

Optimization of reversible LPFG for sensing application



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ABSTRACT

We report here for the first time to our knowledge the characterization of mechanically induced long period fiber gratings in novel MSM fiber structure. Reversible grating of same period and length was induced in single mode fiber, multimode fiber and novel multimode-singlemode-multimode (MSM) fiber structure. The spectral response of reversible LPFG in SMF is verified experimentally as well as from simulation results and then compared with the experimental spectral response of reversible LPFG in multimode fiber and MSM fiber structure. Reversible LPFG in novel MSM fiber structure is the most optimized and suitable grating for sensing application. For this grating we have obtained single resonant wavelength over a wide wavelength range and maximum transmission loss peak of around 20 dB.

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1. Introduction

Long period fiber grating (LPFG) is the special case of FBG. It was first suggested by Vengsarkar and coworkers in 1996 [1]. LPFG can be formed by introducing periodic longitudinal perturbations of refractive index along the core of a single mode fiber. It can couple light between fundamental core mode and co-propagating cladding modes at specific resonance wavelength. The period of a typical LPFG ranges from 100 μm to 1000 μm . The cladding modes of LPFG are absorbed by the polymer coating of the fiber, hence the transmission spectrum consists of number of rejection bands at the resonance wavelengths. In contrast to the Bragg grating, LPFG does not produce reflected light and can serve as spectrally selective absorber. Therefore it is also called as transmission grating.

LPFGs formed by mechanically-induced technique have generated great interest due to its versatility in the process of fabrication. In these gratings the fiber is subject to periodical stress, which results in alternated regions under compression and stretching that modulate the refractive index via the photo elastic effect. These gratings need neither a special fiber nor an expensive writing device for fabrication. These gratings also offer advantages of being simple, inexpensive, erasable, and reconfigurable and also give flexible control of transmission spectrum.

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. In this section, the theoretical framework to describe the long period fiber gratings (LPFG) is discussed. 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 [1].

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

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 $A_{cl}(z)$ [2].

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

where A_{co} and A_{cl} are the slowly varying amplitudes of the core and cladding modes, K_{co-co} , K_{cl-cl} and $K_{co-cl} = K_{cl-co}^*$ are the coupling coefficients, s is the grating modulation depth and

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$\delta = \pi \left(n_{eff}^{co} - n_{eff}^{cl} / \lambda - 1 / \Lambda \right)$ 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

$$K_{ij} = \frac{\omega \epsilon_0 n}{4} \int \Delta n(r) E_i(r) E_j^*(r) dr \quad (3)$$

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

$$T(Z) = \cos^2(KZ) \quad (4)$$

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

The analysis given by Erdogan [3] 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 is calculated by using the following equations:

The normalized frequency of the fiber is given by V .

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

Normalized index difference

$$\Delta = \frac{n_1 - n_2}{n_1} \quad (6)$$

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

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

The commonly used wave-guide parameters u and w are given as follows:

$$u = \sqrt{k_1^2 - \beta_{01}^2} \quad (8)$$

$$w = \sqrt{\beta_{01}^2 - k_2^2} \quad (9)$$

where

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

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

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

Where m is radial order of mode. J_p, k_p are Bessel and modified Bessel functions of order p . The characteristic equation was solved numerically to obtain the curve in Fig. 1.

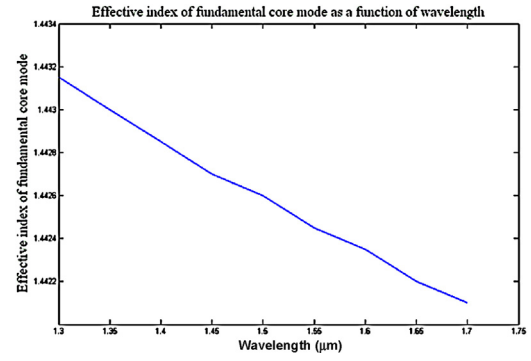


Fig. 1. Plot of effective index of the fundamental core mode as a function of wavelength. For calculation of effective indices of the circularly symmetric, forward propagating cladding modes, consider a multimode step index structure ignoring the presence of core. The eigen value equation for the LP_{0m} cladding mode can then be approximated by that of a uniform dielectric cylinder surrounded by an infinite medium.

$$\begin{aligned} & \left(\frac{J'_1(u_{cl}^{(m)}b)}{u_{cl}^{(m)}J_1(u_{cl}^{(m)}b)} + \frac{K'_1(w_{cl}^{(m)}b)}{w_{cl}^{(m)}K_1(w_{cl}^{(m)}b)} \right) \\ & \times \left(K_1^2 \frac{J'_1(u_{cl}^{(m)}b)}{u_{cl}^{(m)}J_1(u_{cl}^{(m)}b)} + K_2^2 \frac{K'_1(w_{cl}^{(m)}b)}{w_{cl}^{(m)}K_1(w_{cl}^{(m)}b)} \right) \\ & = \left(\frac{\beta_{cl}^{(m)}}{b} \right)^2 \left(\frac{1}{\left[\left(u_{cl}^{(m)} \right)^2 + \left(w_{cl}^{(m)} \right)^2 \right]} \right)^2 \end{aligned} \quad (12)$$

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

$$u_{cl}^{(m)} = \sqrt{k_2^2 - (\beta_{cl}^{(m)})^2} \quad (13)$$

$$w_{cl}^{(m)} = \sqrt{(\beta_{cl}^{(m)})^2 - k_3^2} \quad (14)$$

$$\beta_{cl}^{(m)} = \frac{2\pi n_{cl}^{(m)}}{\lambda} \text{ and} \quad (15)$$

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

where jm are the roots of the Bessel function of order zero ($J_0(jm) = 0$). Effective index difference between the fundamental core mode and cladding modes as a function of wavelength is calculated and plotted in Fig. 2. The phase match curves between the fundamental core mode and the cladding modes with different diffraction orders for a step index single-mode fiber are shown in Figs. 3 and 4.

3. Experiment and result analysis

Reversible grating is induced in a single mode fiber, from Corning (SMF28) with a period of 600 μm . The grating is characterized by passing a light from broadband source SLED, having center wavelength of 1530 nm, and the bandwidth of 69 nm, and the response is observed on optical spectrum analyzer, which is shown in Fig. 5. The resulting resonant wavelengths are compared with the theoretical results from phase matching curve shown in Fig. 3, and summarized in Table 1.

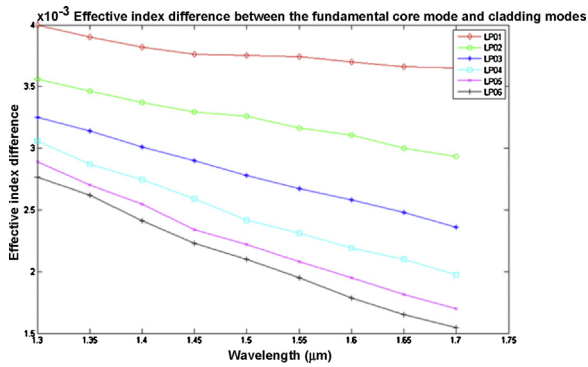


Fig. 2. Plot of effective index difference between the fundamental core mode and cladding modes as a function of wavelength.

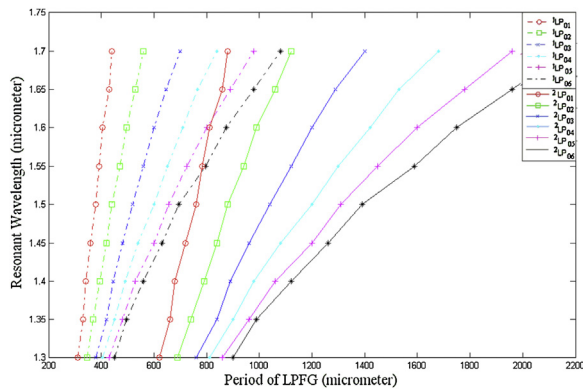


Fig. 3. Phase match curves for first and second order diffraction.

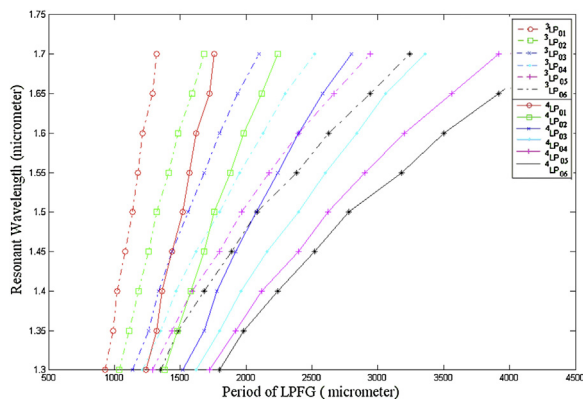


Fig. 4. Phase match curves for third and fourth order diffraction.

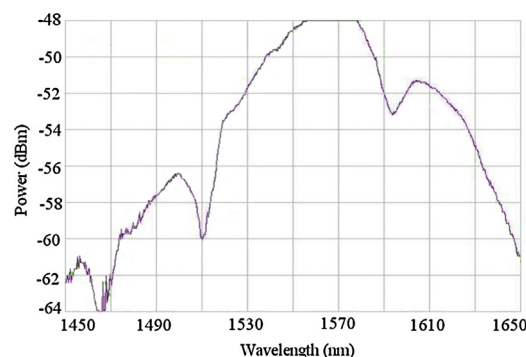


Fig. 5. Complete transmission spectrum of reversible LPFG in single mode fiber.

Table 1

Resonance wavelengths for reversible LPFG in single mode fiber.

Period = 600	Resonance wavelengths		
Theoretical	1450	1500	1600
Practical	1466	1510	1595

Essentially, fiber gratings are fibers with modulated refractive index of the core and are mostly fabricated in single mode fibers. However, recently, it has been reported that fiber gratings formed in multimode fibers also are useful in many applications [4,5].

Multimode fibers (MMFs) offer more flexibility in grating design and performance characteristics compared to single-mode fiber, multimode fibers have a merit of easy coupling with inexpensive light sources and other optical components due to their large core, so gratings in multimode are preferred to yield lower cost systems. Therefore, optical fiber gratings in multimode fibers have also received attention in recent years.

In single mode fibers there exists only one core mode (LP_{01}) and many cladding modes (LP_{1m}), the core–cladding coupling occurs at certain specific wavelengths. However, in the case of a multimode fiber with a large number of core modes and cladding modes, the core–cladding power coupling occurs at all wavelengths and the wavelength dependence is not resolved [6,7].

Reversible grating is induced in Multimode fiber (62.5/125 μm), from Corning with a period of 600 μm and then it is characterized, the spectral response is observed on optical spectrum analyzer, which is shown in Fig. 6.

As compared to reversible LPFG in single mode fiber, these gratings have more number of transmission dips in the spectral response; the corresponding resonant wavelengths are summarized in Table 2.

Single mode gratings gave better response (resonant loss peaks of up to ~ 7 dB) as compared to multimode gratings (resonant loss peaks of up to ~ 5 dB). But multimode fiber has its own advantages because of large core diameter, such as easy coupling with inexpensive light sources and other optical components. Therefore the system cost reduces. Thus to combine the advantages of both single mode fiber and multimode fiber, a novel MSM fiber structure is prepared to induce the reversible LPFG.

A schematic diagram of the MSM fiber structure used in experiment is shown in Fig. 7. The sample is prepared by splicing a 15 cm long section of SMF (SMF-28TM) using a Sumitomo Type39 fusion splicer in between two MMFs (62.5/125). The loss at both splices was 0.02 dB.

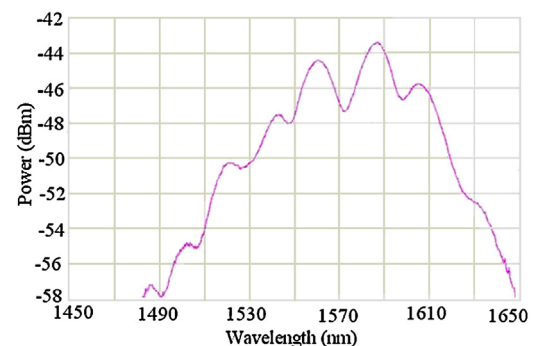


Fig. 6. Complete transmission spectrum of reversible LPFG in multi mode fiber.

Table 2

Resonance wavelengths for reversible LPFG in multimode fiber.

Grating period	Resonance wavelengths for different modes (nm)						
600 μm	1491	1505	1525	1545	1572	1597	1626

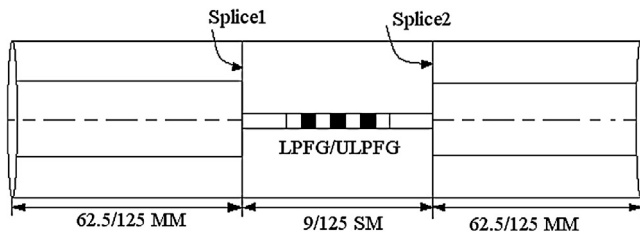


Fig. 7. Multimode-Single mode-Multimode (MSM) fiber structure.

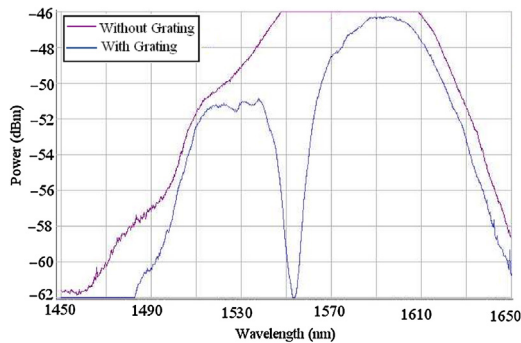


Fig. 8. Spectral response of MLPFG in MSM fiber structure.

The reversible LPFG with period of $600 \mu\text{m}$ and length = 70 mm is induced in single mode fiber in MSM structure. Light is launched from a broadband source to the lead-in MMF, through the device (reversible LPFG) to the lead-out MMF and spectrally resolved using an optical spectrum analyzer (OSA) (Prolite60).

The transmission spectrum of reversible LPFG in MSM fiber structure is plotted in Fig. 8, the input power spectrum is also shown for comparison purpose. The peak loss of around 20 dB is obtained, which is much greater than maximum loss of 8 dB in single mode MLPFG and 5 dB in multimode fiber.

4. Conclusion

The theoretical framework to describe the long period fiber grating (LPFG) is discussed and then the comparison of theoretical and practical resonance wavelengths for reversible LPFG in single mode fiber is done. It is found that the practical results are in close agreement with theoretical values.

As compared to LPFG in single mode fiber (SMF28), LPFG in multimode fiber have more number of transmission dips in the spectral response.

Reversible LPFG in MSM fiber structure gives single transmission dip. Resonant loss peak strength is around 20 dB, which is much greater than maximum loss of 8 dB in single mode reversible LPFG and 5 dB in multimode fiber.

Thus the response of grating is very impressive. There is a single resonant wavelength over a wide wavelength range (only one cladding mode satisfying Bragg condition). This offers extremely wide tunable range without worrying about overlap among different bands in sensing application.

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