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To cite this article: G G Pérez-Sánchez et al 2017 J. Phys.: Conf. Ser. 792 012066

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Erbium Doped Fiber Optic Gravimeter

G G Pérez-Sánchez¹, J R Pérez-Torres², J A Flores-Bravo³, J A Álvarez-Chávez³ and F Martínez-Piñón¹

¹Universidad Autónoma Metropolitana, Av. San Pablo 180, Reynosa Tamaulipas, Azc. México City 02200.
²Tecnológico de Estudios Superiores de Coacalco Av. 16 de Septiembre 54, Cabecera Municipal, Coacalco de Berriozábal, México. 55700.
³Centro de Investigación e Innovación Tecnológica-IPN, Cerrada de Cecati S/N, Santa Catarina, Azc. México City. 02250.

Email: ggps@correo.azc.uam.mx

Abstract. Gravimeters are devices that can be used in a wide range of applications, such as mining, seismology, geodesy, archeology, geophysics and many others. These devices have great sensibility, which makes them susceptible to external vibrations like electromagnetic waves.

There are several technologies regarding gravimeters that are of use in industrial metrology. Optical fiber is immune to electromagnetic interference, and together with long period gratings can form high sensibility sensors of small size, offering advantages over other systems with different technologies.

This paper shows the development of an optical fiber gravimeter doped with Erbium that was characterized optically for loads going from 1 to 10 kg in a bandwidth between 1590nm to 1960nm, displaying a weight linear response against power. Later on this paper, the experimental results show that the previous described behavior can be modeled as characteristic function of the sensor.

1. Introduction

The use of optical fiber has been proposed for several applications due to its features such as small size, lightweight, and immunity to electromagnetic interference; furthermore, in some cases optical fiber can operate as both, a sensor and the transmission media, hence avoiding the optoelectronic conversion. Optical fiber sensors have a significant importance since they offer a great sensitivity on detecting changes in temperature, pressure, strain or polarization.

Fiber Bragg gratings have been used on developing different optical fiber sensors such as long period fiber gratings (LPFG) and mechanically induced long period gratings [1-4].

In [5], an erbium doped fiber with LPFGs in cascade is used to generate an interference pattern around 1550 nm spectrum.

Gravimeters are a type of sensor intended for measuring in several knowledge areas. Such devices use different technologies as direct mass measurement, strain gage load cell, frequency shift technology, force restoration, etc. [6]. This work proposes developing a gravimeter, taking advantage of optical fiber properties.

¹ Grethell Georgina Pérez Sánchez, Depto Ciencias Básicas, Universidad Autónoma Metropolitana, Av. San Pablo 180, Reynosa Tamaulipas, Azc. Mexico City 02200.
Gravimeters are prone to be affected by factors such as local gravity, air buoyancy, tidal effects, moisture condensation, among others. Due to its properties, optical fiber offers an interesting choice when it comes to deal with the previously described factors. This work shows the experimental results of an erbium doped fiber gravimeter with three LPFGs in cascade.

2. Amplified Spontaneous Emission in Erbium doped fiber

The change on the pump and signal powers of augmented radiation along Erbium doped fiber scan be described with the following equations:

$$\frac{dP_p(z)}{dz} = -\gamma_p(z)P_p(z)$$

$$\frac{dP_s^{\pm}(z, \lambda_i)}{dz} = \pm \{ G_s(z, \lambda_i)[P_s^{\pm}(z, \lambda_i) + P_0] - G_a(z, \lambda_i)P_s^{\pm}(z, \lambda_i) \}$$

Where $P_p(z)$ refers to the pump power propagation towards $z$, and $P_s^{\pm}(z, \lambda_i)$ represents the output power in both directions, backward and forward. The absorption value for the pump is represented by $\gamma_p(z)$, and $G_s(z, \lambda_i)$ and $G_a(z, \lambda_i)$ stand for amplification factor and the absorption coefficient of spontaneous emission respectively. $P_0$ is the equivalent of the input noise power, represented by:

$$P_0 = 2h\nu_0\Delta\nu$$

Solving equations 1 and 2 considering the ASE as a weak-signal[7] the signal power solution is:

$$P_s^{+}(z, \lambda_i) = \left( \frac{G_s(z, \lambda_i)}{G_{s0}(z, \lambda_i)} \right) P_0 e^{2\int \gamma(z)dz} - \frac{G_a(z, \lambda_i)}{G_{s0}(z, \lambda_i)}$$

$$P_s^{-}(z, \lambda_i) = \left( \frac{G_s(z, \lambda_i)}{G_{s0}(z, \lambda_i)} \right) P_0 e^{\int \gamma(z)dz} - \frac{G_a(z, \lambda_i)}{G_{s0}(z, \lambda_i)}$$

Where:

$$G_{s0}(z, \lambda_i) = G_{a0}(z, \lambda_i) - G_{a0}(z, \lambda_i)$$

3. Long Period Fiber Gratings

A long period grating can attach light between the fundamental core mode and the propagation modes within the fibercladding. As a result of such attachment, a signal filtering is displayed as a power loss around a frequency. The wavelength of the filter is denominated as resonance wavelength $\lambda_m$, defined by the phase attachment condition $\lambda_m = (n_{\text{eff}1} - n_{\text{eff}2})\Lambda$, where $\Lambda$ is the periodicity of the grating, $n_{\text{eff}1}$ and $n_{\text{eff}2}$ are the effective refraction indices of the core and the cladding respectively. The coupling mode equations are:

$$\frac{dA}{dz} = \kappa B e^{i\beta_2 z}$$

$$\frac{dB}{dz} = \kappa A e^{-i\beta_1 z}$$

$$\Gamma = \beta_1 - \beta_2 - K$$

Where $A$ is the fundamental mode propagated in the fiber core, and $B$ is the propagation mode of the cladding, $\Gamma$ represents the propagation coefficient. $K$ is the coupling coefficient, and the period of the grating is defined as $\Lambda = \frac{2\pi}{\beta_1 - \beta_2}$, where $\beta_1 = \frac{2\pi n_{\text{eff}1}}{\lambda_0}$ and $\beta_2 = \frac{2\pi n_{\text{eff}2}}{\lambda_0}$ are the coefficients of the core and the cladding propagation respectively [5,8].

When light is passed from the first grating towards the second one, being $A_0$ y $B_0$ for the former and $A_1$ y $B_1$ for the latter, where A and B are initial cladding and core powers, respectively, the 7, 8 and 9 equations are solved. The relationship between the Interferometers length and wavelength selective separation can be embodied as:
\[ I(\lambda_m) = I_{\text{core}} + I_{\text{clad}} + 2\sqrt{I_{\text{core}}I_{\text{clad}}} \cos \phi \] (10)

In this equation, \( I_{\text{core}} \) and \( I_{\text{clad}} \) correspond to the core and the cladding-dominant mode magnitudes, respectively. \( \phi = 2\pi \Delta n_{\text{eff}} L / \lambda \) is the phase difference between the core and cladding modes, \( \lambda \) stands for the propagating light wavelength, \( L \) is the length of the MZI, and \( n_{\text{eff}} \) is the variation of the effective refractive indices between the core and cladding modes that propagate light. When \( \phi = (2m + 1)\pi \) the interference signal reaches its minimum. The wavelength of the \( m \)th order attenuation peak is represented by:

\[ \lambda_m = \frac{2\Delta n_{\text{eff}} L}{2m+1} \] (11)

Wavelength spacing between two interference minima can be approximated as:

\[ \Delta \lambda_m = \frac{4n_{\text{eff}}L}{(2m+1)(2m-1)} \approx \frac{\lambda_0^2}{\Delta n_{\text{eff}} L} \] (12)

Taking into account the variation of environment of the \( n_{\text{eff}} \) or the length \( L \).

4. Optical fiber gravimeter development

In figure 1 the optical fiber gravimeter setup is proposed. The gravimeter consists of a 980 nm fiber laser connected to an erbium-doped fiber section, which acts as a superluminescent source, that is an optical source with a broad spectrum that is compatible with single-mode fibers on the end side of the doped fiber an SMF28 fiber section is spliced. The output power signal is inspected in an optical spectrum analyzer. Three mechanically induced long period fiber gratings are fixed in series on the SMF28 section. Experiments with different controlled loads going from 0 kg to 10 kg in steps of 1 kg are placed on top of a plate on the gratings. For such range of weights, the power spectrum variation is well defined between 1590 nm and 1610 nm.

![Er\(^{3+}\) doped fiber and three long period gravimeter setup.](image_url)
Figure 2. Gravimeter emission spectrum Erbium doped implementing three long period gratings with changing weight.

Figure 2 shows the spectral response of the gravimeter in the 1590 nm – 1610 nm band. It is noted that power declines as the weight increases. Particularly, for the 1597 nm wavelength there is a power loss of -4.42 dB for a load increase from 1 kg to 10 kg. We selected three different wavelengths for the analysis: 1580 nm, 1597 nm and 1605 nm. Figure 3 presents the optical power variation as a function of the applied weight. We can see that the curve corresponding to the wavelength of 1597 nm behaves more linearly and it is also the wavelength at which a depression appears because of the LPG mechanism. We propose the use of this wavelength for the integration of a fiber optics gravimeter sensor with an Erbium doped superluminiscent fiber laser.
Figure 3. Optical Power variation for three different wavelengths in the fiber optic gravimeter.

Figure 4 shows the behaviour of the function relating weight versus optical power received at the 1597 nm wavelength. We observe that the function is not exactly linear. In fact, if we make a polynomial fitting, a parabolic model is more appropriate giving a maximum error of 5.2 % in the range of 3 kg to 8 kg (with a minimum error of 0.45%).

Figure 4. Weight as a function of measured optical power for the erbium doped fiber optic gravimeter.
The parabolic model obtained is:

\[ W(p) = a_0 + a_1 p + a_2 p^2 \]  
(13)

\[ a_0 = -979.7108 \]
\[ a_1 = -24.1395 \]
\[ a_2 = -0.1468 \]

\( W \) = Weight in kg.
\( p \) = Optical power in dBm’s.

The dynamic range of this fiber optic gravimeter is then for measurements from 3 to 10 kg. The resolution of this sensor is related to optical power resolution of the OSA. This resolution is about 0.01 dBm that corresponds to approximately 22 grams of weight resolution. Outside this dynamic range the error in weight increases as for example for measuring 2 kg, the error is almost 10% and in 9 kg the error is 5.7%.

The calibration for this sensor is performed by making an initial measurement with a 3 kg load and setting the measurement system to give the optical power of -74.18 dBm’s.

5. Conclusions
In summary this paper presents the results of a gravimeter optical fiber doped with erbium. The erbium section acting as a superluminiscent source and the test section formed by a standard SMF-28 single-mode fiber with three long period gratings coupled mechanically to a load from 0 to 10 kg. It was observed an excellent behavior of the sensor with an error less than 5.2% from 3 to 8 kg with a resolution of 22 grams. The results obtained by the developed device presents a parabolic decreasing behavior of the optical power as the load increases on the sensor. We have selected a 1597 nm wavelength test as this produces a relatively smooth variation which coincides with the depression wavelength peak. We believe that this optical fiber gravimeter will provide a useful instrument for the measurement of mass and weight in may scientific and industrial applications as for example in sismology, geophysics, geodesic.

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