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All-fiber mode converter based on superimposed long period fiber gratings*

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In this paper, a novel broadband all-fiber mode converter is proposed and experimentally demonstrated. Through writing a pair of superimposed long period fiber gratings (SLPFGs) in tow-mode fiber (TMF) with a CO_2 laser, the mode converter can realize the conversion from LP_{01} to LP_{11} owing to the phase matching condition. Numerical and experimental results show that the bandwidth of this mode converter is 3 times broader than that of a single grating converter. The converter has low loss, high coupling efficiency, small size and is easy to fabricate, so it can be widely used in mode-division multiplexing.

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At present, mode-division multiplexing (MDM) has attracted more attention because of its ability to overcome the limitation of transmission capacity in the single-mode fiber (SMF), and to sustain the network traffic growth with larger capacity[1,2]. Mode conversion is the key technology in MDM system which can convert the fundamental mode in SMF to higher-order mode in few-mode fiber (FMF) or multimode fiber (MMF), and vice versa. In the past few years, several methods to realize mode conversion have been proposed, such as spatial light modulators[3], phase plates[4], silicon-based asymmetrical directional couplers[5], fiber-based photonic lantern[6] and long period fiber grating (LPFG)[7-9]. LPFG has the advantages of small size, low loss, low backward noise, high coupling efficiency and easy fabrication, but the bandwidth of this kind of mode converter is relatively narrow.

Superimposed LPFG (SLPFG) is an important optical device with many advantages, such as compact structure and smaller mechanical disturbance, and it can be used as efficient all-fiber mode focusers, beam shapers[10] and mode converter[11].

From the above references, SLPFG is mainly used to realize the conversion between core mode and higher-order cladding modes (HOMs) in an optical fiber. In this paper, we propose a novel broadband all-fiber mode converter for realizing the conversion from LP_{01} to LP_{11} by writing a pair of SLPFGs in two-mode fiber (TMF) with a CO_2 laser[12]. Numerical and experimental results show that the bandwidth of this mode converter is 3 times broader than that of a single grating mode converter.

The schematic diagram of the proposed all-fiber mode converter based on SLPFG is shown in Fig.1. We fabricate two LPGs with different periods in the same spatial domain of TMF to both achieve coupling from LP_{01} to LP_{11}. When light is launched into the SLPFG, the transmission spectrum will generate two resonance peaks at λ_1 and λ_2. According to the coupled mode theory, the coupled mode equations of two superimposed fiber gratings are as follows:

$$\begin{cases} \frac{\mathrm{d}A_1}{\mathrm{d}z} = \mathrm{i}\kappa_{11}^{01-01}A_1 + \frac{1}{2}\mathrm{i}A_2\kappa_{12}^{01-11}\exp\mathrm{i}(-2\delta_1 z) + \\ \frac{1}{2}\mathrm{i}A_2\kappa_{12}^{01-11}\exp\mathrm{i}(-2\delta_2 z) \\ \frac{\mathrm{d}A_2}{\mathrm{d}z} = \mathrm{i}\kappa_{22}^{11-11}A_2 + \frac{1}{2}\mathrm{i}A_1\kappa_{21}^{11-01}\exp\mathrm{i}(2\delta_1 z) + \\ \frac{1}{2}\mathrm{i}A_1\kappa_{21}^{11-01}\exp\mathrm{i}(2\delta_2 z) \end{cases}, \tag{1}$$

where A_1 and A_2 are amplitudes of two guided modes LP_{01} and LP_{11}, κ_{11}^{01-01} and κ_{22}^{11-11} are the self-coupling

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coefficients, κ_{12}^{01-11} and κ_{21}^{11-01} are the cross-coupling coefficients, δ_1 and δ_2 are the detuning parameters for grating I and grating II, respectively, and are given by

$$\delta_1 = \frac{1}{2}(\beta_{01} - \beta_{11} - \frac{2\pi}{\Lambda_1}) , \tag{2}$$

$$\delta_2 = \frac{1}{2}(\beta_{01} - \beta_{11} - \frac{2\pi}{\Lambda_2}) , \tag{3}$$

where β_{n1} is the propagation constant associated with the mode effective refractive index (ERI), Λ_1 and Λ_2 are the periods for grating I and grating II, respectively, satisfying the phase matching relationship.

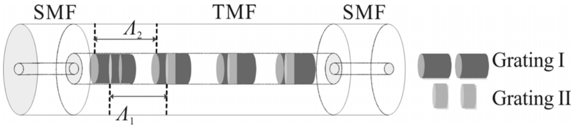

Fig.1 Schematic diagram of all-fiber mode converter based on SLPFG

We compute the ERIs of two core modes (LP_{01}, LP_{11}), and the corresponding dispersion curves are shown in Fig.2. According to the dispersion curves of these two coupling modes (LP_{01}, LP_{11}), we calculate the phase-matching curve of TMF-LPFG as shown in Fig.3.

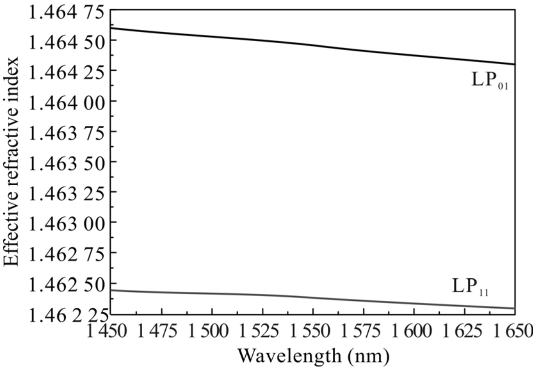

Fig.2 Calculated effective refractive index against wavelength of two modes of LP_{01} and LP_{11}

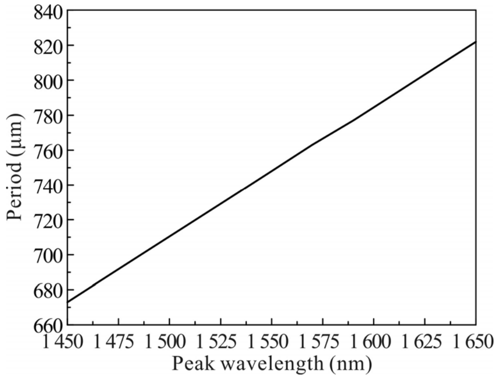

Fig.3 Peak wavelength shift in response to the grating period variation

The gap between these two resonant wavelengths can be changed with the change of period of the second grating. It's found that two resonant dips are closed to each other to one rejection band when the period of second grating becomes shorter, which can broaden the bandwidth, as shown in Fig.4.

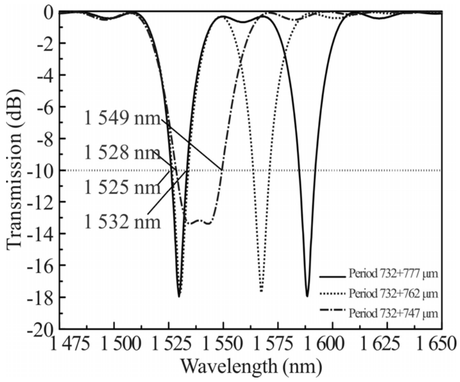

Fig.4 Simulated transmission spectra of SLPFGs with different periods

The experimental system used to fabricate SLPFG is demonstrated in Fig.5. In our experiment, we select a segment of TMF (two-mode graded-index fiber) with a core diameter of 19 μm and a cladding diameter of 125 μm, whose both ends are spliced to an SMF (Corning SMF-28). In order to decrease the mode interference and ensure that only the LP_{01} is launched into the SLPFG, we place two mode trippers on two sides of the SLPFG along the TMF[13].

The light source is an SLED broadband source with the wavelength range of 1 450—1 700 nm and the maximum output power of 2.44 mW. We adopt the optical spectrum analyzer (AQ6370C, YOKOGAWA) with resolution of 0.02 nm to observe the spectrum changing in the process of grating writing in real time. We write the SLPFG in the TMF by irradiating the fiber from one side with a CO_2 laser (CO_2-H10C, Han's Laser).

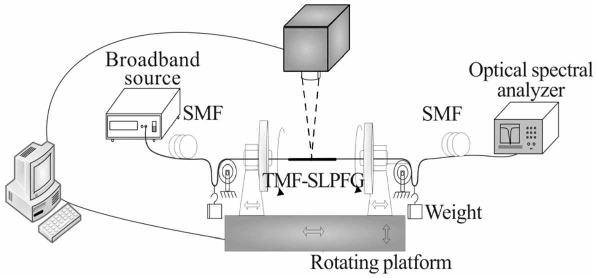

Fig.5 Schematic diagram of SLPFG fabrication with CO_2 laser

According to the numerical results, we fabricate grating I with Λ_1=735 μm and period of 30, then turn the rotating platform with 180°, and fabricate grating II with Λ_2=750 μm and period of 30. The actual pitch used in our experiments is somewhat longer. The parameter of CO_2

laser is set as follows: the average power of the CO_2 laser is 5 W, the frequency of the laser pulses is 10 kHz, and marking cycle is 6. The transmission spectra of the TMF-LPFG and TMF-SLPFG are shown in Fig.6. The resonant wavelengths of LPFG are 1 535.5 nm and 1 555.5 nm, respectively, and the bandwidths at conversion efficiency of 10 dB are both 7 nm, while the resonant wavelengths of SLPFG are 1 559.5 nm, the corresponding bandwidth at conversion efficiency of 10 dB is 21 nm. The bandwidth of SLPFG is 3 times larger than that of LPFG. From Figs.4 and 6, it is found that the transmission spectrum of SLPFG shifts to longer wavelength, because the change of refractive index is induced by irradiation of laser beam when the second grating is written, which changes the coupling efficiency and results in wavelength shift.

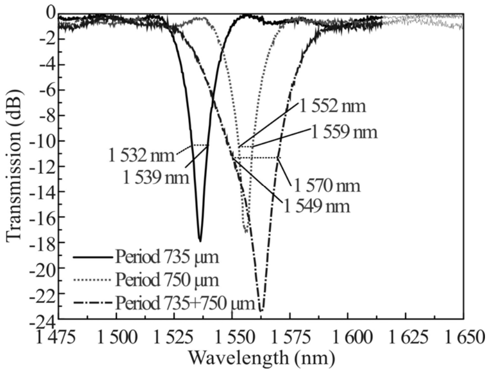

Fig.6 Comparison of the spectra of TMF-LPFG and TMF-SLPFG

In order to confirm that the proposed SMF-SLPFG-SMF structure can realize the conversion from LP_{01} to LP_{11}, we measure mode profiles of the SLPFG at different wavelengths via a tunable laser (Santec Corporatio 1 500—1 630 nm) and an infrared (IR) CCD, as shown in Fig.7. The tunable laser here is used as the light source, the sample with period of 735+750 μm is cut off at the end of grating, and the objective lens (×40) focuses the light to IR CCD (Cinogy, 1 495—1 595 nm). The mode profiles are obtained at 1 525 nm, 1 549 nm, 1 563 nm, 1 570 nm and 1 590 nm, respectively, as shown in Fig.8. It is found that the SLPFG can couple light from the fundamental mode LP_{01} to the higher-order mode LP_{11} at wavelengths of 1 549 nm, 1 563 nm, 1 570 nm.

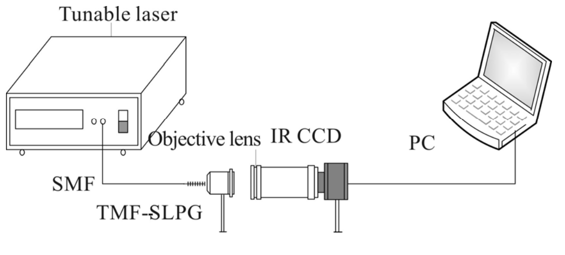

Fig.7 Schematic diagram of experimental setup of mode profile observation

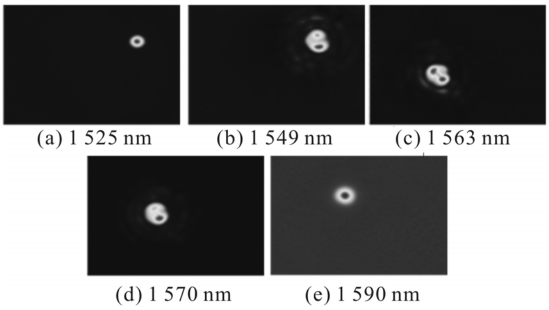
(a) 1 525 nm (b) 1 549 nm (c) 1 563 nm
(d) 1 570 nm (e) 1 590 nm

Fig.8 Images of mode profiles located at different wavelengths

A novel broadband all-fiber SLPFG-based mode converter is proposed and experimentally demonstrated. The bandwidth of the mode converter is 3 times larger than that of a single grating. This all-fiber mode converter may be applied to explore the possibility of conversion from fundamental mode to other higher-order modes (e.g. LP_{21} and LP_{02}) in FMF.

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