The Heterodyne Research on Transmission Signal of Three-layered Cascaded Long-Period Fiber Gratings

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ABSTRACT

Base on spectral characteristics of three-layered cascaded long-period fiber gratings (LPFGS) were analyzed by the coupled-mode theory together with the transfer matrix method, the result show that their spectra have great consistency when the length of the cascading fiber is small or the cascading position is near the end of the cascaded LPFG. The long-period fiber gratings transfer transmission conductive mode in the condition of phase matching. The wavelength, phase and amplitude of same direct transmitted signal were changed by modulation of cladding refractive index. When LPFG set in the state of phase-shift long-period fiber grating, LPFG signal can be demodulated adopting different interference detection method. The transmission spectra of phase-shift long-period fiber gratings were detected by photoelectric heterodyne, and three-layered cascaded long-period fiber gratings (LPFGS) photoelectric heterodyne method demodulate the effects of the length, position of the fiber and film parameters transformation on the transmission spectrum of the cascaded LPFG. The results show that wider scope of frequency and higher resolving ratio can be achieved adopting photoelectric heterodyne detection method with LPFG setup in phase-shift long-period fiber gratings. The combination of LPFG , photoelectric heterodyne device and microwave frequency counter can solve speed and resolving ratio problem of long-period fiber gratings sensors and form cascaded long-period fiber gratings strain and gas sensors. The dual triple-clad cascaded long-period fiber gratings demodulate frequency by electronic filter and counter on the state of different sensor. The system possesses some advantage of higher resolving ratio and adapted integrated circuit and can be produced as small volume and anti-vibration photoelectrical sensor with higher heterodyne sensitivity. The distributed sensor array can be composed by LPFG with wave division multiplexing. It possesses extensive applied foreground in environment and underwater protect inspection and detection domain.

Keywords: Guided wave optics, Cascaded long period fiber gratings, Photoelectric heterodyne, Sensor

1. INTRODUCTION

Long-period fiber grating (LPFG) is a special kind of fiber grating, satisfies the phase matching to form the transmission mode and the cladding mode with the same transmission [1]. Cascaded LPFG is one kind of fiber grating structure which (above two) the even LPFG cascaded becomes by certain. Cascaded fiber gratings will present a series of gaps stop-band and the pass-band under the certain condition with uniform spacing, the line width, high precision, will have a completely different spectral characteristics. Line width, high precision stop-band and pass-band may carry on the high sensitivity and the high resolution examination through the optoelectronic heterodyne detection.

Based on the two-layered structure [2], a sensitive thin film outside the fiber grating clad to constitute three-layered structure LPFG, LPFG cladding mode will be more sensitive to changes in refractive index, may manufacture a variety of sensors. This article based on the coupled-mode equation, uses the transmission matrix method on cascaded LPFG. The effects of the length [3], position of the fiber that connects the LPFG on the transmission spectrum of the cascaded LPFG were discussed. The high sensitivity examination which through optoelectronic heterodyne detection on the three-layered cascaded LPFG's transmission spectrum migration, may constitute chemistry, mechanics, the electricity, the optics precision sensor [4].

International Symposium on Photoelectronic Detection and Imaging 2009: Material and Device Technology for Sensors, edited by Xu-yuan Chen, Yue-lin Wang, Zhi-ping Zhou, Qing-kang Wang, Proc. of SPIE Vol. 7381, 73811R · © 2009 SPIE
CCC code: 0277-786X/09/$18 · doi: 10.1117/12.835688

2. THEORETICAL ANALYSIS

2.1 Three-layered fiber grating structure and coupling theory

Three-layered LPFG thin film level and the external agency respectively are second and the third clad. Fig.1 and Fig. 2 respectively is Three-layered fiber grating structure and the refractive index distributed schematic drawing. n_1 is the core layer refractive index, the grating region's average refractive index increment is σ, n_2 is the clad refractive index, n_3 is the sensitive thin film refractive index, n_4 is the environment refractive index. The core radius, the clad radius is known. The thin film level radius is a_1, a_2, a_3, the film thickness is $h_3 = a_3 - a_2$.

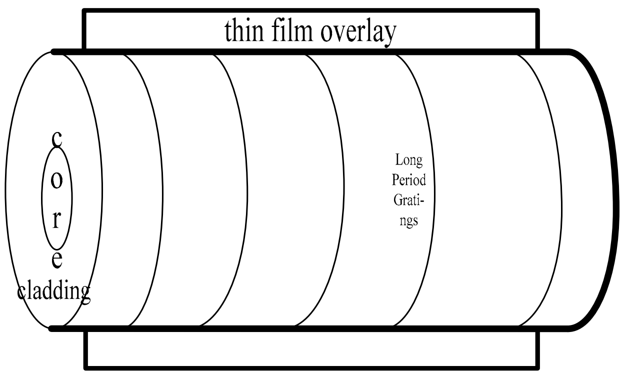

Fig.1. Three-layered fiber grating schematic drawing

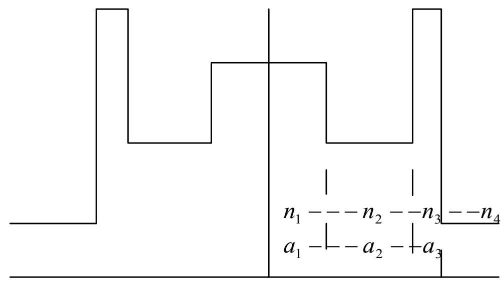

Fig.2. Three-layered fiber grating structure

According to coupled mode theory coupling mode equation[5]:

$$\frac{dA^{co}}{dz} = ik_{11-11}^{co-co} A^{co} + \frac{i}{2} \sum_{\nu} k_{1\nu-11}^{cl-co} A_{\nu}^{cl} \times \sum_{m=1}^{+\infty} \left[A_m \exp\left(-i2\delta_{1\nu-11}^{cl-co} z\right) \right] \tag{1}$$

$$\frac{dA^{cl}}{dz} = +i \sum_{\nu} k_{1\nu-11}^{cl-co} A_{\nu}^{co} \times \sum_{m=1}^{+\infty} \left[A_m \exp\left(-i2\delta_{1\nu-11}^{cl-co} z\right) \right] \tag{2}$$

Where $A^{co}, A_m, A_{\nu}^{cl}, k_{11-11}^{co-co}, k_{1\nu-11}^{ci-co}$ is respectively the oscillation amplitude of core mode z, the mth pattern's amplitude, first-order v envelope's z approaches the amplitude, the core mode from the pale pinkish purple constant, the coupling between the core mold and the first-order v clad mode.

$$k_{11-11}^{co-co}(z) = \frac{\omega \varepsilon_0 n_1^2 \sigma(z)}{2} \int_0^{2\pi} d\phi \times \int_0^{a_1} RdR \left(\left| E_r^{co} \right|^2 + \left| E_{\phi}^{co} \right|^2 \right) \tag{3}$$

$$k_{1\nu-11}^{cl-co}(z) = \frac{\omega \varepsilon_0 n_1^2 \sigma(z)}{2} \int_0^{2\pi} d\phi \times \int_0^{a_1} RdR \left(E_r^{cl} E_r^{co'} + E_{\phi}^{CL} E_{\phi}^{co'} \right) \tag{4}$$

Where ω is light wave angular frequency, $\sigma(z)$ is variable quantity of the core layer refractive index, ε_0 is the dielectric constant in vacuum, R is the radial component, E_r^{co}, E_{ϕ}^{co} is core pattern radial direction and angular electric field component, E_r^{cl}, E_{ϕ}^{cl} is first-order v envelope pattern radial direction and angular orientation electric field component. These components and the transmission constant $\beta_{11}^{co}, \beta_{1\nu}^{cl}$ are closely related, but the transmission constant needs through to solve Triple-Clad fiber grating secular equation to obtain[6]. In Triple-Clad secular equation involves the coating level refractive index and the environment refractive index n_4 [7]. $\sigma_{1\nu-11}^{cl-co}$ is malleable for the core and first-order, the inferior envelope pattern's demodulation parameter, defines as

$$\sigma_{1\nu-11}^{cl-co} = \frac{1}{2}\left(\beta_{11}^{co} - \beta_{1\nu}^{cl} - \frac{2\pi}{\Lambda}\right) \tag{5}$$

$\sigma_{1\nu-11}^{cl-co}$ =0 is long-period fiber grating clad mode coupled mode phase matching condition,

$$\left(\beta_{11}^{co} - \beta_{1\nu}^{cl} - \frac{2\pi}{\Lambda}\right) = \mathbf{0} \tag{6}$$

According to $\beta = k_0 \cdot n_{eff}$, the phase matching condition may also be represented as

$$n_{eff,co}(\lambda) - n_{eff,cl}^{\nu}(\lambda) = \frac{\lambda}{\Lambda} \quad \nu = 1,2,3,\cdots \tag{7}$$

Where $n_{eff,co}(\lambda)$ is effective refractive index of the forward transmission in the wave length λ, $n_{eff,cl}^{\nu}(\lambda)$ is effective refractive index of the first-order clad modes in the wave length λ .

2.2 Three-layered phase-shift grating characteristic

Phase-shift LPFG may regard as two section of even long period gratings (LPFG1 and LPFG2) by the length d cascaded optical fiber and the size φ for initial phase-shift separated. Its transmission characteristic T infers as follows[8]

$$\begin{bmatrix} t \\ r \end{bmatrix} = \begin{bmatrix} t_2 r_2 \\ r_2 t_2^* \end{bmatrix} \times \begin{bmatrix} \exp[i\pi(n_{eff}^{co} - n_{eff}^{cl})d/\lambda)0 & \\ 0 & \exp[-i\pi(n_{eff}^{co} - n_{eff}^{cl})d/\lambda] \end{bmatrix} \times \begin{bmatrix} \exp(i\varphi/2)0 & \\ 0 & \exp(-i\varphi/2) \end{bmatrix} \times \begin{bmatrix} t_1 r_1 \\ r_1 t_1^* \end{bmatrix} \times \begin{bmatrix} 1 \\ 0 \end{bmatrix} \tag{8}$$

Where t is the cascaded long period grating specific order clad mode's transmission amplitude, r is the core mode's transmission amplitude, t_1, r_1, t_2, r_2 expressed separately about the amplitude of LPFG partial specific order clad mode and core mode, may extract according to the transmission matrix technique, the even LPFG transmission matrix may be represented as[9]

$$\begin{bmatrix} t\,r \\ rt^{\bullet} \end{bmatrix} = \begin{bmatrix} \cos(\gamma L) + i(\sigma/\gamma)\sin(\gamma L) i(k/\gamma)\sin(\gamma L) & \\ i(k/\gamma)\sin(\gamma L) & \cos(\gamma\Delta z) - i(\sigma/\gamma)\sin(\gamma L) \end{bmatrix} \tag{9}$$

self-coupled coefficient is

$$\hat{\sigma} = \delta + \frac{\sigma_{11} - \sigma_{22}}{2} - \frac{1}{2}\frac{d\phi}{dz} \tag{10}$$

σ_{11}, σ_{22} is DC coupling coefficient, δ is demodulation parameter. $\gamma = \sqrt{\hat{\sigma}^2 + k^2}$

By (8) formula, using long period fiber grating parallel transfer rate formula $T = |t|^2$, may obtain the long period fiber grating parallel transfer rate T.

$$T = \left|\exp\{i[2\pi(n_{eff}^{co} - n_{eff}^{cl})d/\lambda + \varphi]\}t_1 t_2 + r_1 r_2\right|^2 \tag{11}$$

LPFG1 and the LPFG2 structure parameter may be the same, may also be different. If LPFG1 and the LPFG2 structure parameter is the same, then when $d = 0, \varphi = 0$, might regard as for the even long period grating; when $d = 0, \varphi \neq 0$, become the phase-shift long period grating. Therefore, the even long period grating and the phase-shift long period grating may regard as the cascaded long period grating the exceptional case.

2.3 Three-layered cascaded long period grating characteristic simulation and analysis

Three-layered cascaded long period grating's frequency spectrum characteristic is as follows

According to literature[10]simulation result, LPFG1 and the LPFG2 length respectively is L_1, L_2, L is a total length, takes L=18mm. q is the weight cascaded optical fiber position parameter, when $q = L_1/L - 0.5$, $q = \pm 0.5$, cascaded optical fiber's position in both sides, but when q=0, cascaded position in among. Two section of even long period grating LPFGI and the LPFG2 uses optical fiber parameter:

n_1=**1.458** , n_2=**1.45** , n_3=**1.57** , n_4=**1** ; a_1, a_2, a_3 respectively is **2.625** μm , **62.4** μm , **100** μm**,** film thickness is $h_3 = a_3 - a_2$ =**37.6** μm**,** core average refractive index increment is 0.0004, grating center cycle is 520 μm**.**

1. The effect of cascaded optical fiber length to cascaded grating spectrum

For cascaded LPFG, when LPFG1 and LPFG2 cascaded optical fiber length d are small (d and grating cycle is quite), cascaded LPFG transmission spectrum and phase-shift quantity size $2\pi/\Lambda$ phase-shift LPFG transmission spectrum consistent, but when d increases gradually, **(a)** $d = (3/8)\Lambda$, (b) $d = \Lambda$, (c) $d = (3/2)\Lambda$, (d) $d = 100\Lambda$; The cascaded LPFG transmission spectrum and the corresponding phase-shift LPFG transmission spectrum's deviation increases gradually, presents the completely different characteristic, that is, the cascaded LPFG transmission spectrum will present the gap to be even, line width many loss peak.

Because the electro-optical heterodyne method is insensitive to the amplitude variation, therefore has the extremely high sensitivity and anti-interference ability. The electro-optical heterodyne is most essential lies in the transmission spectrum the frequency shifting. The cascaded choice is mainly determines sensor's operating point and the working mode when optical fiber has different length.

2. Cascaded optical fiber relative position influence on cascaded grating spectrum

In the phase-shift long period grating the phase-shift position's change will have the very tremendous influence to the grating spectrum. Through simulation and found that cascaded long period grating the cascaded optical fiber position's change also has great influence to its spectrum. Take the cascaded optical fiber length of 9.5 grating cycle cascaded long period grating for example, to analyze cascaded grating transmission spectrum characteristic. When $q = 0$, $q = 0.2$, $q = 0.3$, $q = 0.4$ cascaded grating transmission spectrum and the corresponding phase-shift size for phase-shift long period grating transmission spectrum are given by literature [11].

The cascaded optical fiber relative position and the second section of cascaded grating is equal with the first section of fiber grating the starting phase, a detailed analysis is as follows:

The cascaded optical fiber length is 1.5 grating cycles, and the different phase-shift quantity for the transmission situation may see from the chart3, when the phase-shift quantity is $3\pi/4$, the right side of the main stop-band presented a small stop-band (Figure 3(a)); When the phase-shift quantity continues to increase at $3\pi/3$, transmission spectrum with even grating consistent (Figure 3(b)); When the phase-shift quantity increase to $3\pi/2$, the small stop-band has transferred to left side of the main stop-band (Figure 3(C)); Continues to increase the phase-shift quantity to

$3\pi/1.5$, the small stop-band filament light value and the original stop-band is quite, the transmission spectrum presents the symmetrical structure (Figure 3(d)). Compares with the phase-shift grating, the small stop-band appears in longer wavelength side when the cascaded grating has phase-shift and the phase-shift quantity is $3\pi/4$.

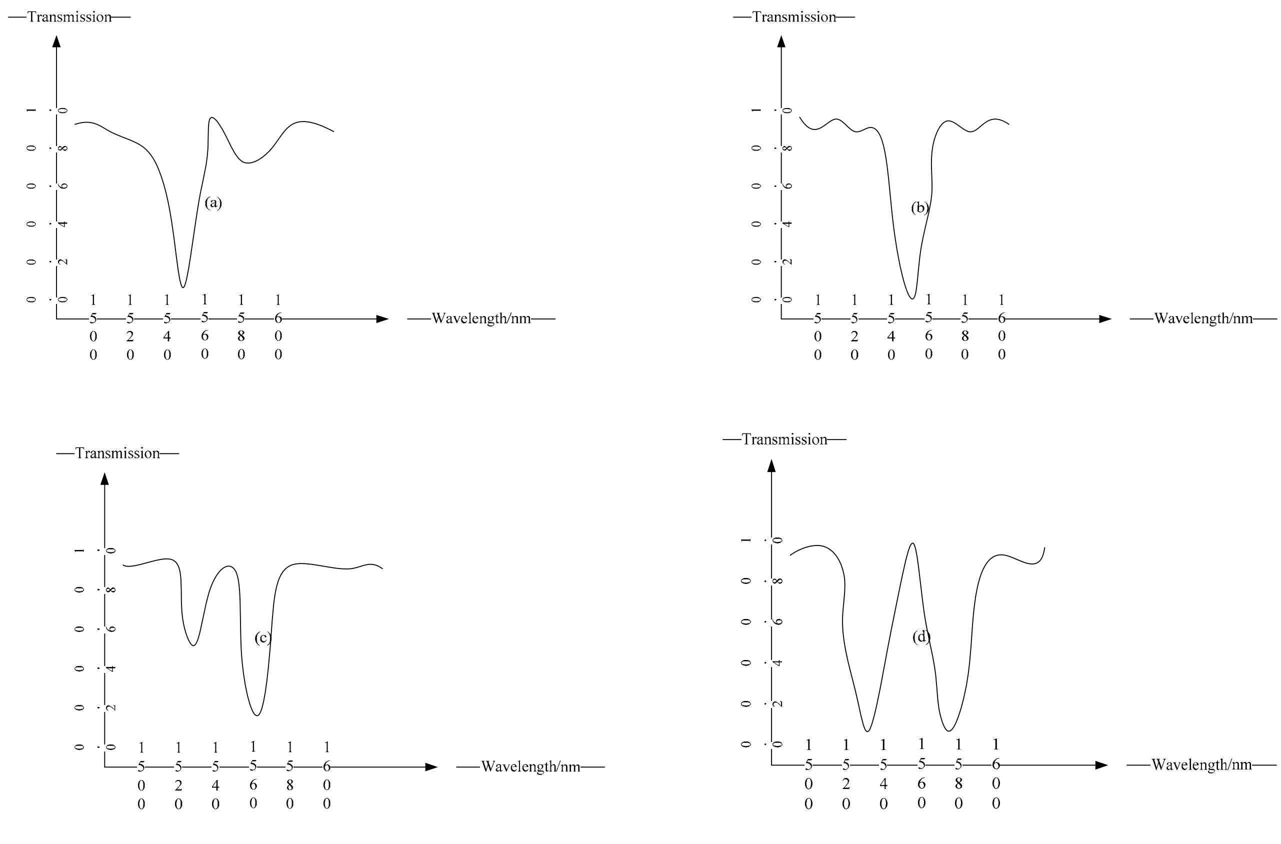

Fig.3Transmission spectra of the cascaded LPFG with different phases

The phase-shift LPFG small stop-band appears in shorter wavelength side; but when the phase-shift quantity is **$3\pi/2$**, the small stop-band appears in shorter wavelength side when the cascaded grating has phase-shift, the phase-shift LPFG small stop-band appears in longer wavelength side [10].

3. Effect of the thickness of the film on the transmission spectrum

Cascade fiber grating length of 1.5 cycles of the situation is discussed. Figure 4 shows the film thickness of 100 ~ 2300nm in the cascade grating transmission spectrum of the attenuation peak position with changes in the relationship between film thickness. As can be seen from Figure 4, film thickness of 100 ~ 425nm, 600 ~ 1500nm, 1900 ~ 2300nm range attenuation of the three peaks are increasing with the film thickness to the movement of short-wavelength, the film the thickness of the location of the transmission spectrum was less affected in the region of 600 ~ 1500nm. However, heterodyne detection is detection frequency. Therefore, the changes of film thickness can constitute sensitive fiber grating sensors.

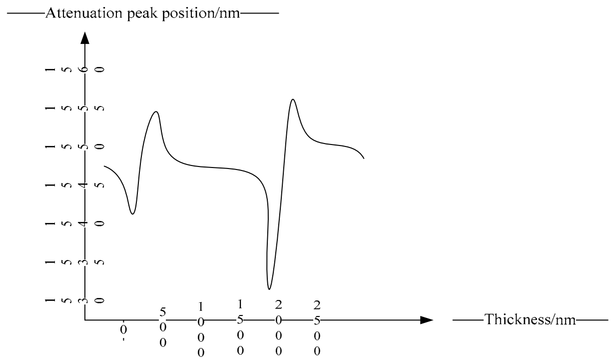

Fig.4 Effect of the thickness of the film on the transmission spectrum

4. The effect of refractive index of film on cascaded LPFG transmission spectrum

Figure 5 and Figure 6 has given change relations of weaken peak positions and the peak value of cascaded LPFG transmission spectrum with the refractive index of film between 1.57~1.97. As can be seen from Figure 5, refractive index of film is separately among 1.57~1.63, 1.65~1.79 and 1.81~197, weakens the peak is along with the refractive index increases, but to shortwave traverse. Figure 6 shows when refractive index of film between 1.72 and 1.77, the transmission spectrum has the big peak value loss [11] . It is crucial for amplitude detection, but the electro-optical heterodyne examination has nothing to do with the amplitude. Therefore we may constitute the very sensitive fiber grating sensor using the refractive index of film change.

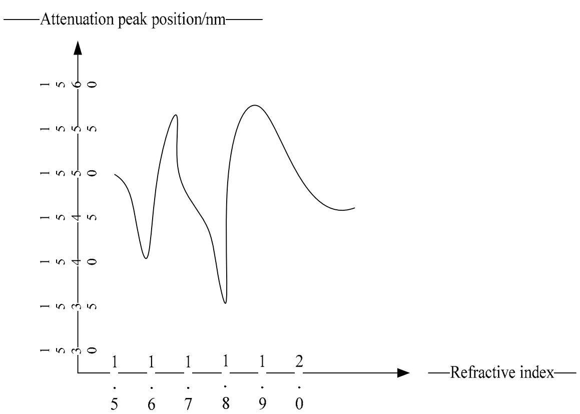

Fig.5 Effect of refractive index of the film on the transmission spectrum

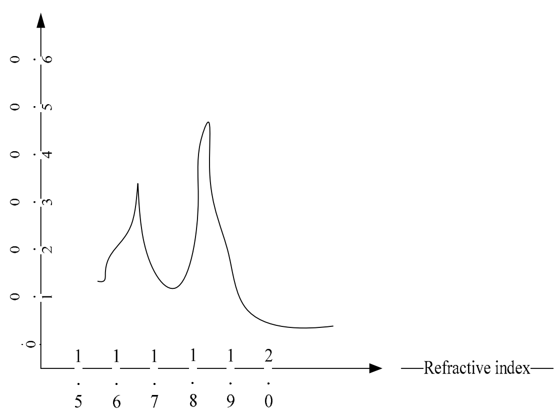

Fig.6 Effect of refractive index of the film on the peak value of the spectrum

2.4 Electro-optic heterodyne examination of long period grating

In the optoelectronic heterodyne detection technology, two bunches of frequencies differ ω_0 laser beam collimation to the photo detector surface, and each output of a linear polarization of the receive beam can be written for the light field.

$$\begin{cases} E_1 \exp(j\omega_1 t) \\ E_2 \exp\left[j(\omega_1 + \omega_0)t\right] \end{cases} \tag{12}$$

Where E_1 and E_1 are the optical field intensity; ω_1 is the fixed laser frequency, ω_0 is the frequency difference of two lasers. Two-beam mixing in the detector surface after vector synthesis, after its electro-optic transforms, and its photoelectric conversion photocurrent intensity can be expressed as

$$I(t) = E_1^2 + E_2^2 + 2\cos\phi\left[E_1 E_2 \cos(\omega_0)t\right] \tag{13}$$

Where ϕ is polarization direction angle of two bunch of light, the electro-optical receiver's frequency response cannot follow the optical frequency, therefore in the above expression oneself leaves out sum-frequency and one time frequency, only has the difference frequency item. The photoelectric current may write as

$$I(t) = \left[\frac{ek}{hv}\right]\left\{E_1^2 + E_2^2 + 2F(\omega_0)\cos\phi\left[E_1 E_2 \cos(\omega_0)t\right]\right\} \tag{14}$$

Where e is the electronic charge, k is the quantum efficiency, hv is the photon energy, $F(\omega_0)$ is detector's frequency response function. The last item is beat frequency signal with the frequency ω_0, therefore beat frequency signal power is

$$P(\omega_0) = 2\left[\frac{ek}{hv}\right]^2 E_1^2 E_2^2 R \cos^2\phi\left[F^2(\omega_0)\right]\arctan(\frac{2\pi B}{\Delta\omega}) \tag{15}$$

Where R is spectrometer's input impedance; B is the spectrometer resolution band width, b is the difference frequency signal line width (FWHM). Classical optical heterodyne measurement system is shown in Figure 3.3

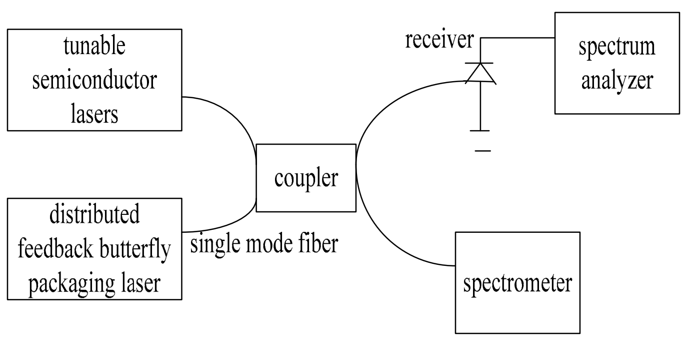

Fig. 7 Classical optical heterodyne measurement system

3. OPTICAL FIBER PHASE-SHIFT GRATING PRINCIPLE AND HETERODYNE APPLICATION

3.1 Optical fiber phase-shift grating principle

Phase-shift grating is controllable optical band-pass filter. The phase-shift grating may have two different gratings with different phase by introduction of a certain phase shift in the conventional optical fiber Bragg grating (FBG), these grating is similar to the Fabry-Perot cavity. The permission resonance wave length's light pours into to the FBG stop-band, opens a line width extremely narrow transmission window in the stop-band.

3.2 The experiment analyzes on transmission spectrum survey of optical fiber long period phase-shift grating

The difference frequency program is adjusted by phase shift degree of curved cantilever dual-type phase shift grating, see Figure 3.10, a grating frequency is shifting, but the other is by the same level size to another traverse, which output to the photoelectric detector by difference frequency, the spectral properties of the fiber Bragg grating sensors can be measured through continuous adjustment.

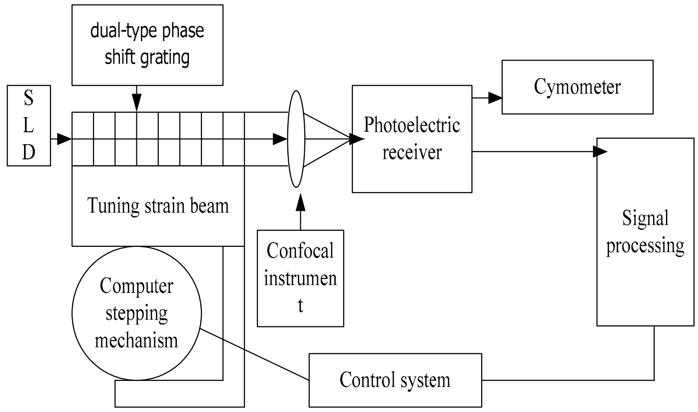

Fig. 8 The dual phase shift gratings difference frequency coherent detection system

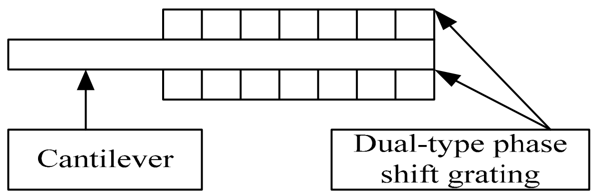

Fig. 9 Cantilever dual phase shift fiber gratings

3.3 Data and analysis

The frequency band can be calculated through under formula

$$\Delta f = c[(1/\lambda_1) - (1/\lambda_2)] = c(\lambda_1 - \lambda_2)/\lambda_1\lambda_2 \approx c\Delta\lambda/\lambda^2 \tag{16}$$

Where λ_1, λ_2 is respectively is two grating transmission frequencies, $\Delta\lambda$ is transmission frequency difference. Δf is a frequency band. The frequency testing result see Table 1.

Table 1 Frequency characteristic measure result

The steps of Stepping Motor	The upper grating frequency window(nm)	The lower grating frequency window(nm)	Theoretical calculation of the difference frequency(MHz)	Measured frequency difference(MHz)
5	1550.010	1549.999	2503	2500
10	1550.015	1549.985	3750	3740
15	1550.020	1549.980	4999	5006
20	1550.025	1549.976	6125	6137
25	1550.030	1549.970	7500	7497
45	1550.036	1549.966	8750	8743
55	1550.041	1549.960	10125	10123

60	1550.046	1549.955	11375	11369

4. THE APPLICATION OF LONG PERIOD PHASE-SHIFT GRATING

Chemistry application

The CH4 gas-sensing film can detect marine gas hydrates. The clad thin film of long period phase-shift grating is similar to gas-sensing film of CH4, methane in seawater has the influence on the long period phase-shift grating clad thin film refractive index. The same clad thin film long period phase-shift grating was sealed in the sensor without methane sea water [12], to form the differential type fiber grating and the electro-optical differential motion on the electro-optical detector, the formation of small changes in the refractive index of the phase-change conversion for the enormous changes in the electronic frequency for UHF frequencies for testing, may obtain the sea natural gas hydrate survey information [13]

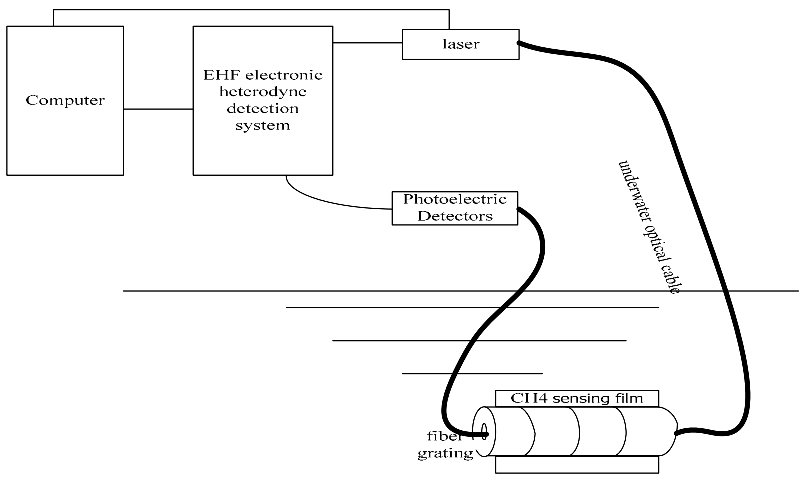

Fig.10 Marine gas hydrate structure with the CH4 gas thin film of long period phase-shift grating sensor

5. CONCLUSION

The effect of the grating parameter on Triple-Clad cascaded long period grating transmission spectrum is equal to the ordinary long period grating [14], the outer layer thin film is very useful for the sensor, may study very high sensitive optical fiber sensor, but its signal processing technology must further studies [15], because its characteristic often is nonlinear. The transmission spectrum and the reflection spectrum of the long period grating in the cascaded situation carry the sensing signal important information, The light heterodyne has high sensitivity [16], is not affected by amplitude. Both wide and narrow spectral line has the very high resolution and has the widespread application.

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