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# Mode-couplings in two cascaded helical long-period fibre gratings and their application to polarization-insensitive band-rejection filter

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Mode-couplings occurring in cascaded single-helix helical long-period fibre gratings (SHLPGs) have been analysed. Using this type of helical long-period fibre grating combined with a cladding-mode stripper, a simple and efficient method of production of a polarization-insensitive flat-top band-rejection filter was proposed and experimentally verified. Unlike the previous SHLPG-based methods in which obtained spectra are strongly dependent on the polarization status of the incident light, the proposed method enables production of a flat-top filter with neither polarization-dependence nor reduction of the rejection depth. As a typical example, a flat-top filter with a rejection depth of ∼17 dB, a bandwidth of ∼14 nm@1 dB, and the maximum polarization-dependent loss (PDL) of ∼1.5 dB was successfully demonstrated.

## 1. Introduction

Long-period fibre grating (LPG) can be used as an optical band-rejection filter with a bandwidth of several tens of nanometres, which is almost one to two orders of magnitude broader than that of the fibre Bragg gratings [1]. However, due to several unrealistic requirements for the LPG's fabrication, such as sink-like apodization [2–5], precisely inserted phase-shifts [6–8], or extremely long grating (>50 cm) [9], it is rather difficult to control the profile of the resulting notch, especially for an LPG with a broad flat-top rejection-band, although these devices are essential for the fibre communication systems, as well as the fibre sensing systems. Recently, Shin et al. have proposed and demonstrated a new approach, which enables production of a tunable flat-top rejection filter [10]. This approach is based on utilization of a helical-type long-period fibre grating (HLPG) [11–15], in which two single-helix HLPGs (SHLPGs) are serially cascaded but maintain a spacing larger than 10 cm. However, due to the inevitable polarization scrambling effect taking place within the separation region, the spectral interferences between these two SHLPGs cannot be avoided, and as a negative result, fluctuations of the obtained spectrum are sufficiently large (>10 dB) that a flat-top rejection-band filter cannot be produced. To overcome this problem, we recently proposed and demonstrated another SHLPG-based method, in which two SHLPGs with opposite helicities are consecutively cascaded without any spacing. As a result, a flat-top band-rejection filter with a bandwidth of ∼12 nm@1 dB has been successfully produced [15]. However, the flat-top rejection band is achieved at the cost of sacrificing the rejection depth of the individual SHLPG [15]; thus, the resulting rejection depth is limited in its magnitude to less than 12 dB. To increase this rejection depth, we recently demonstrated an improved approach [16], in which incident light undergoes double passes of the consecutively cascaded HLPGs and as a result, a flat-top filter with a rejection depth larger than 34 dB has been obtained. However, all of the HLPG-based filters reported above have one critical problem, namely, the resulting spectra are strongly dependent on the polarization state of the incident light, which inevitably excludes them from any practical application. To date, there is a need to develop a polarization-insensitive band-rejection filter, which is essential for fibre communications and fibre sensing systems.

In this study, following the phase- and angular momentum (AM)-matching rules, first, we analysed the mode-couplings present in a two cascaded SHLPGs. Second, based on utilization of this type of HLPGs combined with a cladding-mode stripper, a simple and efficient method enabling production of a polarization-insensitive flat-top band-rejection filter (FBF) has been proposed and experimentally demonstrated. As a typical example, a flat-top filter with a rejection depth of ∼17 dB, a bandwidth of ∼14 nm@1 dB, and a maximum PDL of ∼1.5 dB was successfully tested and, to the best of our knowledge, demonstrated the

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best characteristics obtained to date among the LPG-based polarization-independent band-rejection filters.

## 2. Mode-couplings in cascaded single-helix long-period fibre gratings

In [15], based on the utilization of a conventional single-mode fibre (SMF), we described a flat-top band-rejection filter which consists of two consecutively cascaded SHLPGs with opposite helicities (CC-SHLPGs-OH). However, there were two critical issues: polarization-dependence and the unavoidable small rejection-depth of the resulting spectrum. In the following, by analysing the mode-couplings present in CC-SHLPGs-OH, we qualitatively explain the causes of the two issues mentioned above. Fig. 1 shows the structure of CC-SHLPGs-OH implemented in [15], where the ccSHLPG is assumed to have counter-clockwise helicity, and the cSHLPG is assumed to have clockwise helicity. For any SHLPG, the mode-selection rules of the resonant coupling must obey the momentum conservation, not only in the $z$ (fibre axis) direction but also in the angular direction [17,18]. The angular-matching conditions for ccSHLPG and cSHLPG can thus be expressed as [19]

$$M_{cl1} = M_{co1} + 1, \tag{1}$$

$$M_{cl2} = M_{co2} - 1, \tag{2}$$

where $M_{co1}, M_{co2}$ and $M_{cl1}, M_{cl2}$ are the angular momentum (AM) charges of the core and the $\upsilon$th cladding mode of ccSHLPG and cSHLPG, respectively. The charges are defined as negative integers for circularly polarized modes with the same helicity as that of the SHLPG. Since the ccSHLPG and cSHLPG are consecutively cascaded, we have $M_{cl1} = M_{cl2}$. As stated in [15], within the wavelength region of 1500 to 1620 nm and with the grating period near 648 $\mu$m, there exists a non-zero coupling between the core mode $LP_{01}$ and the hybrid cladding mode $LP_{12}$ ($TE_{02}/TM_{02}/HE_{22}$) for both ccSHLPG and cSHLPG. Therefore, only the cladding number $\upsilon = 2$ will be considered in this study. From Eqs. (1), (2), the mode-couplings occurring between the core mode and the cladding modes of the individual ccSHLPG and cSHLPG can easily be determined and are summarized in Table 1 and schematically shown in Fig. 2. It must be noted that in both Table 1 and Fig. 2, the fundamental core mode $LP_{01}$ is purposely divided into two parts: one is the left circular polarization (LCP) mode $LP_{01-}$, the AM charge of which is defined as $-1$, and the other is the right circular polarization (RCP) mode $LP_{01+}$, the AM charge of which is equal to $+1$. From Fig. 2, it is seen that in the first grating (ccSHLPG), the core modes $LP_{01-}$ and $LP_{01+}$ will be coupled with the cladding modes $TE_{02}/TM_{02}$ and $HE_{22+}$, respectively, and resonate at the wavelengths $\lambda_{L_1}$ and $\lambda_{R_1}$, respectively. Due to the degeneracy of these two cladding modes, these two wavelengths $\lambda_{L_1}(\approx\lambda_{R_1})$ have a nearly identical value and thus cannot be discerned from each other. Regarding the second grating (cSHLPG), one can see that the two fundamental modes will be coupled with the cladding modes $HE_{22-}$ and $TE_{02}/TM_{02}$, respectively, and resonate at wavelength $\lambda_{L_2}$ ($\approx\lambda_{R_2}$). Note that AM charges of the cladding modes $TE_{02}/TM_{02}$, $HE_{22+}$, and $HE_{22-}$are equal to 0, $+2$ and $-2$, respectively. Therefore, when these two gratings are consecutively cascaded, due to the spectral overlaps between them, the newly produced cladding modes $TE_{02}/TM_{02}$ in the first grating (ccSHLPG) will be coupled back with the core-mode $LP_{01+}$of the second HLPG (i.e., cSHLPG), as shown in Fig. 2. Meanwhile, the newly produced cladding mode $HE_{22+}$ in ccSHLPG cannot be coupled back to the cSHLPG (according to Eq. (2), the corresponding core mode becomes $HE_{32+}$, but it physically cannot exist in the core) and thus will keep its propagation in the cladding region and will finally dissipate. Therefore, it is expected that the proposed CC-SHLPGs-OH would exhibit strong polarization dependences, although it is known that an individual SHLPG exhibits no polarization dependence at all [12,17]. We believe that the abovementioned mode-coupling mechanisms that are present in the CC-SHLPGs-OH are the cause of strong polarization-dependence and decrease of the rejection-depth in the spectrum of the proposed CC-SHLPGs-OH.

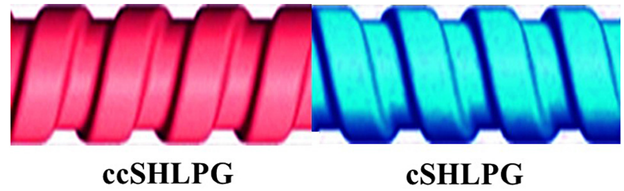


**Fig. 1.** Schematic structure of the proposed CC-SHLPGs-OH.

**Table 1**
Mode-coupling that occurs in ccSHLPG and cSHLPG in cladding mode ($\upsilon$ = 2).

| ccSHLPG | | cSHLPG | |
|---|---|---|---|
| Core | Cladding | Core | Cladding |
| $LP_{01}^-$ | $TE_{02}$<br>$TM_{02}$ | $LP_{01}^-$ | $HE_{22}^-$ |
| $LP_{01}^+$ | $HE_{22}^+$ | $LP_{01}^+$ | $TE_{02}$<br>$TM_{02}$ |

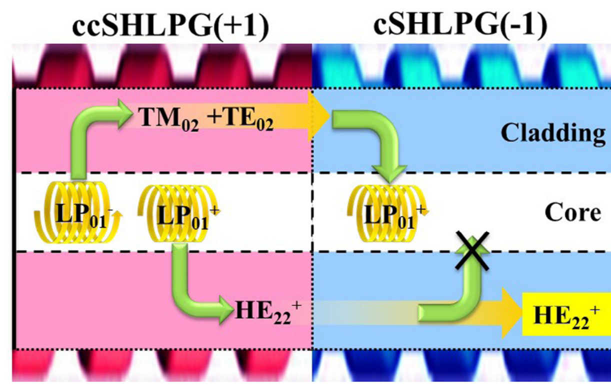


**Fig. 2.** Schematic diagram of the mode coupling in CC-SHLPGs-OH.

## 3. Proposal for polarization-insensitive band rejection filter

Based on the above analysis, we believe that if the cladding modes produced in the first grating were either prohibited to couple back with the second grating or quickly stripped off from the cladding region, the polarization-dependence problem could be avoided. Based on these considerations , we propose a design of polarization-insensitive flat-top band-rejection filter; its schematic diagram is shown in Fig. 3, where a cladding mode stripper (an oil region is utilized in this study) is employed and inserted at the central region of the two cascaded SHLPGs. Due to the higher refractive-index of the oil, the cladding modes produced in the first grating will immediately escape from the cladding layer within the oil region and thus cannot be coupled back to the second SHLPG. Note that unlike the CC-SHLPGs-OH described in [15] where separation between the two HLPGs is zero, here we present two successively cascaded SHLPGs (SC-SHLPGs) localized within a certain spatial region surrounded by oil.

Before investigating experimentally, we performed numerical simulations for the proposed SC-SHLPGs in which two gratings have periods of 657 and 663 μm and grating lengths of 23.7 mm (36 periods) and 23.9 mm (36 periods), respectively. Length of the oil region is assumed to be approximately 25 mm, and refractive index of the oil is approximately 1.471. The other parameters, such as the diameters of the core a1 and cladding $a_2$, refractive indices of the core $n_1$ and cladding $n_2$, and the surrounding material $n_3$, are chosen as $a_1$ = 8.2 $\mu$m, $a_2$ = 125 μm, $n_1$ = 1.4580, $n_2$ = 1.4536, and $n_3$ = 1.0. Note that we assume that all cladding modes excited in the first grating would escape from the cladding layer in the oil region; therefore, the spectrum of the