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# Compensation of Wavelength Thermal Drift for $Er^{+3}$ Superfluorescent Fiber Source by Fiber Grating

CHWEN-SHELL HO

*Department of Physics*
*Chung Yuan Christian University*
*Chung-Li 32023, Taiwan, R.O.C.*

JIUN-WOEI HUANG

*Material & Electro-Optics Division*
*Chung-Shan Institute of Science and Technology*
*Taiwan, R.O.C.*

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**ABSTRACT**

Thermal stability of mean wavelength is crucial for sources to the high precision Sagnac sensor measurement, because that the thermal drift of mean wavelength of light source decreases the linearity of scale factor of the sensor measurement. A method for designing and fabricating a temperature compensated long-period fiber grating for $Er^{+3}$ superfluorescent fiber source (SFS) has been proposed. For SFS an improved thermal stability of 0.2 ppm/°C was achieved by means of CW UV laser fabricated LPG.

**Key words:** *Superfluorescent Fiber Source (SFS), Thermal drift compensation, Long Period Fiber Grating (LPG), Sagnac sensor.*

## I. Introduction

Thermal stability of mean wavelength is crucial for sources to the high precision Sagnac sensor measurement. Typical navigational sensors demand the thermal stability to be less than 1 ppm/°C. Using an Er-doped fiber source backward pumped by a laser diode (980 nm), Hall *et al.* [1] achieved an optimum value of 3 ppm/°C by careful adjustment of related parameters, such as fiber length, power, and wavelength of the pumping source. Lefevre and co-workers [2] suggested that the sensitivity of the thermal drift could be further reduced by means of a pumping source with narrow-band filter. In this context, the long-period fiber grating (LPG) is a practical component in compensating the thermal drift of mean wavelength for $Er^{+3}$ SFS. This may be easily done by inserting LPG at the SFS output of the fiber path while keeping the other components at ambient temperature. Although such technique has been demonstrated by Patrick *et al.* [3], the spectrum is unique for each SFS. The characteristics of SFS spectrum are dependent on the configuration of the source [4], the pump power and the wavelength, the length and doping of the fiber and the polarization state [5]. Several techniques have been used to reshape the spectrum and increase the linewidth [6], in order to meet the requirements for inertial navigation applications. Therefore different SFS could require different compensation. In this work, we concern the universal method of the optimum of compensation for all kinds of SFS.

The optimum is carried out by using a predesigned LPG, made by 'point-by-point' exposure of a controlled dual bands (325 and 441 nm) CW He-Cd laser, in compensating the wavelength thermal drift for high-stability $Er^{+3}$ doped SFS.

## II. Theory

### A. Sagnac Sensor Theory

The optical scale factor of a Sagnac sensor, which is correlated to the induced phase shift $\phi_R$ and rotation rate Ω, is inversely proportional to the mean wavelength $\overline{\lambda}$ of the source by

$$\Delta\phi_R = \frac{2\pi LD}{\overline{\lambda} C}\Omega \quad (1)$$

where D and L respectively represent the diameter and length of sensing fiber coil. C is the speed of the light.

The mean wavelength $\overline{\lambda}$ and the spectral line width $\Delta\lambda$ of SFS can be determined by [1]

$$\overline{\lambda} = \frac{\int P(\lambda)\lambda d\lambda}{\int P(\lambda)d\lambda} \quad (2)$$

$$\Delta\lambda = \frac{\left[\int P(\lambda)\lambda\right]^2}{\left[\int P^2(\lambda)d\lambda\right]} \quad (3)$$

For practical applications, a stable mean wavelength less than 1 ppm/°C, and a bandwidth more than 30 nm are required.

### B. Coupled mode theory of Long Period Fiber Grating

The phase matching condition of the long period gratings between the fundamental mode and the cladding modes, can be expressed by [7]

$$\beta_{01} - \beta_{cl}^{(n)} = \frac{2\pi}{\Lambda} \quad (4)$$

where $\beta_{01}$ and $\beta_{cl}{}^{(n)}$ are the propagating constants of the fundamental mode and the clad mode respectively. Λ is the grating periodicity required to couple the fundamental mode to the *n*th-cladding mode.

Moreover, the wavelength separation between the two nearest modes *p* and *p*+1, can also be approximated by [7]

$$\delta\lambda_{p,p+1} \approx \frac{\lambda_{cut}^3}{8n_{cl}(n_{eff} - n_{cl})} \cdot \frac{(2p+1)}{a_{cl}^2} \quad (5)$$

where $a_{cl}$ is the radius of the cladding and $\lambda_{cut}$. is cut-off wavelength. From Eqs. (5) and (5), the grating periodicity and the wavelength separation between any two modes can be calculated for a specific designed spectrum.

### C. Thermal Drift Compensation Method

The methodology for compensating the wavelength thermal drift is accomplished by inserting the LPG at the SFS output of the fiber path. The spectrum for SFS can thus be obtained at various temperatures. Consequently, the difference between two spectra at separate temperatures which $S_{SFS(T_1)}$ is temperature $T_1$ and $S_{SFS(T_2)}$ is temperature $T_2$ can be expressed by

$$\Delta S_{SFS(T_1-T_2)} = S_{SFS(T_2)} - S_{SFS(T_1)} \quad (6)$$

Similarly, the variation of LPG transmittance with temperature can be expressed by

$$\Delta S_{Grating(T_1-T_2)} = S_{Grating(T_2)} - S_{Grating(T_1)} \quad (7)$$

where $S_{Grating(T_1)}$ and $S_{Grating(T_2)}$ respectively represent the spectra at temperature $T_1$ and $T_2$. A stable mean wavelength in this system could be achieved only if the following condition is fulfilled.

$$\Delta S_{SFS(T_1-T_2)} = -\Delta S_{Grating(T_1-T_2)} \quad (8)$$

The implementation of the compensation in the equation above is crucial for the design of LPG. In this work, a commercial software package, namely IFO_GRATING (Integrated and Fiber Optical Grating Design.), was used for the design of LPG. Another software, Erbium Doped Fiber Amplifier- Design (Optiwave Co.) is used to simulate the characteristics of SFS. The transmittance of LPG and the spectrum of SFS obtained from the experiments can thus be fitted by Eqs. (6)-(8).

## III. Experimental Setup

The schematic of the experimental setup is shown in Fig. 1. A fiber pig-tailing 980 nm laser diode (maximum output 130 mW) was passed through a narrow band Bragg fiber grating to pump an $Er^{+3}$ doped (3%) fiber (length 70 m) via an IWDM (Wavelength Division Multiplexer with Isolator). As the backward light of $Er^{+3}$ doped fiber reflected back through IWDM, the output of SFS is obtained. The pumping light source

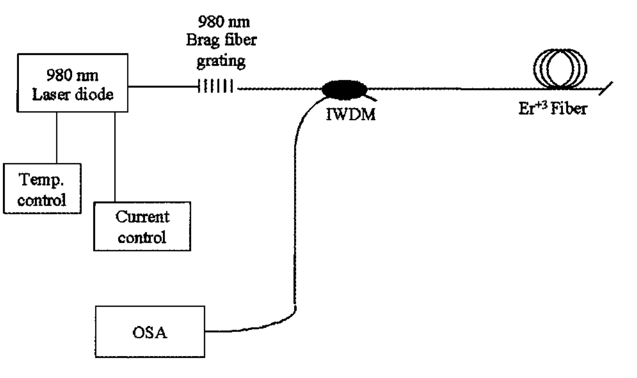


Fig. 1. The SFS light source.

can be optimized by careful adjustment of the pumping current. At constant temperature, the pumping source can be easily maintained at a steady level of less than 5 pm/°C. Subsequently; the thermal stability of the light source can be examined while the system was subjected to thermal treatment in a temperature-controlled oven.

The light source was hooked to a HP71451B Optical Spectrum Analyzer, where signal was obtained and processed by a home-designed LabVIEW program. In order to change the temperature of the source, either the whole system (including the pumping diode, IWDM and the $Er^{+3}$ doped fiber) or part of the system (IWDM or the $Er^{+3}$ doped fiber) was placed in the oven. The variations in mean wavelength, also monitored by the LabVIEW program, were recorded during both raising and lowering the temperature. All collected data were then processed and analyzed by a PC.

The experimental setup for the fabrication of LPG is shown in Fig. 2. A photosensitive fiber [8, 9] must be subjected to hydrogen treatment for at least 7 days. Prior to the experiments, 50 mm of the fibers was stripped off at both ends. Then, one end of the fiber was launched by Tungsten global source (0.3 W), while the other end was adapted to optical spectrum analyzer. To fabricate a precise LPG for compensating the thermal drift of SFS mean wavelength, a He-Cd laser was used. In an earlier study, we have stated [8] that in addition to the absorption at 248 nm, germanosilicate glass is also sensitive to the near UV region (at 330 nm). Thus, in this work, a stable LPG was obtained by 'point-by-point' exposure of the dual-bands (325 and 441 nm), CW He-Cd laser, which was operated at a total output power of 100 mW and was focused by an objective lens. The output power for the 325 and 441 nm band was 20 and 80 mW, respectively.

The target fiber was exposed behind the objective lens. Fiber grating was formed when exposed to He-Cd laser light; a shutter automatically triggered by the PC controlled the step of each periodicity. The process is completed when a desirable number of grating steps was reached. The LPG was followed by annealing treatment in an oven by slowly raising the temperature to 120°C, then maintained at the temperature for 6hrs before it was finally brought down to room temperature. Such annealing treatments were repeated at least three times.

## IV. Results

Optimization and allocation of the best focus position for the laser spot on fiber is crucial in fiber grating. By proper adjustment of the focus location, the transmittance of LPG with a grating period $\Lambda = 200\ \mu m$ was successfully achieved (Fig. 3).

The optimized condition for a fiber grating formed for 100 periods; the absorbance can be reached to 15dB. The absorbance becomes more stable after annealing treatments for three times. Before the LPG was inserted in the fiber path, a typical spectrum of the laser diode pumped $Er^{+3}$ doped fiber is depicted in Fig. 4, showing a mean wavelength of 1541.35 nm with spectral line width of 41.2 nm. The spectrum affected by thermal drift in the absence of LPG is shown in Fig. 5. The difference between two spectra of SFS at 25°C and 70°C exhibits an asymmetric sinusoidal feature, as shown in Fig. 6. On the other hand, the difference between spectra 25°C and 70°C of LPG shows an asymmetric sinusoidal function (Fig. 7) reverse to that of SFS. Due to each SFS having unique spectrum, the variation of spectrum under different temperatures vary with the SFS. To obtain optimum compensation, the compensating

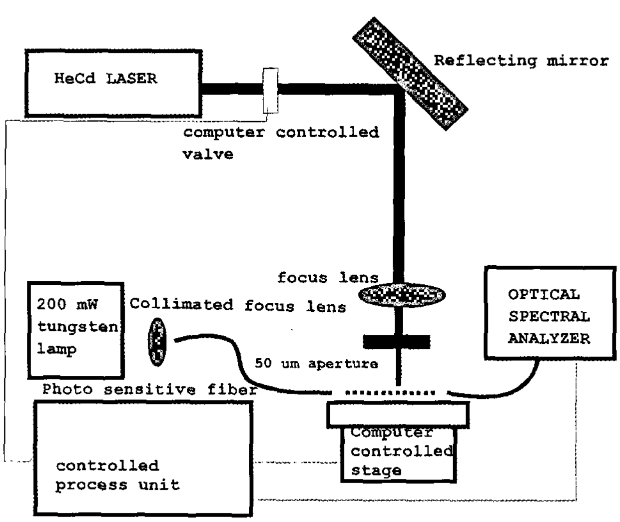


Fig. 2. LPG fabrication setup.

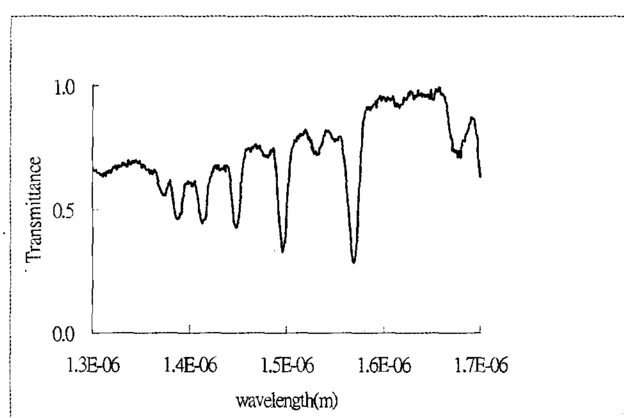


Fig. 3. LPG transmittance with $\Lambda$=200μm grating period.

LPG should be designed to fit the asymmetrical sinusoidal feature, width, depth and reflecting point as Fig. 6. The transmittance spectrum of LPG depends on the characteristics of the fiber, grating periodicity, grating length, and exposure time [5]. Therefore the fabrication parameters can be estimated using the IFO-Grating software, SFS mean wavelength stability could be obtained.

Thus, a long-period grating was designed and fabricated to compensate the thermal drift of SFS mean wavelength. As a result, the correlation between the mean-wavelength and temperature is displayed in Fig. 8, showing an overall slope of only 0.2 ppm/°C, as expected. Clearly, by inserting the designed LPG to SFS, the thermal drift of the mean wavelength was largely reduced. Moreover, as far as the packing of LPG is concerned, straight and unbendable housing is generally considered the only possible way. However, in this study, we also found that the variation rate of mean wavelength with temperature increasing and lowering is 0.028 nm/°C and 0.032 nm/°C respectively for the LPG without housing. It keeps at 0.032 nm/°C with package regardless with temperature increasing or lowering. In other words, the LPG packing applied in this study may merits important impact and practical applications.

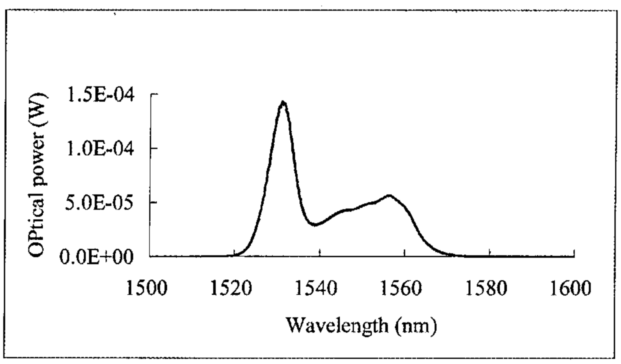


Fig. 4. The spectra of the laser diode pumped $Er^{+3}$ doped fiber.

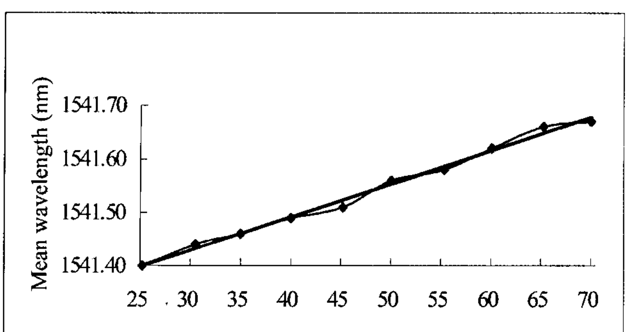


Fig. 5. The spectra of the mean wavelength drift vs. temperature.

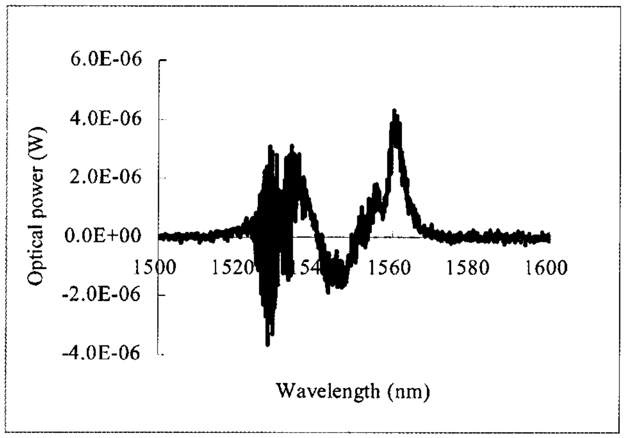


Fig. 6. The difference between two spectra of SFS at 25°C and 70°C.

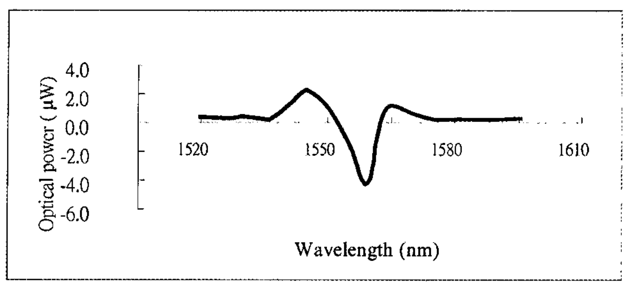


Fig. 7. The difference between two spectra of LPG at 25°C and 70 °C.

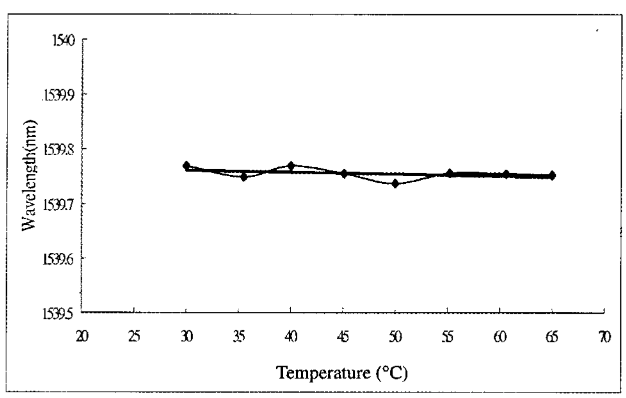


Fig. 8. The mean wavelength of SFS with designed LPG vs. temperature.

## V. Conclusion

This paper illustrated the methodology for achieving thermal stability of mean wavelength of $Er^{+3}$ SFS. For SFS, a compensated wavelength thermal stability of less than 0.2 ppm/°C can easily be obtained. This was achieved by cooling the pumping source with TE cooler and keeping WDM thermally isolated, while the other components, such as LPG, erbium-doped fiber, and isolator were in a non-thermal controlled environments. The technique for fabricating LPG presented in this study should be useful in compensating the thermal drift of mean wavelength of high precision fiber sensors.

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## 利用光纖光柵補償光纖螢光光源因溫度造成之波長飄移

何 淳 雪
中原大學應用物理研究所
中壢市普仁 22 號

黃 君 偉
中山科學研究院
桃園縣龍潭鄉

### 摘 要

高精度Sagnac感測器中，其光源之平均波長將隨溫度之改變造成飄移，此飄移量直接影響測量之標度因子，進而降低其量測精度。因此光源之平均波長對溫度之穩定性相當重要。本文設計並自製合適之長週期光纖光柵，當作補償元件，加入光纖螢光光源中，達到溫度補償效果，其溫度穩定度可達 0.2ppm/°C 。

關鍵詞： 光纖螢光光源，長週期光纖光柵，Sagnac感測器，溫度飄移。