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RESEARCH ARTICLE

Switchable-multi-wavelength fiber laser based on dual-core all-solid photonic bandgap fiber

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Abstract In this paper, we propose and demonstrate a switchable multi-wavelength fiber laser based on a dual-core all-solid photonic bandgap fiber (PBGF) comb-like filter. The transmission properties of the dual-core all-solid PBGF are theoretically and experimentally investigated. Then the fiber ring laser based on the PBGF is realized and its wavelength-selective mechanisms are studied. By adjusting the polarization controller (PC), the number and location of the laser wavelength can be tunable.

Keywords photonic crystal fiber, all-solid photonic bandgap fiber, multi-wavelength fiber laser

1 Introduction

The all-solid photonic bandgap fiber (PBGF) was first described by Luan et al. in 2004 [1]. By laying a two-dimensional array of high refractive index rods periodically to the silica substrate which has a low index, with an absence of rods in the core to introduce defects, photonic bandgaps (PBGs) are formed in PBGF, and the light which spreads in the fiber is confined in the core by the bandgaps. In comparison with other PBGFs such as hollow-core PBGFs, all-solid PBGFs exhibit similar spectral and dispersive characteristics, while they can be more easily fabricated spliced to traditional fibers. Therefore, all-solid PBGFs have great potential applications in optical communications and the fiber sensor field.

Dual-core photonic crystal fibers have attracted much interest because of their special characteristics due to their unusual and flexible structural design. The study of index-guiding dual-core PCFs both in theory and experiment have been reported widely [2–4]. In recent years, dual-core PBGFs have also been theoretically and experimentally investigated, in which some interesting coupling properties, such as the extremum of coupling length and decoupling are observed [5,6].

In this paper, we propose and demonstrate a switchable multi-wavelength fiber laser by using a dual-core all-solid PBGF comb-like filter. The coupling length of the dual-core PBGF is calculated by using the plane-wave method and the full-vector finite element method. Then the transmission properties of the PBGF spliced with conventional single core fibers at two ends are theoretically and experimentally investigated, which exhibits the spectrum of comb-like filter. Finally, the fiber ring laser based on the PBGF is demonstrated. By adjusting the polarization controller (PC), we have experimentally acquired 2–5-wavelength simultaneous lasing oscillation, which could be explained by our theoretical analysis.

2 Coupling length of dual-core all-solid PBGF

In the dual-core fiber, light transmitted respectively in two cores of the fiber will form a pair of supermodes because the evanescent fields of the two modes interact with each other. The symmetric one of the supermodes is called even mode, and the other one which is antisymmetrical is called odd mode. The propagation constants β of the two modes are different from each other. When light is injected into one core, both the even mode and the odd mode are excitated at the same time. During the transmission of the light waves, the two modes are strengthened or offset periodically via intervening each other, due to their different propagation constants, which causes the light energy to periodically displace from one core to the other. The distance that the light propagates along the fiber when the energy does a complete diversion from one core to the other is defined as coupling length L_c,

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$$L_c = \pi/|\beta_{even} - \beta_{odd}| = \pi/(k|n_{even} - n_{odd}|), \quad (1)$$

where β_{even} and β_{odd} are respectively the even and the odd mode propagation constants, n_{even} and n_{odd} are their corresponding effective indices. They depend on the materials and structures of the fiber. $k = 2\pi/\lambda$, λ is the light wavelength in vacuum. Coupling length L_c is an important parameter which describes the strength of the coupling between the two cores.

The theory above is also applicable to the index-guiding PCF. However, for dual-core all-solid PBGF, something is different. The coupling length L_c of the fiber does not change with λ monotonously. Because of the change of propagation constant β and the existence of photonic bandgap, L_c plays a complicated action in the wavelength range that light can be conducted. Some particular phenomenon may occur such as maximum or minimum point, or even decoupling [5,7].

Figure 1(a) shows the cross section of dual-core all-solid PBGF which is used in our experiment and Fig. 1(b) shows its model for calculating. We consider the background material of the fiber as silica, set its refractive index as 1.457. The shade fields express the Ge-doped high index columns, whose refractive indices are set as 1.47288. The diameter of the high index column is $d = 7.12$ μm, and the rod pitch $\Lambda = 9.9$ μm. By removing two high refractive index rods, defects are introduced into the structure as the cores of the fiber. The distance of two cores $D = 3\Lambda$. Ignoring the material dispersion which does no impact on the results, we use the plane wave expansion method to calculate the photonic bandgap. Then we calculate the effective refraction index of both the even mode and the odd mode, using the finite element method. Because of the unsymmetrical fiber structure, the modes of both x and y polarization direction are different and they need to be calculated separately.

Figure 2 depicts both the dispersion curves of even and odd modes in the two orthogonal polarization states in the second bandgap and the coupling lengths of the two polarizations which depend on normalized wavelength. The second bandgap lies on the field between the 6th and 7th band. Laser generated by the erbium-doped fiber is

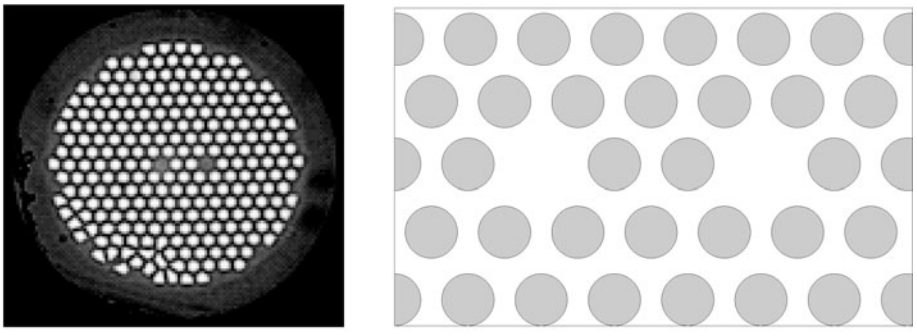


Fig. 1 Dual-core all-solid PBGF. (a) Cross section; (b) model of the fiber

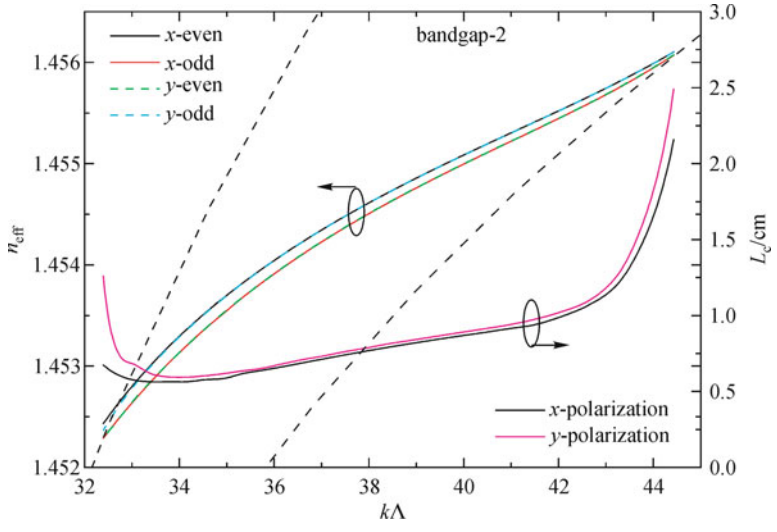


Fig. 2 Dispersion of even and odd modes in both x and y polarization in the second bandgap, and the coupling length L_c of the two orthogonal polarization depends on normalized wavelength

exactly fit for spreading in this bandgap. As can be seen from Fig. 2, there is only a small difference between the effective refractive index curves of the even (or odd) modes in the two polarization directions. In the x polarization direction, for example, while the wavelength increases, the gap between the two effective refractive index curves increases. Because of Eq. (1), L_c will be decreased. However, when the wavelength increases further and the dispersion curves are close to the edge of the bandgap, the gap between the two curves gradually is reduced, then the coupling length L_c increases. Therefore, close to the border of the bandgap the value of L_c exists as a minimum. In the opposite direction, when the curves are close to the edge of the bandgap in the short wave direction, the even and odd modes curves have a trend of intersecting, thus the coupling length L_c approach infinity. In addition, close to the bandgap edge of long wavelength direction, curves in x polarization and in y polarization have a large difference, which can induce a large difference of coupling characteristics.

We assume that light with a power of P_0 inject into a core which is supposed as core-1. After a transmission distance L the power in core-1 becomes P_1, and the power in core-2 is P_2. Without regard to the loss of fiber, that is $P_0 = P_1 + P_2$, we get the normalized output power P:

$$P = P_1/P_0 = \cos^2(\pi L/(2L_c)). \quad (2)$$

For the length-fixed PBGF, the coupling length L_c depends on the wavelength. Therefore, the curve of the normalized output power against wavelength shows as a comb filter. The length of the dual-core all-solid fiber L is 0.22 m, as we measured.

As can be seen from Fig. 3, the output power spectra in different polarizations are actually different though they have a similar trend. However, both of the two polarizations display as a comb filter in the range of the normalized wavelength. From 35 to 42, because the smooth trend of the curves changes, the transmission curves become a little sparse. In normalized wavelength of 34 where it is close to the minimum extreme point of L_c, light nearby is no longer outputted from core-1, and the power is almost coupled into core-2. Using core-2 as an output port we can get a broadband filter theoretically. Because of the different output spectrum between different polarizations, we can get different output powers in different wavelengths by adjusting their polarizations [8]. This can be used in fiber lasers, in order to achieve room-temperature multi-wavelength laser output.

However, the gain characteristics of the erbium-doped fiber (such as the absorption cross section and emission cross section) can also influence the choice of lasing wavelength, for example, inhibiting the wavelength which is outside the range of spontaneous gain spectrum of erbium-doped fiber. As shown in Fig. 3, although many wavelengths have a total transmission, only a few wavelengths are selected due to the spontaneous gain of Er^{3+} and the competition among these few successful lasing wavelengths.

3 Experiment

We measured the transmission characteristics of the dual-core all-solid PBGF with a super continuum source. A polarization dependent isolator is used as a polarizer. Through the polarizer, the continuum light is restricted as a linear polarized light with a single polarization direction. Then the light is filtered by the PBGF, its output spectrum displays as a comb. A fiber polarization controller (PC) is used to adjust the polarization of the light. The spectrum is received by an optical spectrometer analyzer (OSA). The experiment setup is shown in Fig. 4.

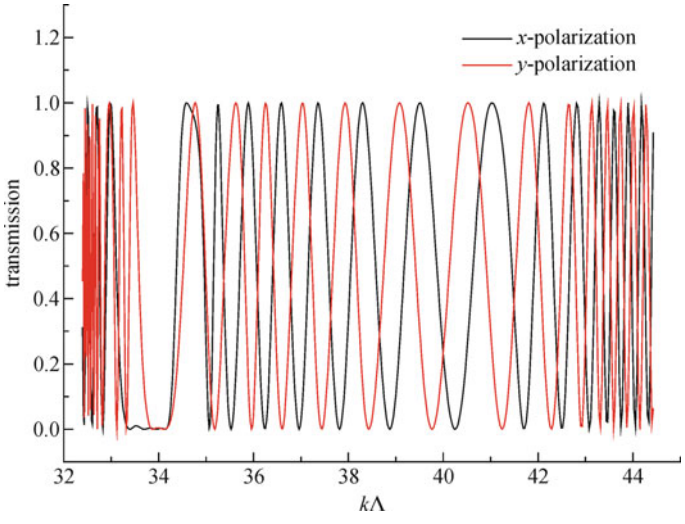


Fig. 3 Transmission depends on normalized wavelength

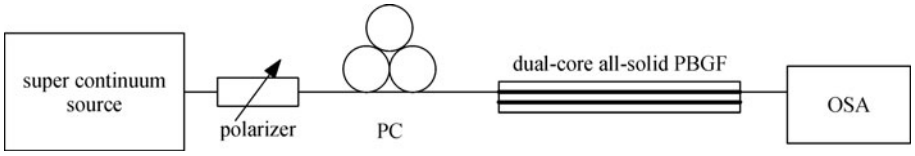


Fig. 4 Experiment of measuring transmission spectrum

By adjust the polarization controller, we observe the transmission spectrum in the two orthogonal polarizations. As Fig. 5 shows, between 1200 and 1560 nm, there is a broad bandgap. In this gap, the output light power shows a remarkable periodicity depending on the wavelength. Between 1527 and 1537 nm, where the lasers are excited, the loss increases rapidly because of its nearness to the band edge. Even then, the spectrum also shows a periodicity. At the same time, due to the different output spectra of light in different polarizations, both of them make it possible for the application of dual-core all-solid PBGF as a wavelength selection device.

The dual-core all-solid PBGF we used in the experiment is shown in Fig. 6, which was fabricated by the University of Bath. The parameter of this fiber has been described in Sect. 2. A 4.6 m long low-erbium-doped fiber is used as gain medium. 980 and 1480 nm LD laser pump the fiber from opposite directions, through 980/1550 and

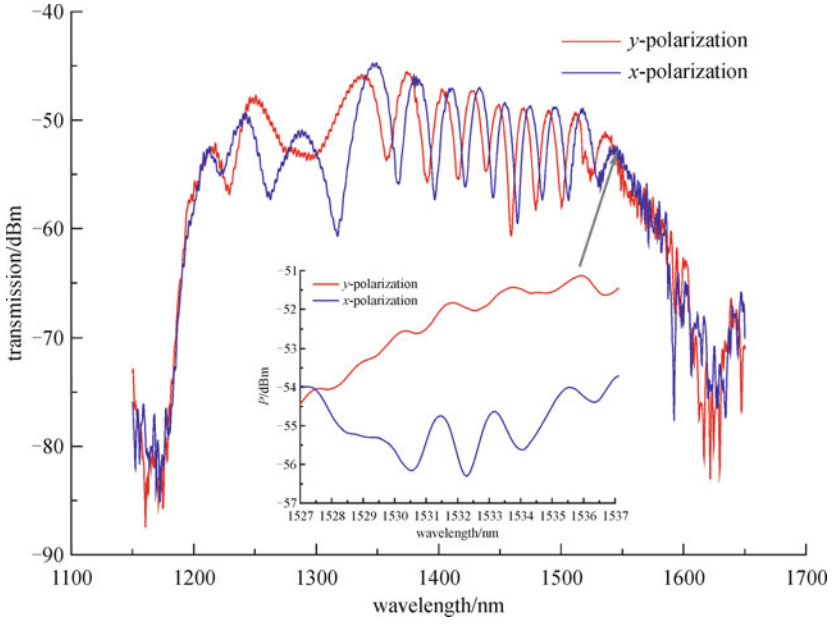


Fig. 5 Output spectrum of continuum light through PBGF in orthogonal polarization

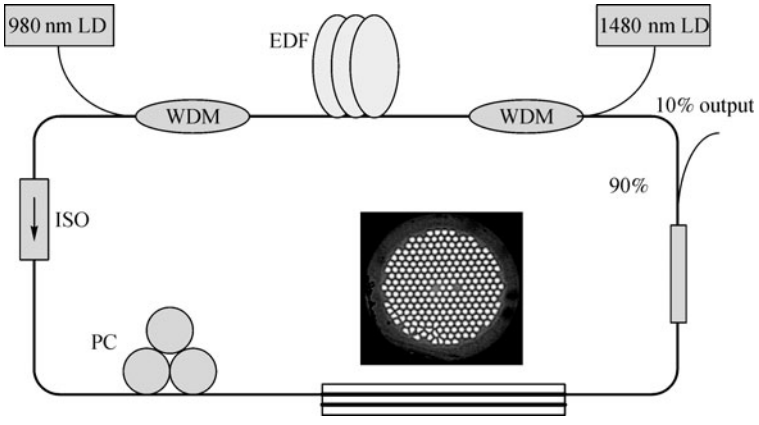


Fig. 6 Experimental setup of switchable multi-wavelength fiber ring laser

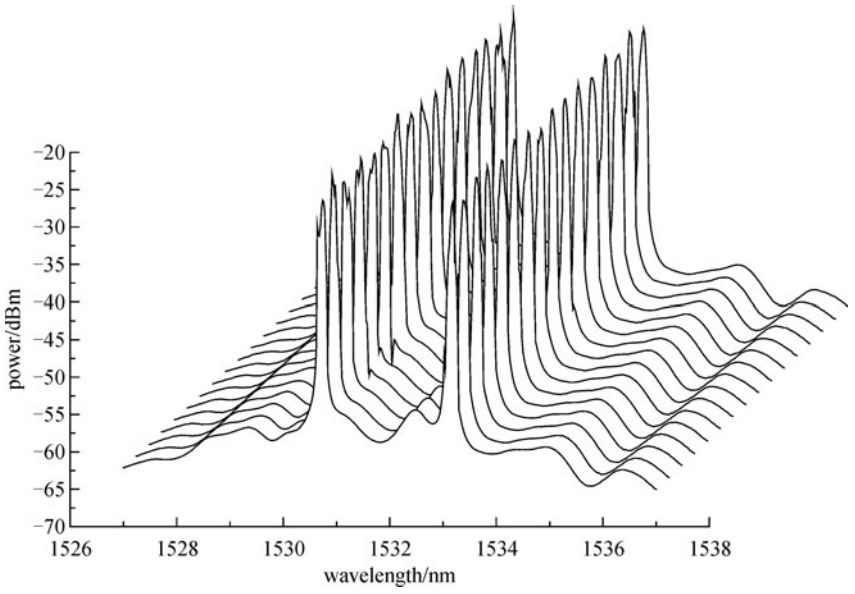


Fig. 7 Stability tests of dual-wavelength laser at room temperature, with scanning interval of 2 min, resolution of 0.1 nm (wavelength of the laser is 1530.74 and 1533.16 nm, respectively)

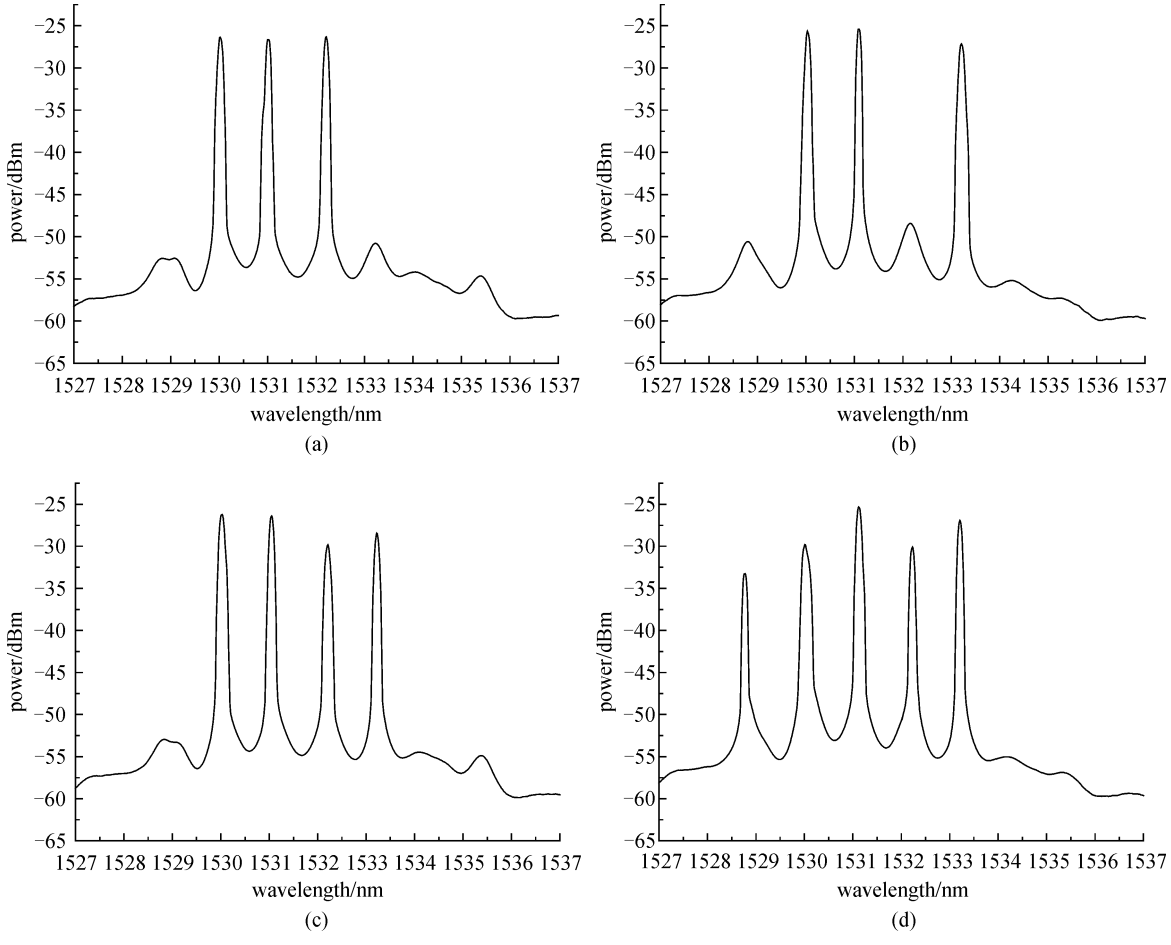


Fig. 8 3–5 wavelength laser we have got by adjusting PC

1480/1550 WDM respectively. The power of the 980 nm LD is about 101.9 mW, and the power of 1480 nm LD is 149.8 mW. By adjusting the PC, we can regulate the polarization of light in the ring cavity. The coupling ratio of the coupler is 1:9, where 10% is output and 90% is feedback to the laser cavity. The resolution of the OSA is 0.1 nm.

By using the PC to adjust the polarization state of the light in the laser cavity, we get some switchable multi-wavelength laser outputs, which have a range of 1528–1533 nm and a number from 2 to 5, as shown in Figs. 7 and 8.

From the spontaneous gain spectrum of erbium-doped fiber, we can realize that the wavelength in the vicinity of 1531 nm may have the maximum gain, and photons here are most easily excited. On the other hand, the PBGF we use in the experiment has a very large transmission loss near 1550 nm due to the lack of its production process. Therefore, multi-wavelength lasers excitated around 1531 nm. Because of the polarization hole burning effect, laser in different polarization states consume the particle in corresponding polarizations. The homogeneous broadening effect of the erbium-doped fiber is effectively reduced. Figure 7 shows the stability of dual-wavelength at room temperature. However, because the number of wavelengths obtained by adjusting the polarization controller increases, the stability of these lasers will get worse. A frequency-stable device is expected to make an improvement.

4 Conclusions

In this paper, we have studied the transmission and coupling characteristics of the dual-core all-solid PBGF. We have experimentally acquired 2–5-wavelength laser output that is switchable by adjusting the intracavity polarization states. However, the additional transmission loss induced by fiber splicing between PBGF and single-mode fiber will increase the lasing threshold, which is a matter that should be considered for practical applications. Owing to the flexible design and versatile construction approaches, we believe the proposed novel multi-wavelength filter will definitely find its applications in future optical fiber communication systems.

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