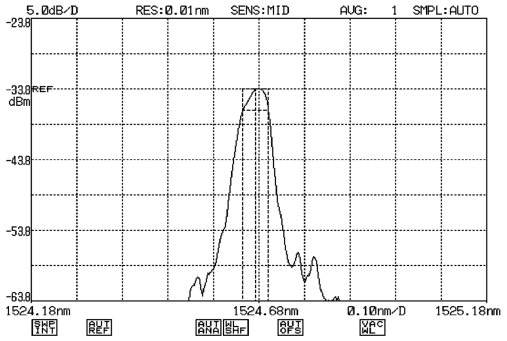


Fig.6. Reflectivity spectrum of the original uniform grating.

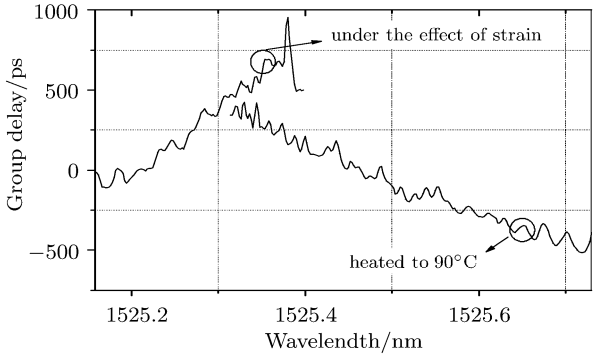


Fig.7. Comparison of inband group delay characteristics of the uniform fibre grating after electroplating when it is under strain or heated to 90 ∘C.

5) After the grating is cooled to room temperature, a force is applied on it, and the group delay in this case is shown in Fig.7. Because the grating is measured with the thicker coating end connected to the optical circulator all the time, so the signs of dispersion in the two cases are opposite as anticipated. The bandwidths and dispersions for the two cases are shown together with the numerical simulation results in Table 2, from which good agreement can be seen.

6) Figure 8 is the reflectivity spectra of another metal-coated fibre grating at three different temperatures.

The non-ideal characteristics of the grating can be attributed to the nonuniformity of the Cu coating.

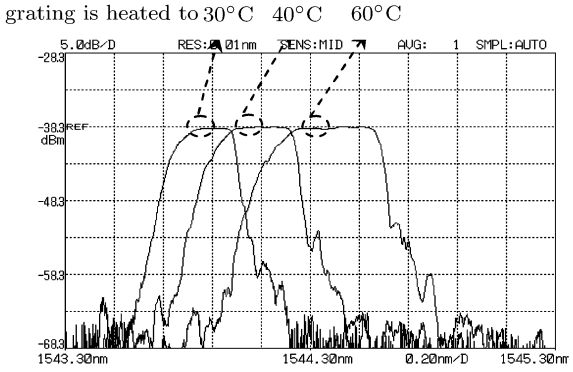


Fig.8. Reflectivity spectra of grating at different temperatures.

5. Conclusions

The temperature and strain characteristics of the uniform grating with tapered metal coating have been analysed in detail. The theoretical analysis shows the feasibility of adjustable chirp of such gratings obtained by temperature change or strain. Electroplating can be chosen to obtain the nonuniform-thick metal coating, and numerical simulation method for the characterization of such grating is proposed. The numerical simulation results agree well with the experiment results.

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