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Research of the Emulsion Concentration Sensor Based on the Long Period Fiber Grating

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Abstract: The Emulsion is a hydraulic support's transmission medium and its concentration directly affects the working life and cost of the hydraulic support and the pillar, so strict testing for emulsion concentration is necessary. Aiming to the common methods of the emulsion concentration detection and development current situation of the fiber grating refractive index sensing technology at home and abroad, This paper puts forward a new detecting methods of emulsion concentration by the long period fiber grating and analyze long period fiber grating's influential factor on the transmission spectrum on the basis of the coupled-mode theory. Finally the relationship between emulsion concentration and refractive index be get by Sensing characteristics and experiment with the characteristics of the refractive index of the emulsion, This wavelength-modulated optical fiber grating sensor has the characteristics of the simple structure, high sensitivity, anti-electromagnetism interference and corrosion resisting, which can realize the online inspection of the emulsion concentration. Test of the long period fiber grating shows that long period fiber grating can realize the emulsion detection and meet the sensitivity requirement. Transmission wavelength's change has good linear relationship with surrounding refractive index. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Long period fiber grating, Emulsion, Resonance wavelength, Transmission spectra, Refractive index.

1. Introduction

Hydraulic support in the coal mines is mechanical equipment which installed in the coal mining face. Action such as Support, promotion and demotion, shift and slide, overload protection depend on prepared emulsion with emulsified oil and concentrated solution can transfer to carry on the energy transfer and conversion. Working reliability of the hydraulic systemic the fully mechanized coal mining face directly affects high, efficient and safe production of the coal mine.

Emulsion is a hydraulic support's transmission medium and its concentration directly affects the working life and cost of the hydraulic support and the pillar plays a role of blood in the hydraulic system. Strict testing for emulsion concentration is necessary. According to the safe rules in the coal mine, the concentration ratio of emulsion should be strictly controlled in 3 % ~ 5 %. Strict testing for emulsion concentration is necessary [1-2].

At present emulsion concentration detection methods fall behind comparing with other 's country main detection methods include refractometer method and demulsification, Saccharimeter in most of the coal mine of our country. These methods need manual sampling and visual reading, with the disadvantage of the low accuracy, long time waiting after sampling which can't detect the emulsion concentration change.

Complex production condition in coal mine and severe environment underground with large coal dust result in difficult observation and big measurement error. Actual concentration perhaps changes in the meantime of sampling and detection waiting .these methods can't represent actual emulsion concentration.

Concentration sensor with the characteristics of the high sensitivity, accuracy, reliability, moisture proof and anti-corrosion is designed to detect the emulsion concentration automatically in real time, which can improve the life of the hydraulic support, hydraulic prop and hydraulic components. And reduce the cost of production as far as possible. It also can adapt to the emulsion automatic detection and matching system, which make it more precision and intelligent. Online detection of the emulsion concentration has great realistic significance.

Comparing with traditional sensor, fiber grating sensor not only have the merit of the anti-electromagnetic interference, anticorrosion, high sensitivity, broad dynamic range, light quality and small size. But also is sensitive to the surrounding medium refractive index. Which can be used in the severe condition such as powerful electromagnetic interference, flammable and combustible; and full of corrosive medium and dust pollution. Fiber grating sensor can make up the underground fiber sensor network. Sensor signal adopt wavelength encoding to assure microbend effect and coupling loss that can not affect the wavelength change [3-4].

Aiming to the common methods of the emulsion concentration detection and development current situation of the fiber grating refractive index sensing technology at home and abroad. This paper put forward a new method of detecting the emulsion concentration by the fiber grating. We study the influence of the long period fiber grating parameter on the transmission spectrum by the coupling mode theory, analyze the refractive index sensitivity characteristics of it, test sensing characteristics with different emulsion concentration and get the relationship between the resonance wavelength and the concentration.

2. Working Principle

2.1. Coupled-mode Theory

Long-period fiber gratings (LPFG) is a kind of transmission type fiber grating whose grating period is more than 100 um. It have been developed and proposed for use innumerous applications in fiber-optic sensor field. Long-period fiber grating have possess high sensitivities and can easily configured for parameter measurements, which can be widely used in the components for realizing wavelength dispersion, conversion, modulation and control of guided wavefronts in optical integrated circuits.

There have been several theoretical studies on the coupling of the core mode to the cladding and radiation. For the coupling to the cladding mode, coupled-mode theory has proved to be a powerful tool for simulation of LPFG structures. We can use the program to perform numerical simulations which are based on solving coupled mode equations that describe the interaction of guided modes by a three layer mode.

According to the coupled-mode theory, for uniform single mode LPFG, core mode coupled with first order ν^{th} –number cladding mode only be considered. In analysis fiber grating's parameter we can discuss the core mode and a cladding mode coupled.

LPFG's transmission can de deduced by a sequence of equation and expressed by the follows:

$$t = \cos^2(\sqrt{\kappa^2 + \hat{\sigma}^2}) + \frac{\hat{\sigma}^2}{\hat{\sigma}^2 + \kappa^2}\sin^2(\sqrt{\kappa^2 + \hat{\sigma}^2}) \quad (1)$$

where $\kappa = \kappa_{co-cl} = \kappa^*_{co-cl}$, which is the Ac coupling coefficient. Indicate the energy exchange degree coupled mode. $\hat{\sigma}$ is the Dc coupling coefficient which can be defined as

$$\hat{\sigma} = \delta + \frac{\sigma_{co-co} - \sigma_{cl-cl}}{2} \quad (2)$$

where σ_{co-co} is the core mode self-coupled coefficient. σ_{cl-cl} is the cladding mode's self-coupled coefficient.

$\hat{\sigma}$ is not involved energy exchange of mode, which only affect core mode 's constant of propagation. When the refractive index modulation take place in core LPFG, σ_{co-co} is great much than σ_{cl-cl} we can neglect the σ_{cl-cl}. So we can get the formula as follows.

$$\hat{\sigma} = \delta + \frac{\sigma_{co-co}}{2} = \frac{1}{2}(\beta_{01}^{co} - \beta_{1\nu}^{cl} - \frac{2\pi}{\Lambda}) + \frac{\sigma_{co-co}}{2} = 0 \quad (3)$$

where δ is the deturing fiber grating mode which can be defined as follows. It meets the resonant wavelength solution equation.

$$\delta = \frac{1}{2}(\beta_{co} - \beta_{cl}^{\nu} - \frac{2\pi}{\Lambda}) \quad (4)$$

The mode coupling between a core mode and a cladding mode occurs in the LPFG at a resonant wavelength λ_ν , which satisfies the following phase-matching condition in the followings equation.

$$\beta_0^{co} - \beta_\nu^{cl} = 2\pi / \Lambda, \quad (5)$$

where β_0^{co} and β_ν^{cl} are the propagation constants of the fundamental mode and the νth number cladding mode respectively, Λ is the grating period of the LPFG. For an each given LPFG coupling the fundamental core mode with several cladding modes at resonant wavelengths. the grating period determines the cladding modes to which light can be coupled.

The constant of propagation β depending on the wavelength, the relationship formula between β and effective refraction can be expressed as follows.

$$\beta = 2\pi n_{eff} / \lambda \tag{6}$$

where n_{eff} is the mode effective refractive index, λ is wavelength. From formula (4) (5) (6) we can get

$$\delta = \pi \Delta n_{eff} (\frac{1}{\lambda} - \frac{1}{\lambda_p}) \tag{7}$$

where λ_P is the resonant wavelength, n_{eff}^{co} and n_{eff}^{cl} are the core mode and cladding mode effective refractive index respectively. When δ equals to zero, we can get

$$\lambda_P = (n_{eff}^{co} - n_{eff}^{cl})\Lambda \tag{8}$$

where

$$\Delta n_{eff} = n_{eff}^{co} - n_{eff}^{cl} \tag{9}$$

Formula (9) indicates core mode effective refractive index minus cladding mode effective refractive index.

It can be seen that effective refractive index change can cause the resonant wavelength shift when fiber grating period remain unchanged.

The core mode and cladding mode can be coupled effectively in the resonant wavelength so that part of the core energy or all coupled into the cladding and loss. From above equation (9), we can see LPFG's transmission spectrum resonant wavelength is decided by the core mode and different number cladding mode. So many loss peaks may correspond to many resonant wavelengths for LPFG's transmission spectrum in a certain wavelength scope.

2.2. Three Layer Step Dielectric Waveguide Model

Three layer step dielectric waveguide model in the weakly guiding approximation cases is adopt. It is composed of core, cladding and external environment. Its refractive index named n1, n2 and n3.corresponding refractive index distribution can be seen in Fig. 2.

The core refractive index is determined by core refractive index and cladding refractive index. Cladding refractive index is determined by core refractive index n1, cladding refractive index n2 and environment refractive index n3.

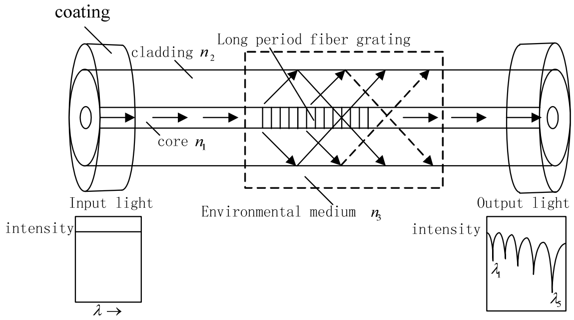

Fig. 1. Fundamental diagram of LPFG.

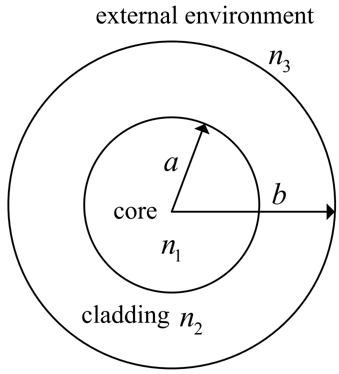

Fig. 2. Three layer model of step-index single-mode.

As can be seen in Fig. 1, the claddig effective refractive index change accordingly when environment refractive index change. If fiber grating immerse into the liquid, different concentration of liquid have different refractive index, which can cause resonant wavelength shift to short wavelength according to formula (8). The transmission light for different environment refractive index will form the loss peak in different wavelength because the core light for certain wavelength can coupled with cladding light. we can detect the liquid concentration by the fiber grating wavelength shift measurement based on this principle.

3. Refraction Characteristics of Emulsion

The refractive characteristics of the emulsion are the foundation of the concentration measurement and the fundamental gist of the sensor experiment. According to the operating requirement of the emulsion concentration in the coalmine production, tap water can be used as the liquid water. Nine different concentration emulsion are prepared by the ME10-5 emulsified oil of the ratio of 0 (pure water), 0.5 %, 1 %, 2 %, 3 %, 4 %, 5 %, 6 % and 8 % which can be seen in Fig. 3.

Fig. 3. Emulsion produced with ME10-5 emulsified oil.

Emulsion is put into the dropping bottle with the 125 ml volume to detect accurately refractive index of the emulsion with different concentration with Abbe refractometer. The corresponding refractive index of the emulsion can be seen in Table 1.

Table 1. Refractive index of the ME10-5 emulsion with different concentration.

No.	Concentration, (%)	Refractive index,
1.	0 (water)	1.3316
2.	0.5	1.3322
3.	1	1.3329
4.	2	1.3340
5.	3	1.3345
6.	4	1.3362
7.	5	1.3368
8.	6	1.3384
9.	8	1.3405

According to the relevant data, ME-5 curve of the emulsion concentration and refractive index can be drawn in the following Fig. 4.

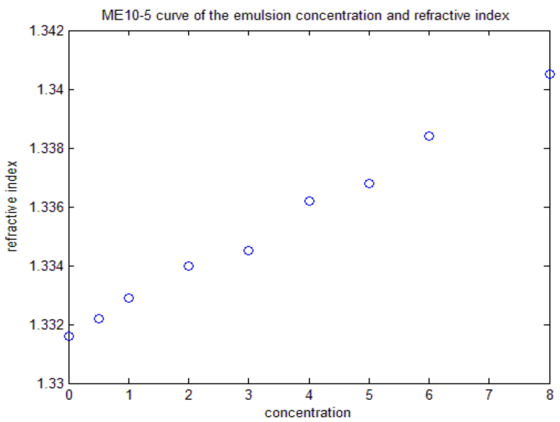

Fig. 4. Refractive index of the ME10-5 emulsion with different concentration.

As can be seen in Fig. 4, ME10-5 emulsion refractive index is increased with the increase of concentration straightly. To get the accurate emulsion concentration, segmented endpoint data is disposed by the piecewise linear interpolation method. According to the concentration interval of 0.5 % build the data table of emulsion and refractive index through which we can get the relationship between concentration and refractive index for each concentration in the interval.

4. Refractive Characteristics of Fiber Grating Sensor

4.1. The Experiment Preparation

Sensor experiment facility consists of the LPFG, FC/PC connector and fiber holder. As can be seen in Fig. 5, the fiber grating is fixed with holder at both sides. LPFG keep straightness state with pressure and hang in the air to avoid measurement error resulting from shift and bending deflection.

Fig. 5. Fiber holder.

FC/PC connector locating in the both sides of the fiber grating is linked with the light source and spectrometer. light source adopt the ASE-C with the feature of 1450 nm ~ 1610 nm wavelength scope and output power is 5 mW, output power of SLED is 6 mW and wavelength is range from 1410 nm to 1540 nm for broadband light. Spectrum analyzer AQ6317 can observe the transmission of the long period fiber grating.

LPFG are customized as follows: fiber grating length is 38 mm, fiber grating period is 480 um, fiber parameter is that cladding radius is 62.5 µm, core radius is 4.15 µm, core refractive index is 1.4681, cladding refractive index is 1.4628. To improve the sensor's sensitivity, HF acid corrosion methods are adopted to change the cladding radius to 50 µm in the grating region. Experiment step can be expressed as follows:

Firstly, solution is dropped to the LPFG with glue dropper and made it completely immersed in the solution. When an obvious loss peak appears, experiment is stopped and its transmission spectrum are observed and the resonant wavelength finally stored the data.

Secondly, emulsion are poured out of the container. Alcohol is used to clean the fiber grating and remove the fiber grating 's left liquid.

Thirdly, we can repeat the above steps, and measure other concentration emulsion's transmission spectrum and resonant wavelength. Record the different refractive index of the resonance wavelength as shown in Table 2.

Table 2. The resonance wavelength ME10-5 emulsion with different Refractive index.

No.	Refractive index	Resonant wavelength (nm)
1.	1.3316	1577.878
2.	1.3322	1577.856
3.	1.3329	1577.837
4.	1.3340	1577.824
5.	1.3345	1577.809
6.	1.3362	1577.778
7.	1.3368	1577.748
8.	1.3384	1577.728
9.	1.3405	1577.677

We can get the corresponding relationship between resonant wavelength and refractive index according to the data in Fig. 6.

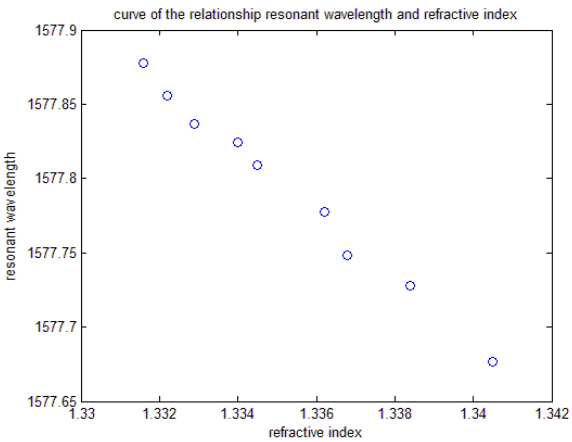

Fig. 6. The resonance wavelength ME10-5 emulsion with different Refractive index.

Now we can give the transmission spectrum for different refractive index of 1.3322 and 1.3405, which can be seen in Fig. 7.

Experiment on the refractive index sensing on the corrosive long period fiber grating can show that wavelength shift approximately is 0.2 nm in the range from 1.3316 to 1.3405 refractive index. The sensitivity of sensor is about 22.2 nm/RIU, and its resonance peak change little.

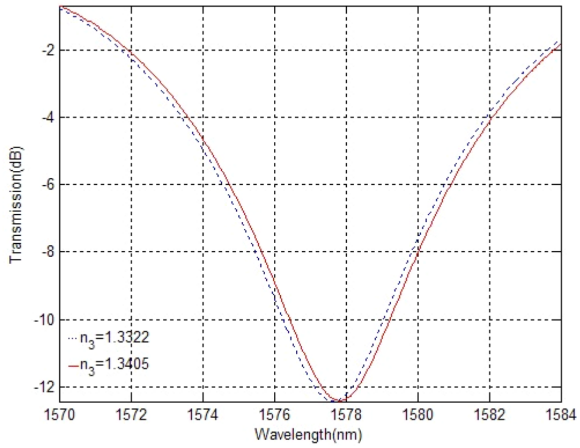

Fig. 7. Spectrum chart for different emulsion.

4.2. Temperature Sensing Characteristics

Considering the LPFG is sensitive to temperature, the temperature's influence on the transmission spectrum with concentration measurement should be considered. the LPFG temperature sensing characteristics experiment should be carried on.

Experiment step can be expressed as follows. The fiber grating is put into the incubator and need not dispose of the surface grating. control the temperature from 25 °C to 60 °C. Temperature is gradually increased and changed 5 °C every 10 minutes. the resonant wavelength change with the temperature and record relevant data can be recorded. it can be seen in Table 3.

Table 3. Table of relationship between temperature and resonance wavelength.

No.	Temperature (°C)	Resonant wavelength (nm)
1.	25	1550.16
2.	30	1549.57
3.	35	1548.99
4.	40	1548.40
5.	45	1547.80
6.	50	1547.20
7.	55	1546.61
8.	60	1546.02

According to the Table 3, the relationship curve between resonant wavelength and temperature can be shown in Fig. 8.

From Fig. 8 we can draw the conclusion that long period fiber grating's resonant wavelength shift to the short wave linearly in the range from 25 °C to 60 °C. The resonant wavelength has well linear with temperature. sensitivity of the resonant with temperature is 0.12 nm/°C through calculation.

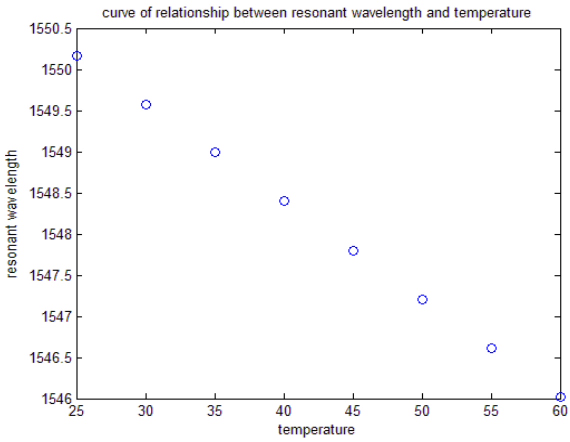

Fig. 8. The relationship between resonance wavelength and temperature for different emulsion.

5. Conclusions

Emulsion with different concentration are prepared and measured accurately by the Abberefractometer. Test of the long period fiber grating shows that long period fiber grating can realize the emulsion detection and meet the sensitivity requirement. Transmission wavelength‘s change has good linear relationship with surrounding refractive index. It can meet the requirement of sensing.

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References

[1]. T. Erdogan, Fiber Grating Spectra, *Journal of Lightwave Technology*, Vol. 15, Issue 8, 1997, pp. 1277-1294.

[2]. A. M. Vergsarker, P. J. Lemaire, J. B. Judkins, et al., Long-period gratings as band – rejection filters, *Journal of Lightwave Technology*, Vol. 14, Issue 1, 1996, pp. 58-65.

[3]. T. Erdogan, Cladding-mode resonances in short- and long-period fiber grating filters*, J. Opt. Soc. Am. A*, Vol. 14, Issue 8, 1997, pp. 1760-1773.

[4]. X. Shu, L. Zhang, I. Bennion, Sensitivity characteristics of long-period fiber gratings, *Journal of Lightwave Technology*, Vol. 20, Issue 2, 2002, pp. 255-266.