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Cascaded coupling: Realization and application to spectral maneuvering

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ABSTRACT

In this paper, we analyze a scheme of three mode coupling referred to as cascaded coupling in an optical fiber by employing a pair of superimposed long period gratings. In the cascaded coupling process, interaction between two modes takes place via an intermediate mode. We show that cascaded coupling gives us an additional degree of freedom to tune the transmission spectrum to achieve desired spectral features by appropriate choice of grating parameters i.e. grating strength, length and wavelength of operation. Applications of the proposed design to achieve flat wavelength response and gain flattening filters for erbium doped fiber amplifiers are presented.

1. Introduction

Fiber gratings are periodic perturbations along the length of a fiber that enable coupling between either co-propagating modes (long period gratings) or between contra-propagating modes (short period gratings) [1,2]. A combination of n ($n \geqslant 2$) gratings effective over the same spatial domain exhibits coupling between $n+1$ modes and is known as superimposed grating. Over the past few decades, such gratings have been studied to observe three mode interactions in waveguides [3–6]. Different schemes of three mode interactions in waveguides enable one to realize different functionalities.

One of the earliest examples of three mode interaction with dual gratings is a double periodic harmonic variation in planar geometry that enabled interaction of forward propagating core mode with backward propagating core as well as cladding modes [3,4]. Interactions between the core modes of three waveguides were shown to provide a fine wavelength response [5]. Coupling between two single-mode cores through cladding mode of the structure in a coupler was experimentally observed to find applications as add/drop multiplexers, signal dividers, etc. [6]. Multiple mode conversion was demonstrated to achieve homogenous beam shaping for an SMF-28 fiber using superimposed LPGs [7]. Recently, coupling between two core modes through a cladding mode was studied in a waveguide for add/drop multiplexing [8]. This design was realized by two parallel identical rectangular long period gratings with equal cross coupling coefficients.

In this paper, we analyze a similar scheme of three mode interaction in an optical waveguide such as an optical fiber or an integrated optic channel waveguide; the three modes could be core modes or cladding modes or any combination of them. The structure is such that power launched in a core mode gets coupled to another mode (referred to as primary coupling) followed by subsequent coupling from this mode to another mode (referred to as secondary coupling). This cascading of light from a core mode to a third mode via an intermediate mode is referred to as cascaded coupling and can be achieved by a pair of superimposed long period gratings. The proposed scheme is easily adaptable to coupling between three core modes of any fiber design that allows multiple guided modes and is independent of other constraints such as special fiber designs of few mode fiber profiles having modes that operate close to the cut-off values to execute suitable tailoring [9]. Also, it is possible to achieve a flat wavelength filtering response over a broad band at any desired wavelength rather than a specific wavelength defined close to the turning point of fixed fiber geometry [10]. Other schemes such as concatenated or cascaded grating structures are less compact and become more susceptible to mechanical perturbations than a grating with superimposed structure [11,12].

As an example of this coupling process, we consider coupling using long period gratings among the core mode and two cladding modes of a standard single mode fiber. We observe the influence of grating strengths corresponding to the pair of non-identical LPGs for cascaded coupling that leads to broadening of the conventional transmission spectrum achieved using two mode interaction. We show that the transmission spectrum can be maneuvered by choosing different phase matching wavelengths as well as grating lengths for the two gratings and multiple functionalities may be achieved.

In Section 2, we present the analysis for three mode coupling and in Section 3 simulation results for fiber have been discussed followed by the conclusions.

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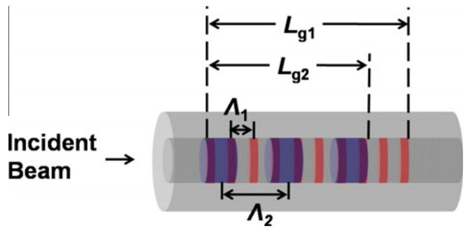

Fig. 1. Schematic of two superimposed long period gratings in fiber.

2. Analysis

We consider an optical fiber in which two overlapping long period gratings lead to interaction among three modes such that one grating leads to coupling from mode 1 to mode 2 (intermediate mode) and the second grating to coupling from mode 2 to mode 3. In order to use the standard coupled mode theory [13], we write for the total field within the coupled region as:

$$E(x,y,z) = a_1(z)E_1(x,y)e^{-j\beta_1 z} + a_2(z)E_2(x,y)e^{-j\beta_2 z} + a_3(z)E_3(x,y)e^{-j\beta_3 z} \tag{1}$$

where E_1, E_2, E_3 are the normalized transverse electric field distributions of the three interacting modes and, $a_1(z)$, $a_2(z)$, $a_3(z)$ are the modal amplitudes of the modes denoted by the subscripts. Power is assumed to get coupled from the first mode to the intermediate second mode enabled via grating I (primary coupling) and further from this second mode to the third mode by grating II (secondary coupling). With the chosen phase matching conditions, we assume that there exists no direct coupling between first and third modes. Using the standard slowly varying approximation, we obtain the following coupled mode equations:

$$\begin{aligned} \frac{dA_1}{dz} &= \kappa A_2 - j2\delta A_1 \\ \frac{dA_2}{dz} &= -\kappa A_1 + \kappa' A_3 \\ \frac{dA_3}{dz} &= -\kappa' A_2 + j2\delta' A_3 \end{aligned} \tag{2}$$

where $A_1(z)$, $A_2(z)$ and $A_3(z)$ are defined through the following equations:

$$\begin{aligned} a_1 &= A_1 e^{j2\delta z}; \\ a_2 &= A_2; \\ a_3 &= A_3 e^{-j2\delta' z}; \end{aligned} \tag{3}$$

δ and δ' are the detuning parameters for grating I and grating II respectively, given by:

$$\begin{aligned} \delta &= \frac{1}{2}\left(\beta_1 - \beta_2 - \frac{2\pi}{\Lambda_1}\right); \\ \delta' &= \frac{1}{2}\left(\beta_2 - \beta_3 - \frac{2\pi}{\Lambda_2}\right); \end{aligned} \tag{4}$$

κ and κ' are the cross-coupling coefficient terms of grating I and grating II respectively:

$$\begin{aligned} \kappa &= \frac{\omega\varepsilon_0}{4} n_{co} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \Delta n_1 E_1(x,y)E_2(x,y)dxdy; \\ \kappa' &= \frac{\omega\varepsilon_0}{4} n_{co} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \Delta n_2 E_2(x,y)E_3(x,y)\,dx\,dy; \end{aligned} \tag{5}$$

with grating length L_{g1} and L_{g2}. Δn_1 and Δn_2 are the peak modulations in the refractive indices for the two gratings. We have included the self-coupling coefficient terms in the calculation of propagation constants. Eq. (2) can be written in the following matrix form:

$$\dot{A}(z) = TA(z) \tag{6}$$

where

$$A(z) = \begin{bmatrix} A_1 \\ A_2 \\ A_3 \end{bmatrix}; \quad \dot{A}(z) = \begin{bmatrix} dA_1/dz \\ dA_2/dz \\ dA_3/dz \end{bmatrix}; \quad T = \begin{bmatrix} -j2\delta & \kappa & 0 \\ -\kappa & 0 & \kappa' \\ 0 & -\kappa' & j2\delta' \end{bmatrix} \tag{7}$$

The above equation is an eigenvalue equation where the eigenvectors and eigenvalues can be numerically determined using standard programming techniques such as using MATLAB© [14].

If we assume that at the input the entire power is launched in mode 1, then we have: $A_1(z=0) = 1$; $A_2(z=0) = 0$ and $A_3(z=0) = 0$. If Λ_1 and Λ_2 are chosen such that at the operating wavelength: $\delta = \delta' = 0$, Eq. (6) gets simplified and has following analytical solutions:

$$\begin{aligned} A_1(z) &= 1 - \frac{2\kappa^2}{\tau^2}\sin^2\left(\frac{\tau z}{2}\right); \\ A_2(z) &= -\frac{\kappa}{\tau}\sin(\tau z); \\ A_3(z) &= \frac{2\kappa'\kappa}{\tau^2}\sin^2\left(\frac{\tau z}{2}\right); \end{aligned} \tag{8}$$

with $\tau^2 = \kappa^2 + \kappa'^2$. Eq. (8) gives us the fraction of power in each of the modes after an interaction length z.

The above analysis is applicable to cascaded coupling in optical fibers as well as in channel waveguides. Here as an example we

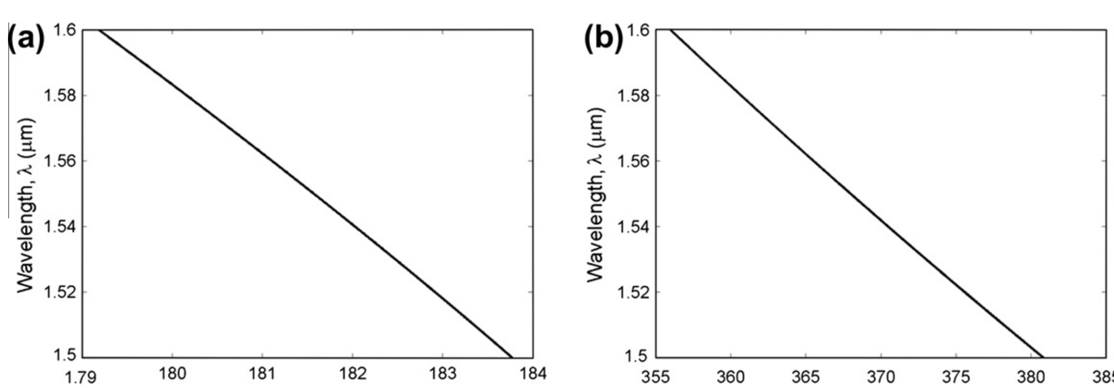

Fig. 2. Phase matching curves for: (a) primary coupling between LP_{01} to LP_{012} mode and (b) secondary coupling between LP_{012} to LP_{015} mode.