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Long Period Fiber Grating Based Novel Optical Fiber Devices

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Abstract | Long Period Gratings (LPGs) in optical fibers have found wide applications as wavelength filters, sensors etc. This paper presents our recent work on superimposed LPG designs which show very interesting transmission characteristics. By appropriate design, these are expected to find applications as wavelength filters, sensors, channel isolation filters and wavelength interrogators. Adiabatic passage of light between two core modes via an intermediate cladding mode without much excitation of the cladding mode is shown as an interesting application.

1 Introduction

Long Period Fiber Gratings (LPFG) are periodic perturbations in the fiber, which enable coupling between two modes propagating along the same direction (co-directional coupling) and find applications in various devices such as filters, sensors etc.[1,2] Most commonly, the periodic perturbations are usually realized by periodic refractive index variations within the core of the fiber; other techniques such as periodic bending of the fiber axis can also lead to coupling between co-propagating modes. Such periodic axial perturbations can also be brought about by launching acoustic waves.[3] Depending on the application, LPGs can induce coupling between co-propagating core modes (guided modes) or between core (guided) and cladding (non-guided) modes.

Efficient coupling among co-propagating modes requires satisfying the phase matching condition given by[4]

$$\beta_2 - \beta_1 = K \tag{1}$$

where β_1 and β_2 are the propagation constants of the two interacting modes and K represents the spatial frequency of the periodic perturbation. For co-propagating modes the difference in propagation constants is small, and thus the spatial frequency required for coupling is small leading to reasonably large grating periods of typically a few hundred micrometers. Apart from this, the coupling coefficient between the interacting modes must be finite. Thus, if the periodic perturbation is azimuthally symmetric then light from LP_{01} core mode can only couple to LP_{0m} modes of the fiber.

A simple LPFG coupling from the core mode to cladding modes has several dips in transmission spectra brought about by the coupling out from the core mode of the fiber to various cladding modes. One can device more complex grating structures with appropriate spatial frequency spectra that can exhibit very interesting characteristics. In this connection, superimposed gratings, wherein more than one grating is written over the same region of the fiber, have been investigated earlier.[5] Concatenated LPFGs and Turn Around Point (TAP) grating geometries have also been studied for various applications.[6]

In this paper we present our recent results on different designs of LPFGs for applications in the area of wavelength filter design and sensing.

2 Three Mode Interaction Using LPFG

A standard LPG leads to coupling among two modes which satisfy phase matching condition. It is possible to have interaction among more modes by having gratings that are characterized by more than one spatial frequency. Thus, when there are two non-identical overlapping gratings, then such a periodic structure will be characterized by many different spatial frequency components, and it is then possible to induce simultaneous coupling among more than two modes using the different spatial frequency components. The refractive

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index perturbation $\delta n(z)$ within the core can be described by:

$$\delta n(z) = \Delta n(z) + \Delta n_1(z)\sin(K_1 z) + \Delta n_2(z)\sin(K_2 z) \qquad (2)$$

where K_1 and K_2 are the spatial frequencies of the two overlapping gratings with peak index variations given by $\Delta n_1(z)$ and $\Delta n_2(z)$ respectively, and $\Delta n(z) = (\Delta n_1(z) + \Delta n_2(z))$, is the average increase in refractive index within the core. In the most general case, these index variations can also depend on z, in which case the coupling coefficient becomes z dependent. With such a structure, we can have different interaction schemes:

a. In the scheme referred to as *cascaded coupling*, power launched into the core mode couples to another (guide or cladding) mode via another intermediate mode. This interaction process is very similar to the evanescent coupling between three parallel waveguides.[7]
b. In a different scheme involving three mode interaction, simultaneous coupling from the core mode to two different cladding modes is possible.

The transmission characteristics of these two types of overlapping gratings are different and can be used for different applications.

Using standard coupled mode theory with three mode coupling, the coupled mode equations can be written in the following matrix form:

$$\frac{d}{dz}\begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix} = \begin{pmatrix} -i2\delta_{12} & \kappa_{12} & 0 \\ -\kappa_{12} & 0 & \kappa_{23} \\ 0 & -\kappa_{23} & -i2\delta_{23} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix} \qquad (3)$$

where a_1, a_2 and a_3 are proportional to the mode amplitudes of the three interacting modes, κ_{ij} represent coupling coefficients between the *i*th and *j*th modes, while δ_{ij} represent the phase mismatch between the *i*th and *j*th modes.

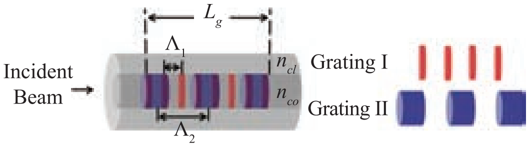


Figure 1: Schematic of SLPG: Grating I and Grating II are the two superimposed gratings with different spatial frequencies.

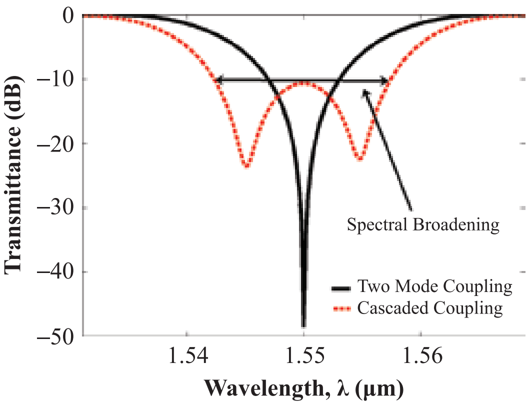


Figure 2: Comparison between transmission spectra for two mode and three mode (cascaded) coupling in fiber.

3 Cascaded Coupling

As an example, we consider two overlapping non-identical LPGs in an optical fiber such that one of them leads to coupling between the core mode and a second intermediate mode (which could either be another core mode or a cladding mode), and the second LPG is assumed to lead to coupling between the intermediate mode and a third mode (core or cladding mode) (see Fig. 1). For simulations, both the gratings are assumed to be of equal length and phase matched at the same wavelength of 1550 nm, the coupling coefficients are assumed to be $\kappa_{12} = 4.67 \times 10^{-5}$ µm^{-1} and $\kappa_{23} = 9.01 \times 10^{-5}$ µm^{-1}. In order to satisfy the phase matching conditions at the same wavelength, the grating periods are chosen to be $\Lambda_1 = 176.65$ µm and $\Lambda_2 = 368.43$ µm.

Figure 2 shows a comparison between the transmission spectra of a single grating and superimposed LPG pair in cascaded configuration. The solid curve is the standard case of two mode coupling, while the dashed curve is for the cascaded coupling. Compared to the single grating case, the cascaded configuration shows significant spectral broadening.[8] SLPG offers designers with more degrees of freedom, wherein grating strength, grating length and wavelength of operation can be selected to obtain the desired transmission spectra. Figure 3 shows the flexibility in the design for achieving various transmission spectra by choosing appropriate parameters (phase matching wavelength, coupling coefficient, length of the grating etc.) of the two superimposed gratings.

Gain flattening filters are very important components in optical amplifiers. As an example, cascaded coupling can be used to design filters with complicated transmission spectra. Figure 4 shows an application of the proposed cascaded grating design for a gain flattening filter when used with erbium doped fiber amplifiers. By

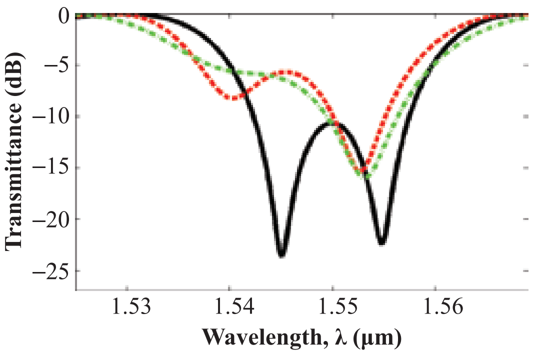


Figure 3: Transmission spectra of superimposed LPGs with different design parameters showing the flexibility of the design. The solid black curve denotes the transmission spectrum for gratings at equal grating lengths and same operating wavelengths. The red dashed curve denotes gratings at equal lengths operating at different wavelengths. The green curve shows two gratings with different lengths and operating wavelengths.

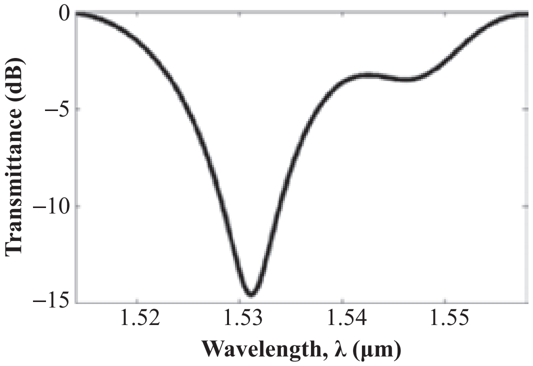


Figure 4: Cascaded LPFG design with a transmittance variation designed for gain flattening in erbium doped fiber amplifiers.

appropriate design of the various parameters it is possible to generate different transmission spectra, and such a design should find applications in gain flattening or attenuation flattening of wavelength filters, wavelength filters with flat top, etc.

4 Superimposed LPG Based Refractive Index Sensor

Superimposed grating designs offer us with the possibility of tuning the transmission spectrum and also improve the sensitivity of sensors based on them. In contrast to cascaded coupling, two overlapping LPGs can lead to coupling from the core mode to two different cladding modes leading to interesting applications.

In order to achieve high sensitivity of the sensor, the two gratings in the superimposed configurations are chosen such that coupling from the core mode occurs to two different cladding modes, one of which is on the lower branch of the turn-around point (TAP) while the other mode is on the higher branch of the TAP. Figure 5 shows the variation of phase matching wavelength with the grating period in a single mode fiber in which LP_{01} couples to LP_{09} and LP_{012} modes. In the case of the first coupling, increase in the ambient refractive index leads to decrease in resonance wavelength, while in the latter case it leads to an increase in the resonance wavelength. For a given ambient refractive index the superimposed LPG would have two transmission dips corresponding to the two coupling processes. As the ambient refractive index increases, one of the peaks moves to shorter wavelengths while the other peak moves towards longer wavelengths, thus the two attenuation dips shift in mutually opposite directions.

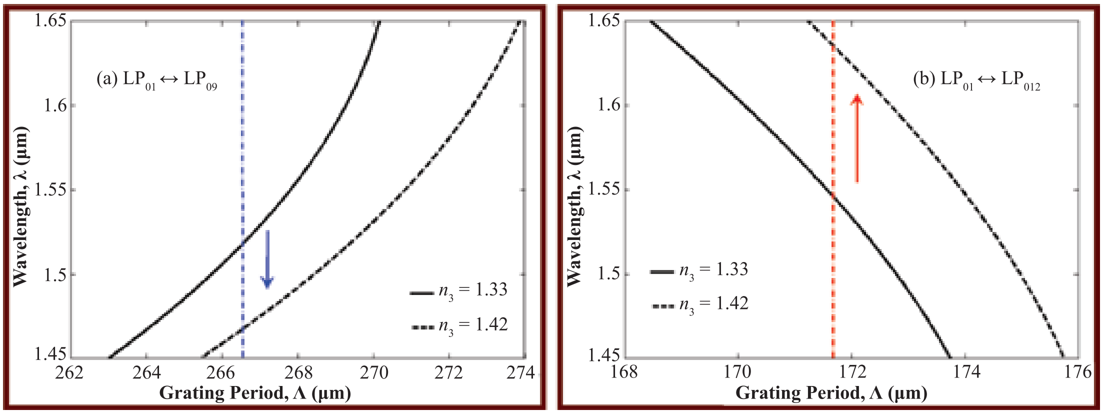


Figure 5: Dependence of the phase matching wavelength of the coupling from (a) LP_{01} to LP_{09} mode and (b) from LP_{01} to LP_{012} mode. Note that as the ambient refractive index increases, the two phase matching wavelengths shift in opposite directions.

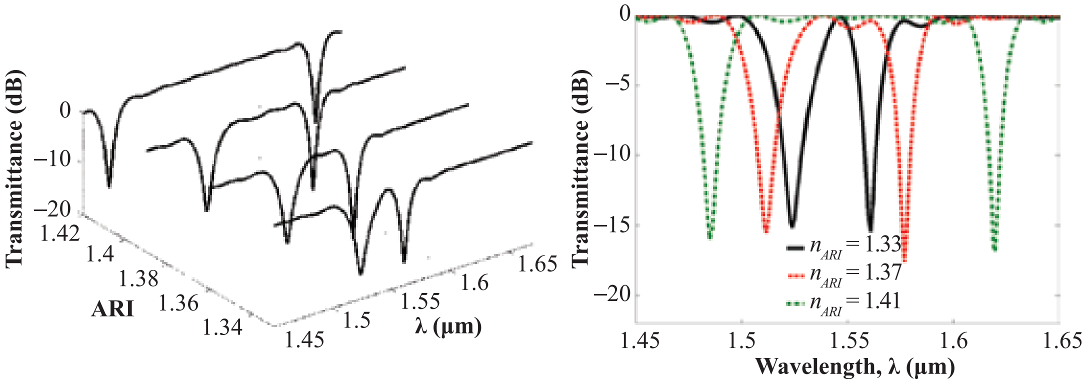


Figure 6: Transmission spectra corresponding to a three mode interaction process in a single mode fiber as the ambient refractive index is changed.

Sensitivity is defined as the variation in separation of the two attenuation dips with respect to the change in ambient refractive index:

$$S = \frac{d|\Delta\lambda^H - \Delta\lambda^L|}{dn_{ARI}} \text{ nm/RIU} \qquad (4)$$

where $\Delta\lambda^H$ and $\Delta\lambda^L$ denote the shift in the wavelength for higher and lower branch, respectively. The involvement of two cladding modes leads to much increased sensitivity of the device as a sensor.

Figure 6 shows the transmission spectra corresponding to a three mode interaction process in a single mode fiber as the ambient refractive index is changed.[9] The sensor shows a sensitivity range of 500–1545 nm/RIU over a wide span of refractive index ~1.33–1.42 providing an index resolution of ~10^{-6}–10^{-7} if wavelength discriminators with a minimum detectable change of 1 pm are used.

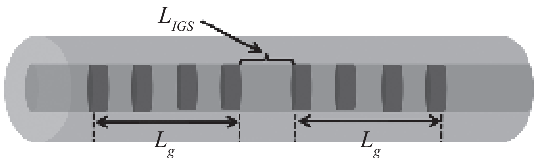


Figure 7: A concatenated LPG with an inter-grating spacing.

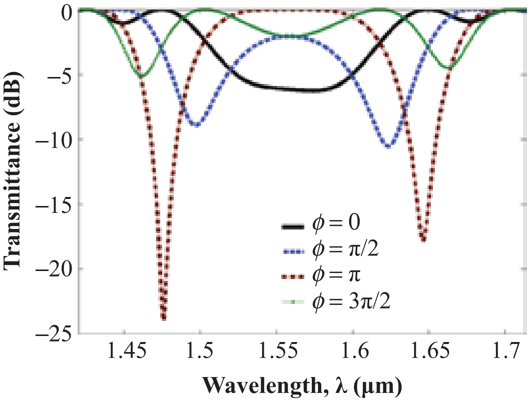


Figure 8: Dependence of the transmission spectrum with different accumulated phase difference between the core and cladding modes. Appearance of two separated dips is clearly seen.

5 Highly Sensitive Refractive Index Sensor Using TAP LPGs in an Optical Fiber

LPGs operating at the turn around point (TAP) of the phase matching curve have shown high sensitivity as a sensor. The conventional scheme uses LPG designed at TAP, the transmission spectrum is very broad making the spectral (wavelength) interrogation technique impossible. This scheme works on intensity interrogation which is relatively inefficient. Introduction of an intergrating space between two identical LPGs (see Fig. 7) designed to operate at the TAP leads to a splitting of the transmission dip into dual dip rejection bands. Light launched into the core mode gets partially coupled to the cladding mode, due to the interference between the light propagating in the core mode and the cladding mode through the inter-grating space, transmission spectrum splits into dual bands. This working is similar to the Mach-Zehnder interferometer. The double dip transmission spectrum can probe two measurand quantities simultaneously, such as temperature and refractive index with high sensitivity.

Figure 8 shows the variation of transmission spectrum of a pair of identical LPGs with variation in the spacing between the two gratings. φ is

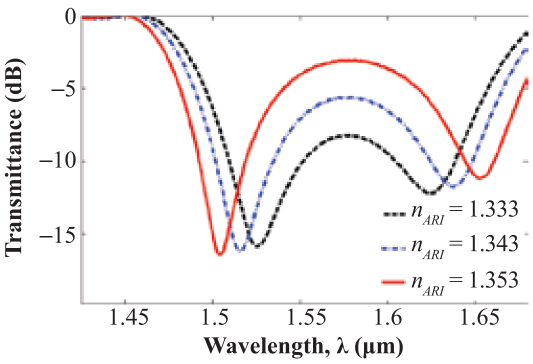


Figure 9: Variation of transmittance of a TAP-LPFG with an inter-grating space for different refractive indices of the ambient medium.

the phase difference accumulated over an inter-grating space due to the difference in the propagation constants of the two participating modes. Depending on the amount of phase shift we can obtain well separated pair of dips.

Figure 9 shows the variation of the designed transmission spectrum with changes in ambient refractive indices with the prospects of using this scheme in refractive index sensing.[10] The scheme shows a very high sensitivity of 2500 nm/RIU in the RI range 1.333–1.353.

6 Coherent Tunneling Adiabatic Passage Using Superimposed LPGs

In three level atomic systems, it is possible to transfer atoms from the ground state to another energy state via a third energy state with very little excitation of the intermediate level. Such a technique, called STImulated Raman Adiabatic Passage (STIRAP), is a well known technique in a three level atomic systems. This technique has been used in three waveguide directional couplers to transfer light between the two outermost waveguides via the intermediate waveguide without much excitation of the intermediate waveguide.[11] This technique can be used to design novel devices in guided wave optics.

A similar scheme can be realized using superimposed LPGs in which the refractive index perturbations of the two gratings vary along the length of the fiber.[12] Like in the case of STIRAP process, the z-variation of the coupling coefficient needs to be counter intuitive for the scheme to work.

As an example adiabatic coupling from LP$_{01}$ mode to LP$_{02}$ mode is considered in a two mode fiber via the cladding mode LP$_{017}$. There is no direct coupling between modes LP$_{01}$ and LP$_{02}$, while the coupling coefficients between LP$_{01}$ and LP$_{017}$ and LP$_{02}$ and LP$_{017}$ are taken to be *z*-dependent. The chosen *z*-variation of the coupling coefficients are shown in Fig. 10. The power in each of the modes along the length of the device can be calculated using the coupled mode theory. Figure 11 shows the power variation in the three modes along the length of the device. The design is such that power launched in LP$_{01}$ mode gets coupled to LP$_{02}$ mode without much excitation of the LP$_{017}$ mode. As can be seen from Fig. 10, the z-variation of coupling coefficient is counter intuitive since at the input end the coupling between LP$_{02}$ and LP$_{017}$ is strong, although power is incident in the LP$_{01}$ mode. The power variation in the three modes when input light is coupled into the LP$_{02}$ mode is completely different; the observations are very similar to the case of interaction of three level systems with photons.

Such an analogous phenomenon in guided wave optics, besides helping us to visualize quantum phenomenon, is usually difficult to

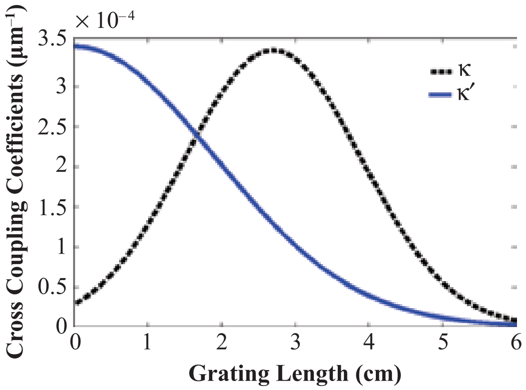


Figure 10: Variation of the coupling coefficients κ_{12} (black solid curve) and κ_{23} (blue dashed curve) with respect to the grating length to achieve adiabatic conversion from LP$_{01}$ to LP$_{02}$ mode.

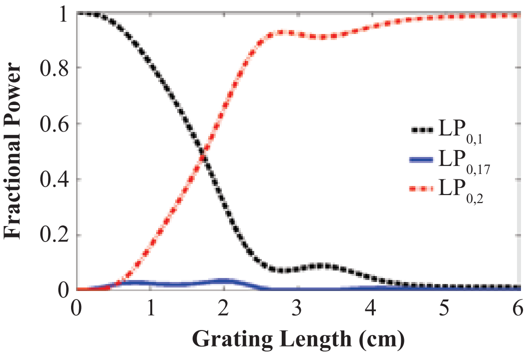


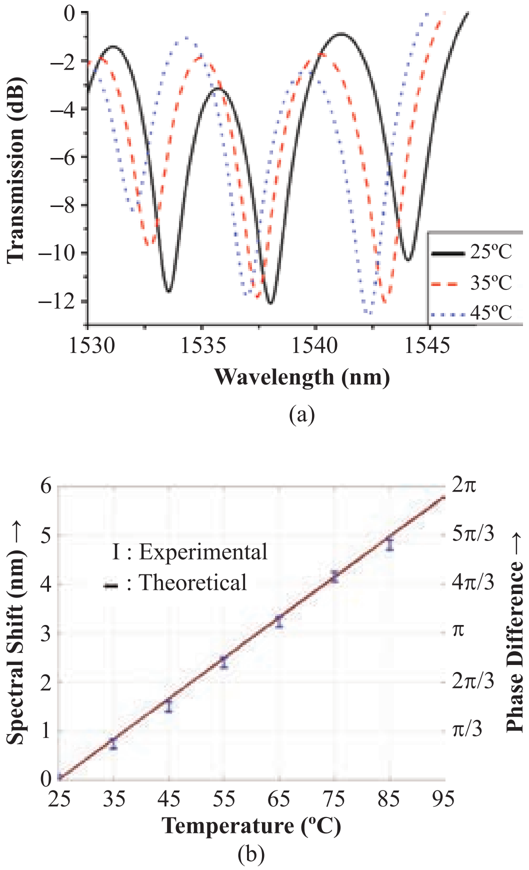
Figure 11: Variation of power in the three participating modes with respect to propagation distance for the designed SLPGs showing adiabatic transfer of power.

demonstrate, and can be used in various guided wave optical devices.

7 WDM Channel Isolation Filter Based on Concatenated Chirped LPG

Concatenated LPGs have been studied earlier for various applications. Two concatenated chirped LPGs effectively form a Mach-Zehnder interferometer over the range of wavelengths for which coupling is enabled by the chirped gratings. Because of the phase difference developed between the core-mode and the cladding-mode, a periodic transmission spectrum is observed at the output of the second grating. By varying the grating period, chirp or the total device length, the periodicity of the interference pattern can be changed. In such a structure if an *inter-grating space* (IGS) is introduced between the two chirped LPGs, it is possible to realize a wavelength-tunable WDM channel isolation filter. The IGS provides an extra phase difference between the core and cladding modes, changing which for example, by means of heating this space, the filter channels can be tuned to a desired wavelength. Further, since the gratings are not being perturbed, the proposed WDM filter provides an increased linear operational tuning range with not much effect on the transmission spectrum.

The experimentally obtained transmission spectrum over a wavelength range of 1530 nm to 1546 nm, at three different temperatures of the heated section is plotted in Fig. 12(a). Figure 12(b) shows a comparison of measured and simulated variation of spectral shift due to temperature change, where an excellent match is observed.[13]



(b)

Figure 12: (a) Experimentally measured spectral transmission of a concatenated LPFG. (b) Comparison of experimental values with simulation.

8 Summary

Superimposed LPGs show very interesting transmission characteristics and can be designed to possess different transmission spectra. With the control of the transmission spectrum possible with superimposed gratings, these should find applications in sensing, wavelength filtering, gain flattening etc. This paper presents some of our recent results in different designs of LPFGs using superimposed gratings. It is shown that using such superposed grating pairs it is possible to achieve devices showing adiabatic behavior.

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