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### ABSTRACT

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# Polarizing ytterbium-doped all-solid photonic bandgap fiber with $\sim 1150\mu\text{m}^2$ effective mode area

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**Abstract:** We demonstrate an Yb-doped polarizing all-solid photonic bandgap fiber for single-polarization and single-mode operation with an effective mode area of  $\sim 1150\mu\text{m}^2$ , a record for all-solid photonic bandgap fibers. The differential polarization mode loss is measured to be  $>5\text{dB/m}$  over the entire transmission band with a 160nm bandwidth and  $>15\text{dB/m}$  on the short wavelength edge of the band. A 2.6m long fiber was tested in a laser configuration producing a linearly polarized laser output with a PER value of 21dB without any polarizer, the highest for any fiber lasers based on polarizing fibers.

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## 1. Introduction

Polarizing optical fibers are an important component for building compact fiber lasers with linearly polarized laser output. Conventional polarization-maintaining (PM) optical fibers preserve the polarization of the incident beam when it is launched properly aligned with one of the birefringent axes of the fiber. However, the polarization extinction ratio (PER) can still degrade along a fiber due to polarization mode coupling arising from random perturbations. Recent reports demonstrate that birefringence in a Bragg fiber and a hybrid micro-structured fiber can provide a polarizing effect [1,2]. This is due to the fact that the birefringence shifts the transmission bands, arising from the bandgap effect in the Bragg fiber [1] and a quasi-bandgap effect in the hybrid micro-structured fiber [2], in wavelength for orthogonal polarizations, thus creating a staggered region at the band edges where the two polarization modes have high differential losses.

In the last few years, we have demonstrated that all-solid photonic bandgap fiber is a very promising candidate for high power fiber lasers and amplifiers [3,4]. The cladding with the unique combined effects of bandgap transmission and high differential mode losses enables higher-order mode suppression at levels unmatched by any other design, leading to a true single-mode regime in 50 $\mu\text{m}$ -core fibers [4]. This is critical for further power scaling of fiber lasers to mitigate nonlinear optical effects as well as mode instabilities [5–7]. Steep transmission bands in all-solid photonic bandgap fibers can also provide strong suppression of stimulated Raman scattering (SRS) and amplified spontaneous emission (ASE) [8].

Here, we report the demonstration of an Yb-doped polarizing all-solid photonic bandgap fiber over its entire transmission band with a 160nm bandwidth from 1010nm to 1170nm. The differential polarization mode loss is >15dB/m near the short wavelength edge of the transmission band from 1010nm to 1030nm. In the remaining region of the transmission band, the differential loss is >5dB/m. Furthermore, a 2.6 meter long fiber was tested in a laser configuration and a linearly polarized laser output at 1026nm was achieved with PER value of 21dB without using any polarizers. To our knowledge, this is the first demonstration of a polarizing all-solid photonic bandgap fiber with the polarizing effect over its entire transmission band. The effective mode area of the straight fiber is  $\sim 1150\mu\text{m}^2$ , a record for polarizing all-solid photonic bandgap fibers. The PER of 21dB at the laser output is, to our knowledge, also the highest ever demonstrated in any fiber laser based on polarizing fibers. The other comparable Yb-doped polarizing fiber demonstrations are a  $\sim 700\mu\text{m}^2$  effective-mode-area photonic crystal fiber with a PER of 15.5dB at the laser output [9] and a rod-type photonic crystal fiber with  $2300\mu\text{m}^2$  effective mode area with a PER of  $\sim 8\text{dB}$  at the laser output [10].

## 2. Principle

The cladding lattice structure of high index cladding rods in the photonic bandgap fibers provides the photonic bandgap effect of the cladding lattice, i.e. anti-resonant effects of the cladding lattice, which guides light in the core of the fiber with certain transmission band [3]. Combined with the introduced birefringence and refractive index depression in the core, the photonic bandgap fibers can have the property of polarizing effect not only on the edge of the transmission band [9,10], but also over the entire transmission band. Figure 1 shows schematically the principle of the polarizing effect over the entire transmission band in our birefringent all-solid photonic bandgap fiber. The horizontal axis is the normalized frequency  $V$  of a germanium doped node in the periodic cladding structure shown in the fiber cross section in Fig. 2(a), and the vertical axis is the effective modal index. The white area in the middle represents the photonic bandgap of the cladding structure, where the core modes can be guided. The surrounding blue (grey) area represents the region where cladding supermodes exist [3]. The solid and dashed lines represent the fundamental core modes at the two orthogonal polarizations respectively. The non-degeneracy is a result of the fiber birefringence. The effective mode index of the polarization mode on the fast axis is very close to the bottom edge of the bandgap. This very small  $\Delta n_e$ , i.e. the index difference between the

fast-axis-mode and the bottom edge of the bandgap, causes a very strong coupling of the polarization mode on the fast axis to the cladding super-modes, leading to a very high loss for this polarization mode. The polarization mode on the slow axis, on the other hand, does not suffer much transmission loss due to the much larger  $\Delta n_s$ , i.e. the index difference between the slow-axis-mode and the bottom edge of the bandgap, due to the strong birefringence of the fiber.

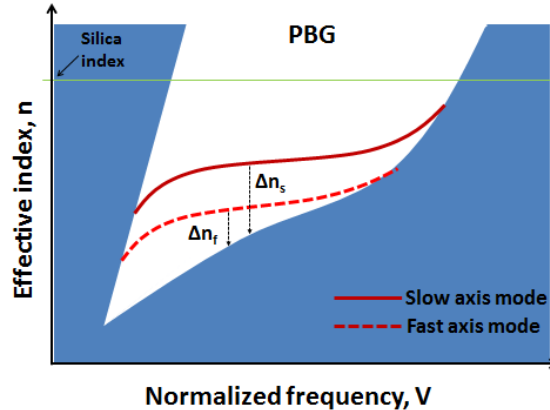


Fig. 1. Schematic of the polarizing effect in an all-solid photonic bandgap fiber.

### 3. Experiments

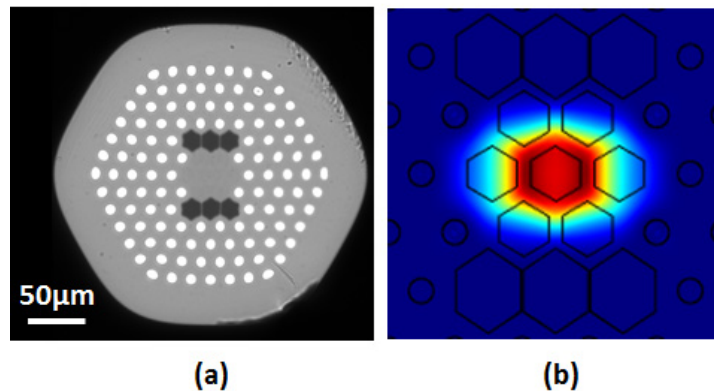


Fig. 2. (a) Cross section of the polarizing all-solid photonic bandgap fiber, (b) simulated mode pattern in the straight fiber.

A cross section image of the fabricated polarizing all-solid photonic bandgap fiber is shown in Fig. 2(a), with the simulated mode pattern shown in Fig. 2(b) which has an elliptical beam shape and an effective mode area of  $\sim 1150\mu\text{m}^2$  when straight. The numerical simulations have been performed with Finite Element Method (FEM) from COMSOL Multiphysics software. Birefringence and the stress of the boron-doped rods were not considered in this simulation, as it is expected to have minimal impact on the optical mode on the slow axis. The structure of the fiber is similar to the Yb-doped all-solid photonic bandgap fiber that we demonstrated previously [3,4], except for the three low-index boron-doped stress rods on

either side of the core to create birefringence. These rods also provide light confinement by total internal reflection in addition to bandgap guidance. By moving the stress rods away from the core, a more circular mode can be achieved in the core. This, however, also reduces the birefringence. The fiber outer cladding is 255 $\mu\text{m}$  flat-to-flat and 270 $\mu\text{m}$  corner-to-corner. The periodic cladding structure is made of germanium doped high-index rods with a node diameter of 6.71 $\mu\text{m}$  and pitch of 16.96 $\mu\text{m}$ . At the center, the missing seven high-index rods are replaced by Yb-doped active glass to form the active core of the fiber with a size of 40 $\mu\text{m}$  and 62 $\mu\text{m}$  along the two axes. The Yb-doped glass is the same active glass used in the previously reported Yb-doped fibers with a refractive index  $\sim 2 \times 10^{-4}$  below the background silica glass [4,11]. This index depression in the core contributes to the lowering of the effective index of core modes closer to the bottom edge of the bandgap, thus enhancing the loss for the fast-axis polarization mode. A very strong phase birefringence of  $3.2 \times 10^{-4}$  around 1025nm was measured in this fiber in the transmission band using the cross polarizer method [12]. This strong birefringence is also critical to the observed polarizing effect.

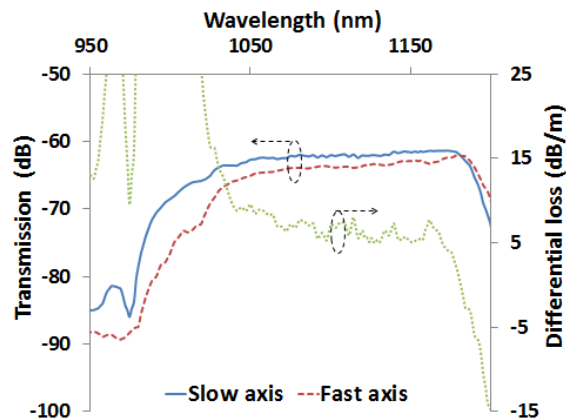


Fig. 3. Transmission spectrum and differential polarization mode loss.

The polarization-dependent transmission spectrum of the all-solid photonic bandgap fiber was measured using a polarized white light source. A short length of straight fiber, 25cm long, was used in this experiment to minimize the impact of Yb absorption. The linearly polarized white light was free-space coupled into the fiber. The transmission spectra through this 25 cm long active fiber were measured with the incident light polarized separately along the slow and the fast axis of the fiber, indicated by solid blue and dashed red lines respectively in Fig. 3. The dotted green line is the differential polarization mode loss per unit length for the orthogonal polarization modes. On the short wavelength edge of the transmission band from 1010nm to 1030nm, the differential polarization mode loss is  $>15\text{dB/m}$ . While on the long wavelength edge, the differential polarization mode loss is smaller. This is due to the fact that on the short wavelength edge, the fast-axis mode is totally coupled into the cladding while the slow-axis mode still remains guided in the core, which is clearly illustrated in Fig. 1. Strong differential polarization mode loss was observed only at the band edge in the previous report of a hybrid micro-structured fiber [1]. Our fiber shows a significant differential polarization mode loss even within the bandgap of  $> 5\text{dB/m}$  with a total 160nm bandwidth. This is due to the strong coupling of the fast-axis mode to cladding super-modes in this fiber thanks to a combination of strong birefringence and the depressed index of the ytterbium-doped glass, making the fiber suitable for broadband laser and amplifier applications where a single polarization output is desired.

This fiber was tested for laser performance with a straight 2.6m long section used in the experiment. The fiber was right-angle cleaved on both ends to construct a 4%- and 4%-reflection laser cavity and then pumped by a diode laser emitting at 975nm. Local weak bending was also applied to this fiber in order to strip out the higher-order modes propagating

in the straight fiber. Lasing was achieved at 1026nm with a lasing efficiency of 71% relative to the absorbed pump power inside the fiber, which is shown as the triangle line in Fig. 4.

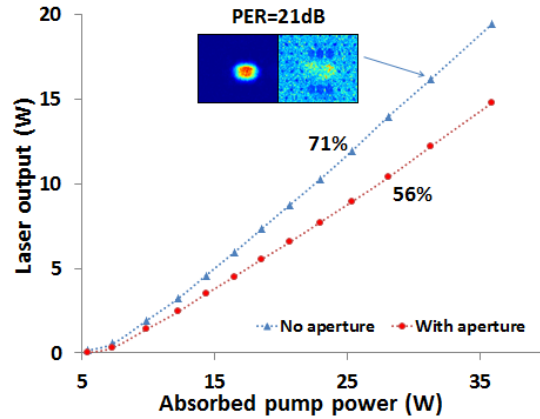


Fig. 4. Lasing efficiency and PER measurement. An aperture was used to strip off laser light in the cladding. The insets show mode images of the two polarizations.

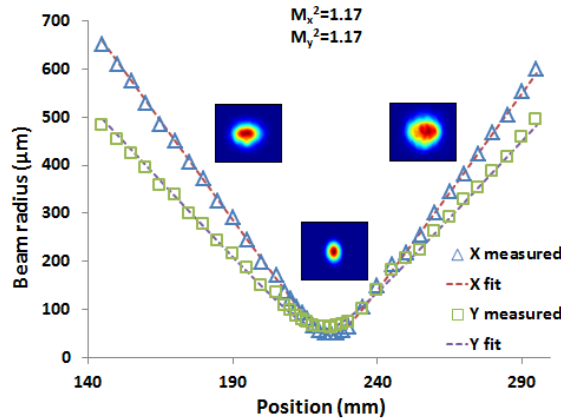


Fig. 5.  $M^2$  measurement of the output laser beam. The insets show the mode image at various locations.

We could not measure the absolute waveguide loss of this fiber due to ytterbium absorption. Similar passive fibers in our previous work [3] have shown negligible fiber losses. We, however, found that the laser light was leaking into the cladding, indicating weak guidance. In order to minimize this leakage, we had to use a straight fiber in our laser test. Maximum length is limited to 2.6m due to space limitation. With the help of an aperture to only block the light in the cladding, the lasing efficiency relative to the absorbed pump was measured to be 56%, which is shown as the dotted line in Fig. 4. The lasing efficiency corresponding to the launched pump power was measured to be 32% due to the short fiber length used in the experiment which has the cladding pump absorption of only 0.6dB/m at 975nm under straight condition. The PER value of the output laser beam from the fiber core was measured to be 21dB at 16W output power level, indicated in Fig. 4. This is a significant improvement over the best PER of 15.5dB obtained in the ytterbium-doped polarizing photonic crystal fiber [9]. The inset images in Fig. 4 are the laser beam patterns after a linear polarizer along the fast and slow axis of the fiber respectively. A larger PER value of the laser output is expected for longer fibers.

The output laser beam quality was also examined by  $M^2$  measurement, giving the same measured value of 1.17 in both X and Y orientations, as is shown in Fig. 5. The measurement



was performed with an aperture to block the light only in the fiber cladding, which would affect the measurement. The beam waists in the two directions are not identical to each other, although they have the same  $M^2$  value. This is because the shape of the laser beam is elliptical instead of circular, thus the laser beam does not have the same beam waist and divergence in the two orientations. The  $M^2$  value of 1.17 indicates robust single mode operation in this fiber. This  $M^2$  is also very close to the  $M_x^2 = 1.13$  and  $M_y^2 = 1.16$  measured in non-polarizing all-solid photonic bandgap fiber lasers [4].

#### 4. Conclusion

In conclusion, a polarizing Yb-doped all-solid photonic bandgap fiber with  $\sim 50\mu\text{m}$  core size has been demonstrated and characterized. Polarization was measured over a 160nm bandwidth covering the entire transmission band from 1010nm to 1170nm. The differential polarization mode loss was  $>5\text{dB/m}$  over the entire bandgap and  $>15\text{dB/m}$  on the short wavelength edge of the bandgap. A linearly polarized laser output at 16W with 21dB PER was achieved from a 2.6m fiber laser without any polarizer. In summary, we have demonstrated an ytterbium-doped polarizing all-solid photonic bandgap fiber with a record effective mode area and a record PER in a fiber laser without polarizer.

Despite the demonstration of a strong polarizing effect and record PER, we have also observed leakage of laser light into the cladding due to the weak guidance of the polarization mode along the slow axis. The weak guidance of the polarization mode along the fast axis enables the strong polarizing effect. Stronger birefringence could allow a raise of the effective mode index of the slow-axis polarization mode while keeping the effective mode index of the fast-axis polarization mode close to the bottom of the bandgap and could, therefore, provide improved guidance for the slow-axis polarization mode while maintaining a strong differential polarization mode loss. Given a fixed birefringence, a compromise has to be made between the guidance of the slow-axis polarization mode and the differential polarization mode loss. This work, nevertheless, demonstrates the potential for strong polarizing effect in active all-solid photonic bandgap fibers with very large mode areas.

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