Broadband and Dynamic Mode Switching Converter Based on Acoustically Induced Fiber Grating

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***Abstract*—Broadband acoustically induced fiber grating was fabricated to realize the dynamic mode switching from LP$_{01}$ to LP$_{11}$ within 100 nm bandwidth by etching the cladding of two-mode fibers at 1.0 and 1.5 μm wavebands.**

Keywords—acoustically induced fiber grating, long period fiber grating, broadband mode conversion, dynamic switching

I. Introduction

With the rapid development of information technology, the capacity of optical fiber communication system is approaching the limit [1]. Since different-order linear polarized (LP) modes in optical fiber are orthogonal to each other during the transmission, mode division multiplexing (MDM) technology has become one of the important methods to scale up the capacity [2]. Mode converters can realize the conversion between the fundamental core mode and high order core modes, such as mode selective couplers (MSC) [3], long period fiber gratings (LPFG) [4], acoustically induced fiber gratings (AIFG) [5], and photonic lanterns [6]. However, the typical bandwidth of the LPFG is only tens of nanometers, limiting the broadband conversion of femtosecond pulse from the mode-locked (ML) lasers. Alternatively the LPFG operating at the dispersion turnaround point (TAP) can achieve broadband mode conversion with a bandwidth of hundreds of nanometers [7]. Therefore, combining the dynamic switching of the AIFG with the broadband conversion of TAP-LPFG, the TAP-AIFG has unique broad band and dynamic property in the mode-locked lasers and MDM.

We experimentally exploited two kinds of TAP-AIFG by using the etched two-mode fiber (TMF) and broadband and dynamic mode switching between LP$_{01}$ and LP$_{11}$ modes with a 3 dB bandwidth of 100 nm are achieved centered at 1550 nm and 1100 nm, respectively.

II. Simulation Results

The core diameter of the home-fabricated TMF is 12 μm and the refractive index difference between the core and cladding is 0.31%. According to the phase matching conditions [8]: $L_B = \Lambda$, where the beat length $L_B = \frac{\lambda}{n_{01}-n_{11}}$ and the period $\Lambda = \sqrt{\frac{\pi RC}{f}}$, λ is the resonance wavelength; n_{01} and n_{11} refer the effective refractive index coefficients of LP$_{01}$ and LP$_{11}$ modes, respectively; R means the radius of the fiber; C = 5760 m/s is the propagating speed of acoustic wave; f represents the applied frequency of the radio-frequency (RF) signal. It is proved by the experiment that the mode conversion occurs at the central wavelength of 1500 nm by loading an RF signal when f = 2.263 MHz. When the diameter of the fiber is decreases by etching the cladding layer, the required frequency of RF signal will be greatly reduced, and the coupling between sound wave and light wave can be enhanced, so as to improve the efficiency of mode conversion.

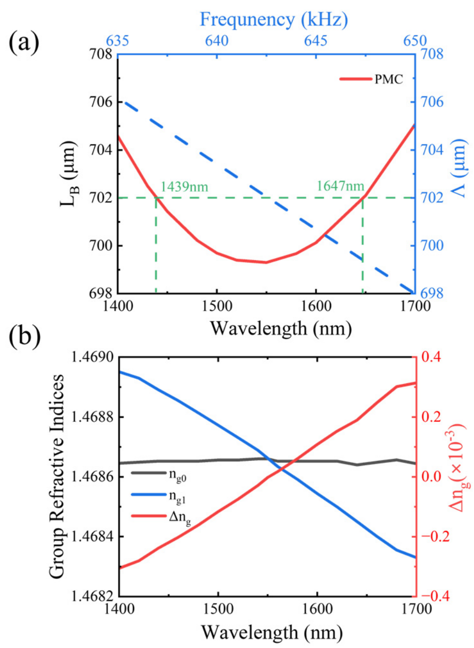

Fig. 1. (a) The PMC from LP$_{01}$ to LP$_{11}$ modes; (b) Calculated group refractive indices of LP$_{01}$ and LP$_{11}$.

The transmission mode of the AIFG is investigated with the diameter of 35 μm by using COMSOL Multiphysics. The phase-matching curve (PMC) is shown in Fig. 1(a). A grating period about 699.3 μm occurs at a frequency of 648 kHz, which can achieve broadband conversion at 1550 nm. When increasing the generated period, the phase matching condition will be met at two different resonant wavelengths. The principle of broadband mode conversion is that the group velocity matching condition [9]: $n_{g0} = n_{g1}$ is satisfied. The spectral dependence of the group refractive index difference is depicted in Fig. 1(b). A dispersion turnaround point is located at 1550 nm, equivalent to the inflection point on the PMC.

III. Experimental Results

In the experiment, the acousto-optic interaction length is 10 cm, and the diameter of the TMF is etched to 35 μm by a mixture of HF and NH_4F. Fig. 2(a) describes the evolution of the transmission spectrum with the frequency change of the RF signal. A broadband conversion peek appears at 1550 nm with a 3 dB bandwidth of about 100 nm and the conversion efficiency of about 90%, when the RF signal with f = 730 kHz is loaded into the AIFG. The inset displays the mode pattern of LP_{11} observed by a Charge-coupled device (CCD). Due to the non-uniformity of the etched fiber, there might be differences between the actual frequency and the simulated frequency. Furthermore, we also proposed a TAP-AIFG by etching the diameter of another TMF to 30 μm. Fig. 2(b) expresses the transmission spectrum of the AIFG at 1.0 μm waveband. The center wavelength of mode conversion is 1100 nm, and the 3 dB bandwidth is about 100 nm. In the subsequent experiments, the conversion efficiency of the TAP-AIFG will be improved by optimizing the etching parameters.

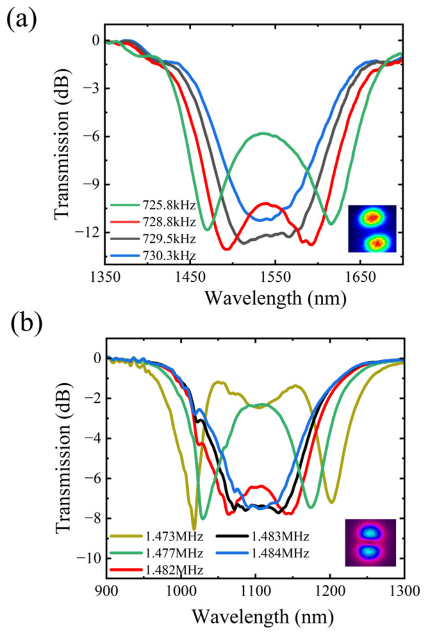

Fig. 2. The transmission spectrum of the broadband LPFG using the TMFs (a) at 1.5 μm; (b) at 1.0 μm. The insets are mode patterns at resonance wavelength.

Combining the TAP-AIFG with a commercial ML laser with a bandwidth of 40 nm and a central wavelength of 1560 nm and a repetition rate of 40.6 MHz, it is verified that the extra-cavity mode conversion could be accomplished. The experimental diagram is shown as the Fig. 3(a), and the pulse trains of the ML laser are illustrated in Fig. 3(b). Fig. 3(c) represents that the LP_{11} spectrum after mode conversion is consistent with the original LP_{01}, but the power is slightly reduced due to the loss of the dissipated cladding mode. The mode patterns also indicate that LP_{11} mode can be achieved by adding a TAP-AIFG outside the fiber laser cavity.

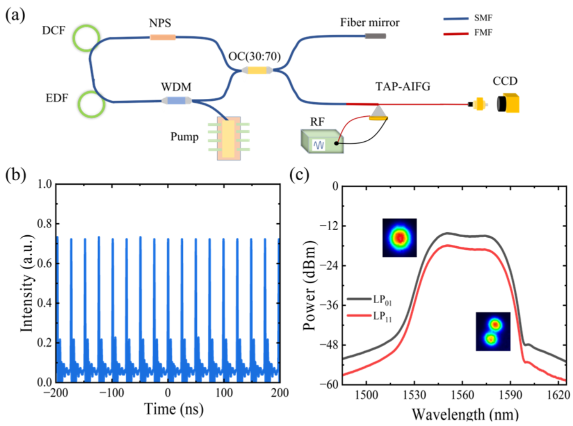

Fig. 3. (a) The experimental setup of a ML laser based on a TAP-AIFG to output LP_{11} mode pulse; (b) The pulse trains of the commercial ML laser; (c) The transmission spectrum and mode patterns of extra-cavity mode conversion.

IV. Conclusion

In conclusion, we have experimentally demonstrated a mode converter based on a TAP-AIFG that can dynamically switch mode between LP_{01} and LP_{11} modes at 1.0 and 1.5 μm wavebands with a bandwidth of 100 nm, respectively. The TAP-AIFG has potential in mode-locked fiber lasers and MDM fiber communication system.

References

[1] G. Li, N. Bai, N. Zhao, and C. Xia, “Space-division multiplexing: the next frontier in optical communication,” Adv. Opt. Photonics, vol. 6, no. 4, pp. 413-487, 2014.

[2] J. Vuong, P. Ramantanis, and Y. Frignac, “Mode coupling at connectors in mode-division multiplexed transmission over few-mode fiber,” Opt. Express, vol. 23, no. 2, pp. 1438-1455, 2015.

[3] H. Yao, F. Shi, and Z. Wu, “A mode generator and multiplexer at visible wavelength based on all-fiber mode selective coupler,” Nanophotonics, vol. 9, no. 4, pp. 973-981, 2020.

[4] Z. Liu, Y. Liu, and X. Zhao, “Bandwidth optimization of cascaded long-period gratings for broadband mode conversion over 1.0-2.2 μm waveband,” Opt. Express, vol. 28, no. 21, pp. 31882-31892, 2020.

[5] W. Zhang, L. Huang, and K. Wei, “Cylindrical vector beam generation in fiber with mode selectivity and wavelength tunability over broadband by acoustic flexural wave,” Opt. Express, vol. 24, no. 10, pp. 10376-10384, 2016.

[6] Y. Shen, Z. Wan, and X. Fu, “Vortex lattices with transverse-mode-locking states switching in a large-aperture off-axis-pumped solid-state laser,” J Opt Soc Am B, vol. 12, pp. 2940-2944, 2018.

[7] L. Teng, J. Lu, and Y. He, “Vortex soliton oscillation in a mode-locked laser based on broadband long-period fiber grating,” Opt. Lett., vol. 46, no. 11, pp. 2710-2713, 2021.

[8] K. J. Park, K. Y. Song, and Y. K. Kim, “Broadband mode division multiplexer using all-fiber mode selective couplers,” Opt. Express, vol. 24, no. 4, pp. 3543-3549, 2016.

[9] S. Ramachandran, Z. Wang, and M. Yan, “Bandwidth control of long-period grating-based mode converters in few-mode fibers,” Opt. Lett., vol. 27, no. 9, pp. 698-700, 2002.