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Pressure Sensor Based on Mechanically Induced LPFG in Novel MSM Fiber Structure

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ABSTRACT

We have proposed and demonstrated experimentally a novel and simple pressure sensor based on mechanically induced long period optical fiber gratings. We report here for the first time to our knowledge the characterization of mechanically induced long period fiber gratings in novel multimode-singlemode-multimode fiber structure. The MLPFG induced in single mode fiber and multimode fibers are studied separately and the results are compared with MLPFG induced in MSM fiber structure. MLPFG in MSM structure has much greater sensitivity. We have obtained maximum transmission loss peak of around 18 dB, and the sensitivity of pressure sensor is 8 dB/Kg.

Keywords: Mechanically Induced Grating; Pressure Sensor; Sensitivity

1. Introduction

Fiber optics sensors based on gratings are still in the development stage in laboratories and lot of work is needed to be done to promote and develop their use in advanced applications. In-fiber grating sensor technology has become one of the most rapidly progressing sensing topics of this decade in the field of optical fiber sensors. These sensors are currently emerging from the laboratory to find practical applications. Rapid progress has been made in both sensor system developments and applications in recent years.

The spectral characteristic of Long period optical fiber grating (LPFG) is more flexible as compared to fiber Bragg grating (FBG). LPFG have low insertion loss and low back reflection. It can offer the advantages of absolute measurement, high sensitivity, all-fiber in-line, small size, etc. The other advantages of LPFG sensor include simple fabrication and easiness in adjusting the resonant wavelength well within the spectrum of optical source by simply adjusting the grating period. All these attractive features of LPFGs are the strong points to push towards detail study of this device. Because of much longer Pitch Λ (almost 100 times that of FBG) the forward propagating core bounded modes and cladding-bounded modes couple to each other. Therefore there are several resonant peaks depending on the involved number of cladding modes in the interesting wavelength range and the core mode is coupled to several copropagating cladding modes.

Many methods have been demonstrated for the fabrication of LPFG. The techniques can be divided into two groups: the one that enables the fabrication of permanent gratings, and the other that allows the fabrication of reversible or mechanically induced gratings, *i.e.* by removing the external perturbation the grating disappears [1]. As the period of LPFG is of the order of micrometers, it can be induced through microbending using various mechanical means. The important advantage of this technique over other techniques is that it can be applied to any kind of fiber and is also simple, flexible and low-cost. These are very sensitive to external pressures enabling a good control over their transmission characteristics [2,3].

2. LPFG Mathematical Model

If a periodical pressure is applied on the waveguide, a long period grating is formed owing to the photo elastic effect and the microbending effect. The energy of the core mode LP_{01} is coupled into that of the cladding modes LP_{1m} if the phase matching condition as follows is satisfied [4].

$$\frac{2\pi n_{eff}^{co}}{\lambda} - \frac{2\pi n_{eff}^{cl}}{\lambda} = \frac{2\pi}{\Lambda} \quad (1)$$

where n_{eff}^{co}: is the effective index of the core mode, n_{eff}^{cl}: Is the effective index of cladding mode.

For a given periodicity Λ one can induce mode-coupling between the fundamental mode and several different cladding modes, a property that manifests itself as a set of spiky losses at different wavelengths in the transmission spectrum. In design of optical filters concatenation of gratings are required and the relatively close spaced resonance peaks of cladding modes can cause serious difficulties to generate a desired spectrum.

The coupled mode equations describe their complex amplitude, $A_{co}(z)$ and $A_{cl}(z)$ [5].

$$\begin{aligned}\frac{\mathrm{d}A_{co}(z)}{\mathrm{dz}} &= iK_{co-co}A_{co}(z) + i\frac{s}{2}K_{co-cl}A_{cl}(z)\mathrm{e}^{-i2\delta z}\\ \frac{\mathrm{d}A_{cl}(z)}{\mathrm{dz}} &= iK_{cl-cl}A_{cl}(z)\mathrm{e}^{i^2\delta z} + i\frac{s}{2}K_{cl-co}A_{co}(z)\end{aligned} \tag{2}$$

where A_{co} and A_{cl} are the slowly varying amplitudes of the core and cladding modes, $K_{co\text{-}co}$, $K_{cl\text{-}cl}$ and $K_{co\text{-}cl} = K^*_{cl\text{-}co}$ are the coupling coefficients, s is the grating modulation depth and $\delta = \pi\left(\frac{n_{eff}^{co} - n_{eff}^{cl}}{\lambda} - \frac{1}{\Lambda}\right)$ is the detuning from the resonant wavelength. The coupling is determined by the transverse fields of the resonant modes E_I and the average index of the grating Δn_I

$$K_{ij} = \frac{\omega\varepsilon_0 n}{4}\int \Delta n(r)E_i(r)E_j^*(r)\mathrm{d}r \tag{3}$$

According to coupled mode theory, grating transmission is a function of coupling coefficient K_{ij}

Assuming the detuning from resonant wavelength is balanced by the dc coupling, simplified expression for grating transmission is given by

$$T(Z) = \cos^2(KZ) \tag{4}$$

Cross coupling coefficient κ depends on the grating index profile and field profiles of the resonant modes.

The analysis given by Erdogan (Erdogan 1997) [6] is followed for the calculation of core and effective cladding refractive index.

Consider a step index fiber with three layers: central core with refractive index n_1, cladding with refractive index n_2 and the external medium with refractive index n_3 is considered. The core radius is a and the cladding is assumed to extend to infinity.

Variation of effective index n_{eff}^{co} of fundamental LP_{01} guided mode as a function of wavelength in a fiber shown in **Figure 1** is calculated by using the following equations.

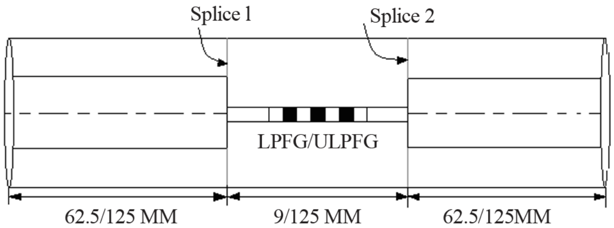

Figure 1. Multimode-Single mode-Multimode (MSM) Fiber Structure.

The normalized frequency of the fiber is given by V.

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} \tag{5}$$

Normalized index difference

$$\Delta = \frac{n_1 - n_2}{n_1} \tag{6}$$

The approximate value of index as a function of wavelength is given by Sellmeier equation

$$n^2(\lambda) = 1 + \sum_{i=1}^{M}\frac{A_i\lambda^2}{\lambda^2 - \lambda_i^2} \tag{7}$$

The commonly used waveguide parameters u and w are

$$u = \sqrt{k_1^2 - \beta_{01}^2} \tag{8}$$

$$w = \sqrt{\beta_{01}^2 - k_2^2} \tag{9}$$

where

$$k_1 = \frac{2\pi n_1}{\lambda}, k_2 = \frac{2\pi n_2}{\lambda}, \beta_{01} = \frac{2\pi n_{eff}^{co}}{\lambda} \tag{10}$$

The characteristic equation for a LP_{0m} guided propagation in a weakly guiding fiber ($n_1 \approx n_2$) is given by

$$\frac{1}{u}\frac{J_1(ua)}{J_0(ua)} = \frac{1}{w}\frac{k_1(wa)}{k_0(wa)} \tag{11}$$

where m is radial order of mode. J_p, k_p are Bessel and modified Bessel functions of order p.

Calculation of effective indices of the circularly symmetric, forward propagating cladding modes.

Consider a multimode step index structure ignoring the presence of core.

The Eigen value equation for the LP_{0m} cladding mode can then be approximated by that of a uniform dielectric cylinder surrounded by an infinite medium.

$$\left(\frac{J_1'\left(u_{cl}^{(m)}b\right)}{u_{cl}^{(m)}J_1\left(u_{cl}^{(m)}b\right)} + \frac{K_1'\left(w_{cl}^{m}b\right)}{w_{cl}^{(m)}K_1\left(w_{cl}^{(m)}b\right)}\right)\times\left(K_1^2\frac{J_1'\left(u_{cl}^{(m)}b\right)}{u_{cl}^{(m)}J_1\left(u_{cl}^{(m)}b\right)} + K_2^2\frac{K_1'\left(w_{cl}^{(m)}b\right)}{w_{cl}^{(m)}K_1\left(w_{cl}^{(m)}b\right)}\right) = \left(\frac{\beta_{cl}^{(m)}}{b}\right)^2\left(\frac{1}{\left[\left(u_{cl}^{(m)}\right)^2 + \left(w_{cl}^{(m)}\right)^2\right]}\right)^2 \tag{12}$$

$u_{cl}^{(m)}$ and $w_{cl}^{(m)}$ are the waveguide parameters for cladding

$$u_{cl}^{(m)} = \sqrt{k_2^2 - \left(\beta^{(m)}\right)^2} \tag{13}$$

$$w_{cl}^{(m)} = \sqrt{\left(\beta^{(m)}\right)^2 - k_3^2} \tag{14}$$

$$\beta^{(m)} = \frac{2\pi n_{cl}^{(m)}}{\lambda} \tag{15}$$

and

$$n_{eff}^{cl(m)} = \sqrt{n_2^2 - \left(\frac{\lambda}{2\pi}\right)^2 \left(\frac{jm}{b}\right)^2} \tag{16}$$

where jm are the roots of the Bessel function of order zero ($J_0(jm) = 0$).

3. Experiment and Results

The Reversible LPFG with period of 600 μm and length = 70 mm is induced in single mode fiber in Multimode-Single mode-Multimode (MSM) structure. Light is launched from a broadband source to the lead-in MMF, through the device (MLPFG) to the lead-out MMF and spectrally resolved using an optical spectrum analyzer (OSA) (Prolite60).

A schematic diagram of the MSM structure used in experiment is shown in **Figure 1**. The sample is prepared by splicing a 15 cm long section of SMF (SMF-28™) using a Sumitomo Type39 fusion splicer in between two MMFs (62.5/125). The loss at both splices was 0.02 dB.

The MLPFG induced in single mode fiber and multimode fibers are also studied separately. It is observed that single mode grating produced resonant loss peaks of up to ~7 dB and multimode grating produced resonant loss peaks of up to ~5 dB. The transmission spectrum of MLPFG in MSM structure is plotted in **Figure 2**, the input power spectrum is also shown for comparison purpose. The peak loss of around 17 - 18 dB is obtained, which is much greater than MLPFG in Single mode and multimode fiber.

Thus the MSM structure has a higher sensitivity than just writing the MLPFG the single mode or multimode fiber individually.

The transmission spectra of the MLPFG in SMS structure with periods of 600 μm and length L = 70 mm for different pressure applied on it is shown in **Figure 3**. We can see that a high pressure has a deep notch in the transmission spectrum and the high coupling efficiency at the resonant wavelength. The results of those measurements are given in **Table 1**, and plotted in **Figure 4**.

The curve fitting polynomial P for pressure sensor is

$$P = 0.2087x^3 - 0.9442x^2 + 2.6336x + 0.0449 .$$

Resonant loss peaks with strengths of up to ~17 dB have been generated in the MLPFG in MSM structure. There is no change in resonance wavelength with external applied pressure. Therefore MLPFGs, can find application as pressure gauges.

Sensitivity of pressure sensor = Change in transmis

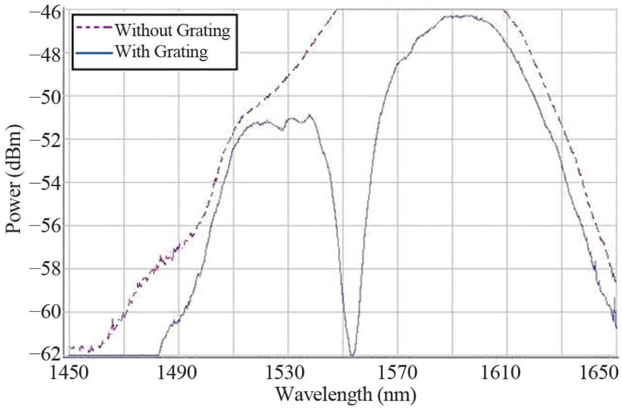

Figure 2. Spectral response of MLPFG in MSM fiber structure.

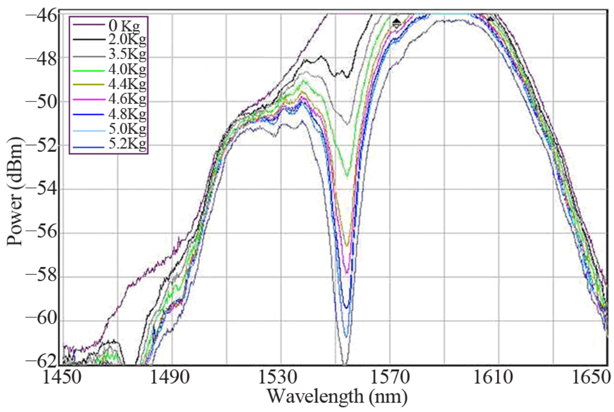

Figure 3. Complete transmission spectrum of MLPFG in MSM structure (Λ = 600 μm) with different pressures

Table 1. Transmission loss to applied pressure.

Applied Weight (Kg)	Transmission loss (dBm)
0	45.0
2.0	48.5
3.5	51.0
4.0	53.5
4.4	56.7
4.6	57.8
4.8	59.3
5.0	60.8
5.2	62.0

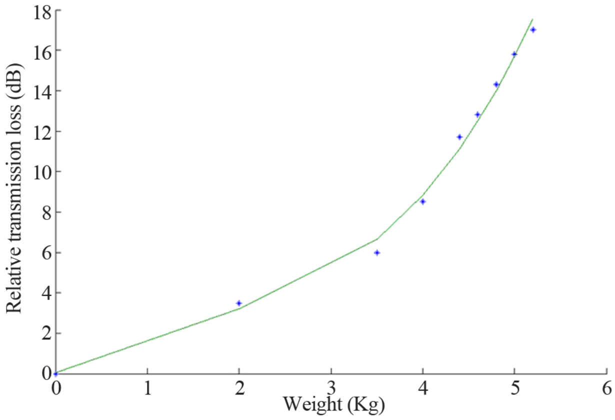

Figure 4. Response of grating to external applied pressure.

sion loss/ change in applied weight

$$S = \frac{56.7 - 53.5}{4.4 - 4.0} = \frac{3.2}{0.4} = 8\ \text{dB/Kg}$$

4. Conclusion

We report here, for the first time to our knowledge, the characterization of mechanically induced LPFGs in MSM fiber structure. MLPFG in MSM structure gives single transmission dip. Resonant loss peak strength is around 18 dB, which is much greater than maximum loss of 8 dB in Single mode MLPFG and 5 dB in multimode MLPFG. The MLPFG in MSM structure with Λ = 600 μm and length = 70 mm can be used as a pressure sensor.

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