Optics & Laser Technology 92 (2017) 150–155

Contents lists available at ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

Theoretical study on core-mode to radiation-mode coupling in chiral fiber long-period gratings

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ARTICLE INFO

Keywords:
Chiral fiber gratings
Polarization-selective devices
Radiation mode
Mode coupling

ABSTRACT

The chiral fiber long-period gratings (CLPGs) could be fabricated by twisting a high-birefringence (Hi-Bi) fiber. However, when it is immersed into a material whose refractive index (RI) is higher than that of the cladding, there exists a complicated coupling between the core modes and the radiation ones. In this paper, for the first time to our knowledge, we theoretically investigate the mode coupling characteristics in such a CLPG. It is found that, owing to a strong mode transfer from the co-handed core mode to continuous radiation ones under the phase-matching condition, the CLPG can be regarded as a broadband circular polarizer since only the cross-handed circularly polarized light is left when a linearly polarized light is injected. Furthermore, the influence of the RI of the surrounding medium on the bandwidth and extinction ratio of this circular polarizer is investigated in detail. As a result, a broadband all-fiber circular polarizer can be constructed. Considering its simple configuration, it might have some potential applications, such as filters, broadband polarizers, and sensors.

1. Introduction

The chiral fiber long-period gratings (CLPGs) formed by twisting high-birefringence (Hi-Bi) fiber were first proposed by Kopp et al. in 2004 [1]. The correlated theoretical and experimental investigations were extensively reported, and various promising applications were also demonstrated [1–17]. The most remarkable property of the CLPG is the polarization-selective coupling of circularly polarized modes [1], which was well explained by the coupled-mode analysis [3–5] and the quantum theory of the angular momentum modulation [16–22]. It is known that, for the determinate resonant wavelengths of a CLPG with certain twist handedness (right-handed as shown in Fig. 1 or left-handed), the co-handed (right-handed or left-handed) circularly polarized core mode will couple to the co-propagating cross-handed (left-handed or right-handed) circularly polarized cladding modes and finally vanish, in contrast, the cross-handed circularly polarized core mode will pass through the CLPG without any loss [3,4]. In view of the above coupling merits of CLPG, one or several attenuation bands can be generated in the transmission spectrum of co-handed circularly polarized core mode [2–5], which means the CLPG could be used as the polarizer, the strain or temperature sensor, etc. [6,9,10,14]. Indeed, the investigation on the CLPG-based polarizer has been reported extensively. Unfortunately, when such polarizer is exposed in air, its bandwidth is only a few nanometers (less than 10 nm), which is detrimental to the real application [4]. To enhance the bandwidth of the cross-handed circular polarizer, the chiral intermediate period gratings (CIPG), whose twist pitch is about tens of microns, is proposed by Kopp et al. [1], and the CLPG with a slowly varying twist rate is reported as well [3,5,23], in particular Ref. [23] reported the parameter optimizations of broadband circular polarizers based on leaky mode couplings. Unfortunately, the correlated fabrication process is complicated. Hence, a CLPG-based broadband polarizer with a simpler configuration is expected.

Actually, the refractive index (RI) of the surrounding material of fiber grating has a critical impact on the coupling process [24–26]. When the RI of the surrounding material is higher than that of the cladding, the radiation mode coupling principle is always used to analyze the performance of general long-period gratings [25,26]. Based on this principle, in this paper we focus on the radiation mode coupling in two cases where the refractive index of the surrounding is higher than or equal to that of the cladding in CLPG. Note that for the case where the refractive index of the surrounding is lower than that of the cladding, the cladding mode coupling in CLPG has been well addressed in previous work [3–5]. It is observed that the bandwidth of such a

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http://dx.doi.org/10.1016/j.optlastec.2017.01.022
Received 12 September 2016; Accepted 24 January 2017

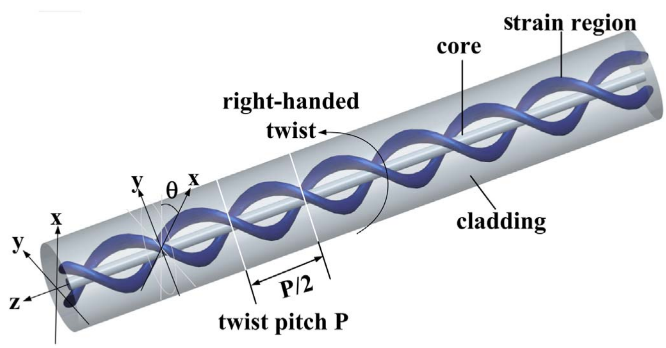

Fig. 1. Twisted high linear birefringence fiber.

CLPG wrapped by a high index medium is much broader than that of a CLPG exposed in air. As a result, only by immersing the CLPG into a high index material, the CLPG-based polarizer could operate with a much broader bandwidth. It is noteworthy that, we not only comprehensively introduce the radiation couple-mode theory into solving the coupling characteristic of the CLPG, but also propose a new scheme of broadband circular polarizer by selecting a suitable high index of external medium.

The rest of the paper is organized as follows. In Section 2.1, the general radiation coupled-mode perturbation theory specific to the problem of light propagation in CLPGs is developed. In Section 2.2, the electric field distribution of the circularly polarized core modes and radiation modes with a round core are reviewed. Based on the complex coupling coefficients are solved, the unified radiation coupled-mode equations for CLPGs are derived in Section 2.3. In Section 3, the transmission spectra of CLPGs with different surroundings and specific applications for broadband circular polarizers and sensors are summarized. Conclusions are drawn in the final section.

2. Theoretical analysis

2.1. Radiation couple-mode theory of CLPGs

A double-helix CLPG is shown in Fig. 1. The pitch of this CLPG is several hundred microns. In this paper, the CLPG is surrounded with a high refractive index material. Based on the correlated long-period fiber grating radiation couple-mode theory [24–26] and the CLPG cladding couple-mode theory [3–5], we propose a CLPG radiation couple-mode theory, and utilize this theory to analyze the coupling between the core mode and a continuum of radiation modes in CLPG. Modes propagating along a spun Hi-Bi fiber are generally described by the coupling between two orthogonal linearly polarized modes. Because we only intend to explore the circularly polarization characteristic of CLPG, the circularly polarized core mode and radiation modes are preferable to be employed to analyze the mode propagation as other group did [5]. Based on the above discussions, as shown in Fig. 1, for a right-handed twisted structure with a constant twist rate τ (τ=2π/P, where P is the pitch), the coupled-mode equations for x- and y-polarized core mode are formulated directly in local coordinates, as well as the radiation mode. It should be pointed out that the twist rate has a significant influence on the coupling among x- and y-polarized core and/or radiation modes [5,6]. The theoretical model will be described in detail as follows.

The RI profile of the fiber and the surrounding material is shown in Fig. 2, where a and b are the radii of the core and the cladding, respectively. It can be seen that the thickness of the cladding is finite, and the RI of surrounding material, n_3, is greater than that of the cladding, n_2. In this case, continuous radiation modes can be supported [25]. Note that as compared with the coupling between the core mode and radiation mode, the coupling between different radiation modes is usually quite weak thus can be neglected. In this case, the radiation

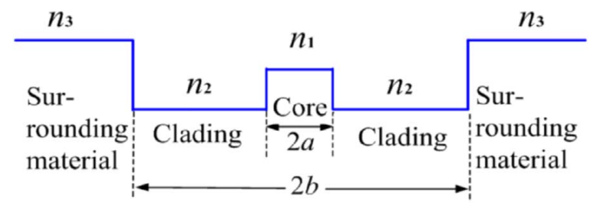

Fig. 2. Radial distribution of the refractive index in the fiber and surrounding material.

coupled-mode equations can be expressed as:

$$\frac{\mathrm{d}}{\mathrm{dz}}\begin{bmatrix} W_{\mathrm{co}}^{\mathrm{L}} \\ W_{\mathrm{co}}^{\mathrm{R}} \\ W_{\xi}^{\mathrm{L}} \\ W_{\xi}^{\mathrm{R}} \end{bmatrix} = -j\begin{bmatrix} \beta_{\mathrm{co}}+\tau & 0 & \kappa' & j\kappa \\ 0 & \beta_{\mathrm{co}}-\tau & j\kappa & \kappa' \\ \kappa' & -j\kappa & \beta_{\xi}+\tau & 0 \\ -j\kappa & \kappa' & 0 & \beta_{\xi}-\tau \end{bmatrix}\begin{bmatrix} W_{\mathrm{co}}^{\mathrm{L}} \\ W_{\mathrm{co}}^{\mathrm{R}} \\ W_{\xi}^{\mathrm{L}} \\ W_{\xi}^{\mathrm{R}} \end{bmatrix}, \tag{1}$$

$$\begin{aligned} \kappa &= \omega\varepsilon_0 \iint (\Delta\varepsilon_x \vec{e}_{11}^{\,x}\cdot\vec{e}_{1\xi}^{\,x} - \Delta\varepsilon_y \vec{e}_{11}^{\,y}\cdot\vec{e}_{1\xi}^{\,y})ds/2 \\ \kappa' &= \omega\varepsilon_0 \iint (\Delta\varepsilon_x \vec{e}_{11}^{\,x}\cdot\vec{e}_{1\xi}^{\,x} + \Delta\varepsilon_y \vec{e}_{11}^{\,y}\cdot\vec{e}_{1\xi}^{\,y})ds/2 \end{aligned}. \tag{2}$$

Note that in above equations, we have decomposed the linearly polarized mode into a right and left circularly polarized modes. Here κ and κ' are the coupling coefficients, ξ denotes the radial wave number of the radiation mode in surrounding material, and τ is the constant twist rate. $\delta_{c\xi} = \beta_{co} - \beta_{\xi} + 2\tau$, $\beta_{\xi} + \tau$ and $\delta_{c\xi} = \beta_{co} - \beta_{\xi}$, $\beta_{co} - \tau$ indicate the amplitudes of the left and right circularly polarized core and radiation modes, respectively. HE_{11} and $HE_{1\xi}$ are the circularly polarized core mode and radiation mode, respectively. β_{co} and β_{ξ} are the propagation constants of HE_{11} and $HE_{1\xi}$ modes in the perfect isotropic fiber, respectively. $\delta_{c\xi} = \beta_{co} - \beta_{\xi} - 2\tau$, $\delta_{c\xi} = \beta_{co} - \beta_{\xi}$, $\vec{e}_{1\xi}^{\,x}$ and $\vec{e}_{1\xi}^{\,y}$ are the corresponding normalized modal fields of these modes. The superscript x or y denotes the polarization direction of the dominant transverse components of the mode. The dielectric constant distribution in the cross-section of a Hi-Bi fiber includes the isotropic part, ε_0, and the anisotropic perturbation parts ($\Delta\varepsilon_x$ and $\Delta\varepsilon_y$ for x- and y-polarized modes, respectively). We use this model to analyze the coupling process, and we will find that a noticeable coupling between two modes is existence when the phase-matching condition is fulfilled. Thus, there are four cases of two-mode coupling. Case No. 1: The left circularly polarized (LCP) core mode (the propagation constant: $\beta_{co} + \tau$) is coupled to the right circularly polarized (RCP) radiation mode (the propagation constant: $\beta_{\xi} - \tau$), where the propagation constant difference between the two modes can be defined as $\delta_{c\xi} = \beta_{co} - \beta_{\xi} + 2\tau$. Case No. 2: The LCP core mode is coupled to the LCP radiation mode (the propagation constant: $\beta_{\xi} + \tau$), where the propagation constant difference is $\delta_{c\xi} = \beta_{co} - \beta_{\xi}$. Case No. 3: The RCP core mode (the propagation constant: $\beta_{co} - \tau$) is coupled to the LCP radiation mode, where the propagation constant difference is $\delta_{c\xi} = \beta_{co} - \beta_{\xi} - 2\tau$. And case No. 4: The RCP core mode is coupled to the RCP radiation mode, where the propagation constant difference is $\delta_{c\xi} = \beta_{co} - \beta_{\xi}$. Note that in these four cases, the phase-matching condition can only be satisfied when the propagation constant difference between the two modes is zero.

For all radiation modes, β_{co} is larger than β_{ξ}. As shown in Fig. 1, τ is positive for this right-handed structure. Hence, the phase-matching condition can be realized only when the following relationship is fulfilled:

$$\beta_{co} - \tau = \beta_{\xi} + \tau. \tag{3}$$

Note that this is corresponding to the case No. 3 we mentioned above, where only RCP core mode is coupled with the LCP radiation modes, and LCP core mode can propagate unaffected. In this case, the interaction between the RCP core mode and the LCP radiation mode is the most conspicuous comparing with all the interactions between any other modes. Thus, we only take this interaction into consideration in theoretically study, and consequently Eq. (1) is deduced into only two