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# Yb-Doped and Hybrid-Structured Solid Photonic Bandgap Fibers and Linearly-Polarized Fiber Lasers Oscillating above 1160 nm

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**SUMMARY** We review our recent work on Yb-doped and hybrid-structured solid photonic bandgap fibers (Yb-HS-SPBGFs) for linearly-polarized fiber lasers oscillating in the small gain wavelength range from 1160 nm to 1200 nm. The stack-and-draw or pit-in-jacket method is employed to fabricate two Yb-HS-SPBGFs. Both of the fiber shows optical filtering property for eliminating ASE in the large gain wavelength range from 1030 nm to 1130 nm and enough high birefringence for maintaining linear polarization, thanks to the photonic bandgap effect and the induced birefringence of the hybrid structure. The fiber attenuation of the Yb-HS-SPBGF fabricated by the pit-in-jacket method is much lower than that of the Yb-HS-SPBGF fabricated by stack-and-draw method. Linearly-polarized single stage fiber lasers using Yb-HS-SPBGFs are also demonstrated. Laser oscillation at 1180 nm is confirmed without parasitic lasing in the fiber lasers. High output power and high slope efficiency in linearly-polarized single-cavity fiber laser using the low-loss Yb-HS-SPGF fabricated by the pit-in-jacket method are achieved. Narrow linewidth, high polarization extinction ratio and high beam quality are also confirmed, which are required for high-efficient frequency-doubling. A compact and high-power yellow-orange frequency-doubling laser would be realized by using a linearly-polarized single-cavity fiber laser employing a low-loss Yb-HS-SPBGF.
***key words:*** *fiber laser, Yb-doped fiber, photonic bandgap fiber, frequency-doubling*

## 1. Introduction

High-power and large-size yellow-orange lasers such as dye lasers are applied in medical applications and astronomical applications. For a long time, a high-power and compact yellow-orange laser is desired in these applications. Moreover, such a laser will create new application fields. Frequency-doubling of near-infrared light in the wavelength range from 1160 nm to 1200 nm is an attractive way to generate high-power yellow-orange light. Recently, various high-power lasers in the wavelength range from 1160 nm to 1200 nm have been proposed as a seed laser for high-power yellow-orange frequency-doubling lasers [1]–[6].

An Yb-doped fiber laser is one of the highest power fiber lasers oscillating around 1 $\mu$m [7], [8]. The conventional oscillation wavelength range of an Yb-doped fiber laser is mainly from 1030 nm to 1130 nm in which the gain of the fiber is enough large [9]. As a result, high-power laser oscillation in the small gain wavelength range from 1160 nm to 1200 nm is challenging against the parasitic lasing in the large gain wavelength range, which limits the output power of the fiber laser oscillating in the small gain wavelength range [1].

Several approaches for eliminating the parasitic lasing have been proposed [10]–[12]. In particular, employing an Yb-doped and hybrid-structured solid photonic bandgap fiber (Yb-HS-SPBGF) as a gain fiber is an excellent way [12]. The hybrid structure contributes to photonic bandgap effect for suppressing a gain in the large gain wavelength range and to induced birefringence for maintaining linear polarization. High-power laser oscillation in the small gain wavelength range can be achieved without parasitic lasing. Yb-HS-SPBGFs for linearly-polarized single-cavity fiber lasers oscillating above 1160 nm have been studied [13]–[18]. High-power laser oscillation in the wavelength range above 1160 nm has been successfully achieved by using a fabricated Yb-HS-SPBGF.

In this paper, we review our work on Yb-HS-SPBGFs and introduce the high-power and high-efficient linearly-polarized single-cavity fiber laser oscillating at 1180 nm using the fabricated Yb-HS-SPBGF. This paper is organized as follows. In Sect. 2, the structure and concept of the hybrid structure are reviewed. In Sect. 3, two fabrication methods for Yb-HS-SPBGF are illustrated. In Sect. 4, the characteristics of fabricated Yb-HS-SPBGFs are summarized. In Sect. 5, the measurement results of fabricated fiber lasers using fabricated Yb-HS-SPBGFs are presented. Conclusions follow in Sect. 6.

## 2. Concept of Hybrid-Structured Solid Photonic Bandgap Fiber

Employing double-cladding Yb-doped solid photonic bandgap fibers (Yb-SPBGFs) is an effective way to eliminate the parasitic lasing in the large gain wavelength range. However, there have been two problems in conventional double-cladding Yb-SPBGFs; high-index elements which occupy large area of a cladding capture the significant fraction of pump power, and additional isotropy such as stress applying part in the cladding is required to induce birefringence.

To overcome these problems, we have proposed a hybrid-structured SPBGF. The features of the fiber are as follows; (1) the numbers of periodically located high-index elements are reduced, and (2) the high-index elements are aligned in two fold rotational symmetry.

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Figure 1 shows the schematic cross-section and the refractive index profile of an Yb-doped and hybrid-structured solid photonic bandgap fiber (Yb-HS-SPBGF). A core is located in the center of the fiber. The refractive indices of the inner and outer claddings are lower than that of the core. The refractive index of the outer cladding is much lower than that of the inner cladding as those in conventional double-cladding fibers. Pump light launched into the Yb-HS-SPBGF is transmitted in the inner cladding and absorbed by the Yb-doped core. The high-index elements are aligned periodically on each side of the Yb-doped core. As a result, light in the Yb-doped core is confined by total internal reflection and photonic bandgap effect as well [19].

The calculated photonic band structure of the above mentioned Yb-HS-SPBGF is shown in Fig. 2. The parameters used for calculation are as follows: the refractive index of the inner cladding is fixed to 1.45, the relative refractive index difference between high-index element and the inner cladding is 2.7%, the diameter and pitch of the high-index elements are 4.7 $\mu$m and 7.5 $\mu$m respectively, the relative refractive index difference between the Yb-doped core and the inner cladding is 0.15%. Three photonic bandgaps are appeared in Fig. 2. The transmission of light in the wavelength range around 1000 nm, which corresponds to the third photonic band, is forbidden. ASE in the large gain wavelength range of an Yb-doped fiber would be eliminated.

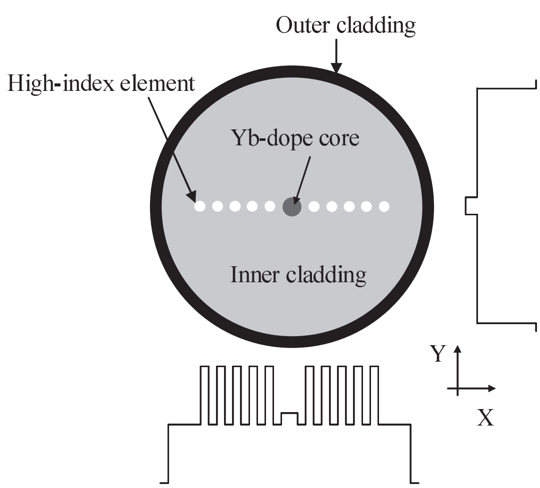


**Fig. 1** Schematic cross-section and refractive index profile of Yb-HS-SPBGF.

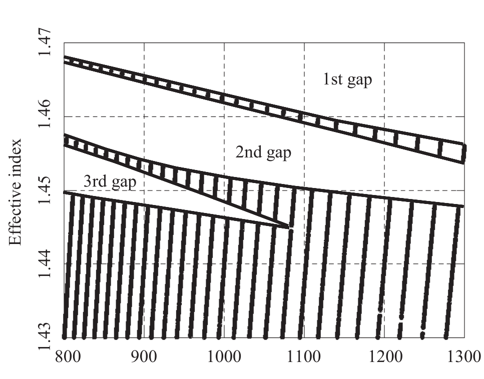


**Fig. 2** Calculated photonic band structure of Yb-HS-SPBGF.

If we employ glass material with a thermal coefficient which is much higher than that of the inner cladding as high-index elements, the elements induces large birefringence. This effect was not expected at the time of the original proposal [19] but was confirmed later [20] with insight and careful analysis. The Yb-HS-SPBGF would have the birefringence of the order of $10^{-4}$.

## 3. Fabrication Methods

### 3.1 Stack-and-Draw Method

Figure 3 shows the schematic cross-section and the refractive index profile of the Yb-HS-SPBGF employing the stack-and-draw method. The high-index elements are Ge-doped silica with silica outer layer. The inner cladding is made of F-doped silica with silica outer layer. The outer cladding is low index polymer.

Figure 4 shows the schematic cross-sectional view of the fiber preform fabricated by the stack-and-draw method. The Yb-doped core rod, the Ge-doped rods with silica outer layer, the F-doped rods and the silica rods are stuffed into the substrate silica tube and stacked to form the hybrid structure. Then, the fiber preform is drawn into a fiber.

### 3.2 Pit-in-Jacket Method

Figure 5 shows the schematic cross-section and the refractive index profile of the Yb-HS-SPBGF employing the pit-in-jacket method [21]. The numbers of the Ge-doped silica elements which consist of the high-index periodic structures in the silica increases for enhancing the distributed optical filtering property by the photonic bandgap effect.

Figure 6 shows the schematic cross-sectional view of the fiber preform fabricated by the pit-in-jacket method. The original glass preform with the Yb-doped core is fabricated by the modified chemical vapor deposition (MCVD)

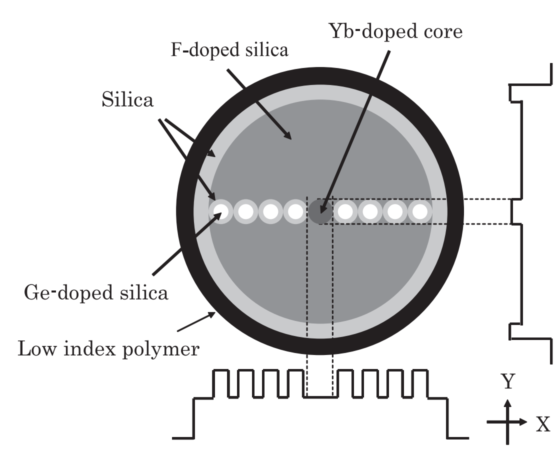


**Fig. 3** Schematic cross-section and refractive index profile of Yb-HS-SPBGF employing stack-and-draw method.

method. Two holes are drilled on each side of the Yb-doped core of the original glass preform. After that, a number of silica rods and Ge-doped rods with silica outer layer are stuffed into the two holes and stacked to form the high-index periodic structures. Finally, the fiber preform is drawn into a fiber.

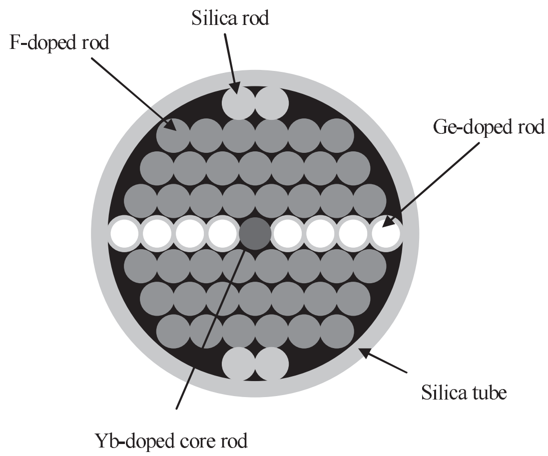


**Fig. 4** Schematic cross-sectional view of fiber preform by stack-and-draw method.

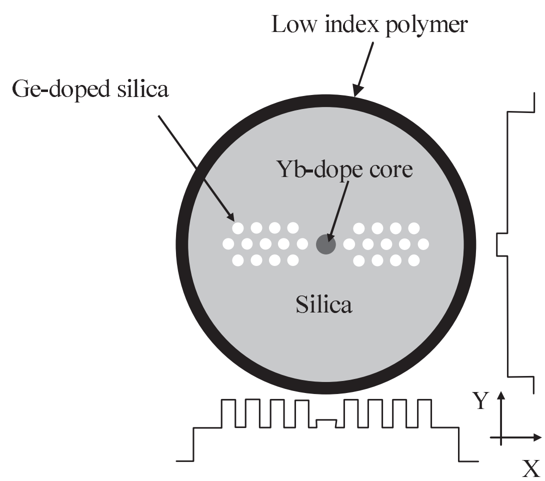


**Fig. 5** Schematic cross-section and refractive index profile of Yb-HS-SPBGF employing pit-in-jacket method.

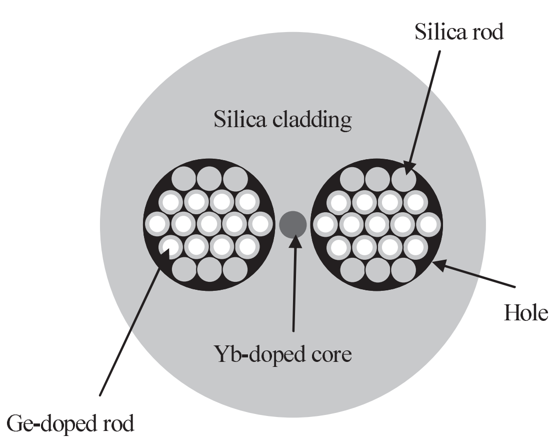


**Fig. 6** Schematic cross-sectional view of fiber preform by pit-in-jacket method.

## 4. Characteristics of Fabricated Yb-HS-SPBGFs

Figure 7 shows the cross-sectional photo of the Yb-HS-SPBGF fabricated by the stack-and-draw method (Fiber A). Figure 8 also shows the cross-sectional photo of the Yb-HS-SPBGF fabricated by the pit-in-jacket method (Fiber B).

The photonic band structures of the Yb-HS-SPBGFs are designed to transmit laser light in the small gain wavelength range and reject ASE in the large gain wavelength range [13], [15]. The third photonic band which corresponds to the stopband is from 1000 nm to 1130 nm. The second photonic bandgap which corresponds to the transmission band is above 1130 nm. The fiber parameters of the Yb-HS-SPBGFs are adequately chosen to realize the above mentioned photonic band structures.

Table 1 summarizes the fiber parameters of the fabricated Yb-HS-SPBGs. A remarkable improvement from Fiber A to Fiber B is a fiber attenuation at 1180 nm. The fiber attenuation of Fiber A is much higher than that of Fiber B, which would cause the low slope efficiency of the fiber

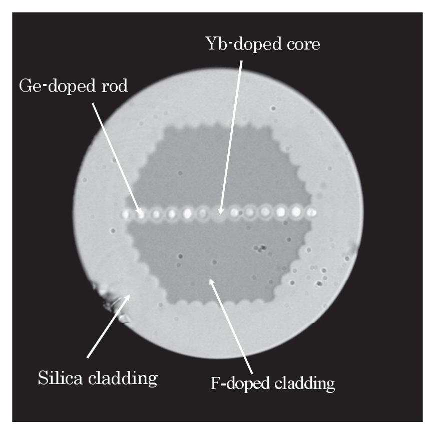


**Fig. 7** Cross-sectional photo of Fiber A.

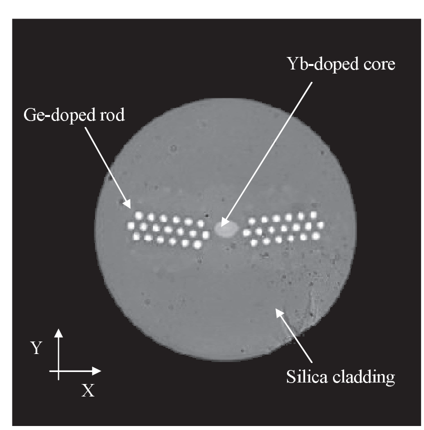


**Fig. 8** Cross-sectional photo of Fiber B.

**Table 1** Fiber parameters of fabricated Yb-HS-SPBGFs.

| | Fiber A | Fiber B |
|---|---|---|
| Fabrication method | Stack and draw | Pit-in-jacket |
| Core diameter | 7.3 μm | 14.4 μm (X)<br>9.8 μm (Y) |
| Fiber diameter | 137 μm | 153 μm |
| Pitch between high-index elements | 3.7 μm | 4.7 μm |
| Refractive index difference of high-index element | 2.8% | 2.8% |
| High-index element diameter | 7.3 μm | 7.5 μm |
| Fiber attenuation at 1180 nm | 150 dB/km | 19 dB/km |
| Birefringence | $2.1 \times 10^{-4}$ | $1.5 \times 10^{-4}$ |

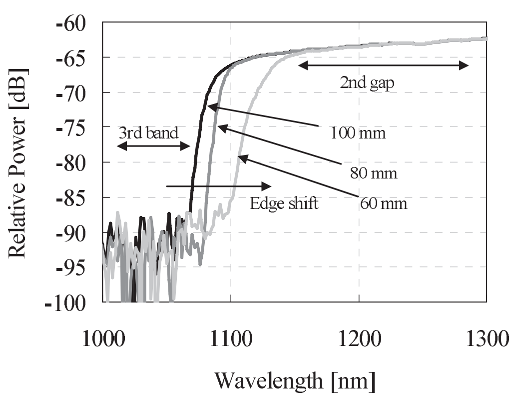


**Fig. 9** Measured transmission spectra of Fiber A with different coil diameters.

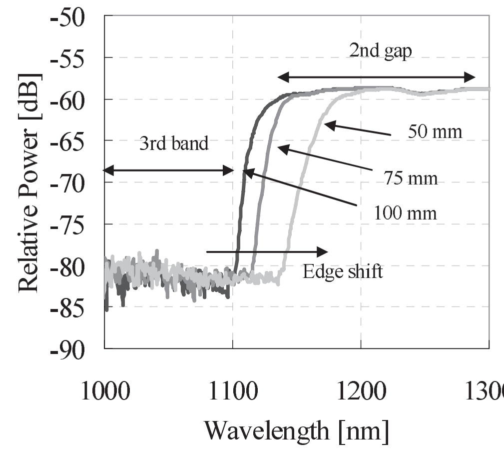


**Fig. 10** Measured transmission spectra of Fiber B with different coil diameters.

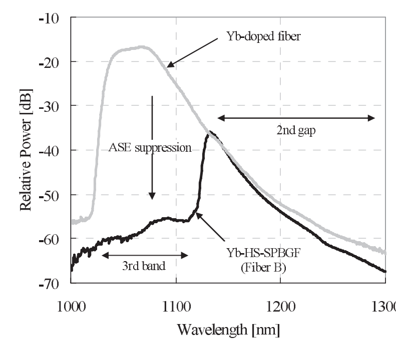


**Fig. 11** Measured ASE spectra of Fiber B and conventional Yb-doped fiber.

laser. The Yb-doped core rod would be contaminated in the fabrication process. On the other hand, the Yb-doped core has no opportunity to contact contaminations in the pit-in-jacket method. A low-loss Yb-HS-SPBGF can be fabricated easily.

Figure 9 shows the measured transmission spectra of Fiber A. The length of the measured fiber is 1 m. The transmission in the wavelength range below 1100 nm is forbidden. On the other hand, light in the wavelength range above 1100 nm is transmitted. Attenuation at 1180 nm is 150 dB/km. The shift of the short-wavelength edge of the second photonic bandgap is also observed in Fig. 9. It is necessary to adjust the edge wavelength of the transmission band for suppressing ASE in the large gain wavelength range strongly without additional fiber attenuation in the small gain wavelength range. In the Yb-HS-SPBGF, the edge of the second photonic bandgap is sensitive to fiber bend and can be easily shifted to the optimum wavelength by changing the coil diameter of the Yb-HS-SPBGF. The optimized coil diameter is 60 mm for Fiber A.

Figure 10 shows the measured transmission spectra of Fiber B. The length of the measured fiber is 10 m. The transmission in the wavelength range below 1130 nm is forbidden. On the other hand, light in the wavelength range above 1130 nm is transmitted. Attenuation at 1180 nm is 19 dB/km, which is equivalent to that of a conventional Yb-doped fiber. Although the two microstructured regions are tilted slightly away from the x-axis as shown in Fig. 8, the optical filtering property is not lost. The bandgap edge shift to the longer wavelength is also observed by decreasing the coil diameter of the fiber as shown in Fig. 10. Fiber attenuation above 1160 nm increases at a coil diameter of 50 mm. The slope efficiency of a fiber laser becomes worse. The optimized coil diameter is 75 mm for Fiber B.

The ASE spectrum of Fiber B is shown in Fig. 11. The fiber length of Fiber B is 10 m with the coil diameter 75 mm. The pump power at 915 nm is 2 W. Strong ASE suppression below 1130 nm is confirmed. For purpose of comparison, Fig. 11 includes the ASE spectrum of a conventional Yb-doped fiber.

## 5. Characteristics of Fabricated Fiber Lasers

First, we show the validity of the Yb-HS-SPBGF to realize a single-cavity fiber laser oscillating above 1160 nm. Figure 12 shows the configuration of a linearly-polarized single-cavity fiber laser oscillating at 1180 nm using Fiber A. The laser cavity consists of only PM fibers, which are single moded at 1180 nm. A PM-fiber based polarizer is placed in the laser cavity. As the result of the configuration, a single-mode and a linear-polarization operation in the fiber

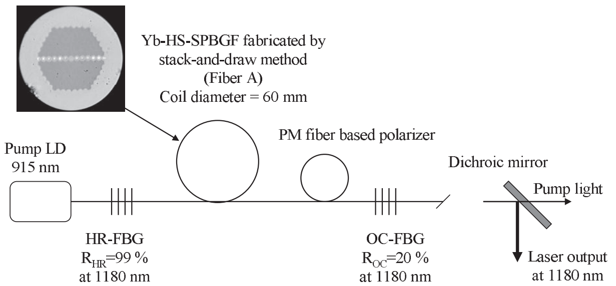


**Fig. 12** Configuration of 915-nm pumped linearly-polarized single-cavity fiber laser oscillating at 1180 nm using Fiber A.

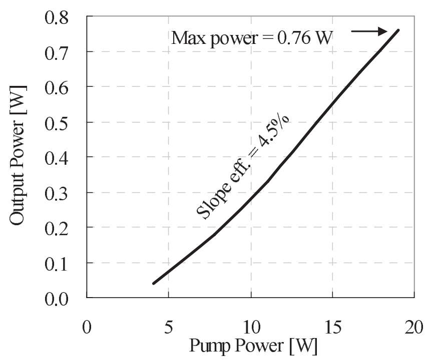


**Fig. 13** Output power of fabricated fiber laser using Fiber A.

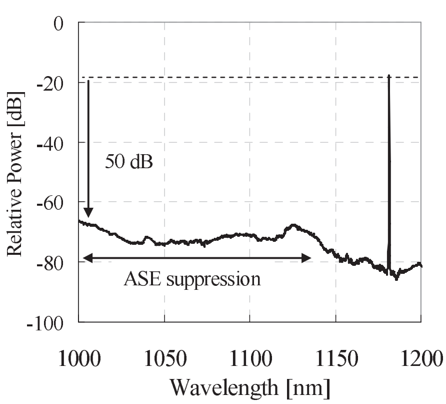


**Fig. 14** Measured spectrum of output light from fiber laser using Fiber A at a pump power of 19 W.

laser can be achieved. Reflectance ratios of HR-FBG and OC-FBG are 99% and 20% at 1180 nm respectively. The total loss of the laser cavity at 1180 nm is 3.0 dB. A 915-nm multi-mode LD is used as a pump source as an Yb-doped fiber has a broad absorption peak around 915 nm.

Figure 13 shows the output power of the fiber laser as a function of the pump power. The laser output power increases linearly with the launched pump power. The maximum output power is 0.76 W at a pump power of 19 W. The conversion and slope efficiencies are only 4.0% and 4.5%, respectively owing to the high attenuation of Fiber A.

Figure 14 shows the laser output spectrum at a pump power of 19 W measured by an optical spectrum analyzer with a spectral resolution of 0.01 nm. ASE in the large gain

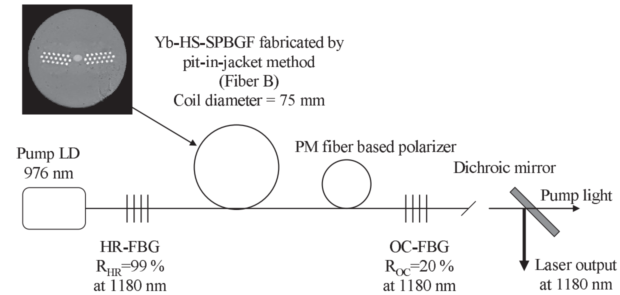


**Fig. 15** Configuration of 976-nm pumped linearly-polarized single-cavity fiber laser oscillating at 1180 nm using Fiber B.

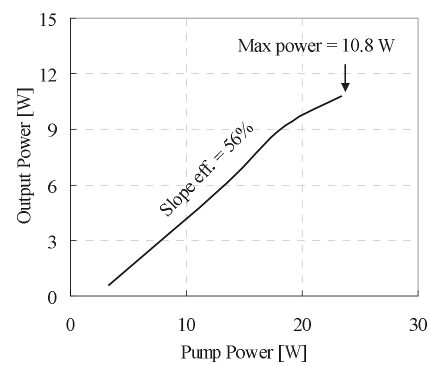


**Fig. 16** Output power of fabricated fiber laser using Fiber B.

wavelength range below 1100 nm is strongly suppressed by the distributed filtering property of Fiber A. The power at the oscillation wavelength is 50 dB higher than that of ASE around 1000 nm.

Laser oscillation at 1180 nm without parasitic lasing was confirmed by using Fiber A, which verifies the validity of the hybrid structure to realize fiber lasers oscillating above 1160 nm.

Next, we show the best performance that have never achieved in the linearly-polarized single-cavity fiber laser employing a fiber with improved attenuation property, Fiber B. Figure 15 shows the configuration of a linearly-polarized single-cavity fiber laser using Fiber B. The total loss of the laser cavity at 1180 nm is 0.9 dB. A 976-nm multi-mode LD is used as a pump source to achieve higher slope efficiency and higher output power.

Figure 16 shows the relationship between the output power and the launched pump power. The output power increases with the launched pump power. The output power reaches 10.8 W at a pump power of 23.4 W. Slope and the maximum conversion efficiencies of 56% and 50% are successfully achieved thanks to the low-loss property of Fiber B and 976-nm pumping.

Figure 17 shows the laser output spectrum at a pump power of 23.4 W. The spectral resolution of the optical spectrum analyzer is 0.01 nm. The power at the oscillation wavelength is 45 dB higher than that of the ASE. ASE in the wavelength range below 1130 nm is strongly suppressed and parasitic lasing is perfectly eliminated by photonic bandgap

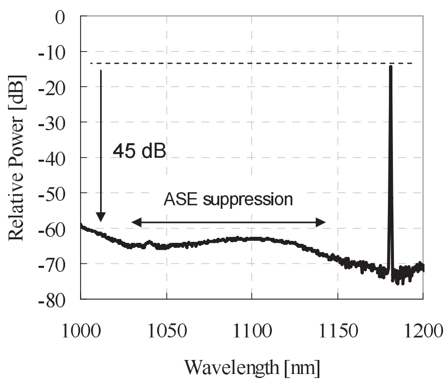


**Fig. 17** Measured spectrum of output light from fiber laser using Fiber B at a pump power of 23.4 W.

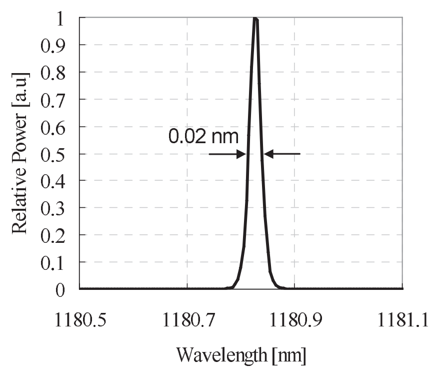


**Fig. 18** Measured spectrum of output light around oscillation wavelength.

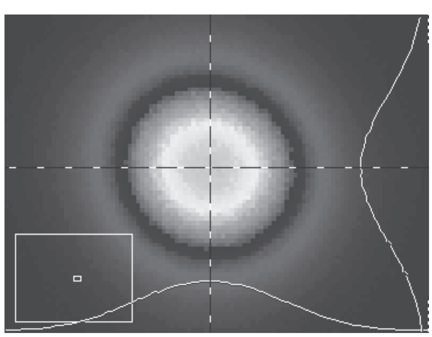

**Fig. 19** Near-field pattern of output light.

effect.

Figure 18 shows the spectrum of output light around the oscillation wavelength. The spectral resolution of the measurement is 0.01 nm. The spectral width is 0.02 nm, which is narrow enough for efficient frequency-doubling.

Figure 19 shows the near-field pattern of output light. The $M^2$ is 1.2. Nearly diffraction-limited output light is successfully obtained. This would also contribute efficient frequency-doubling.

Figure 20 shows the relationship between the power of transmitted light through a rotatable polarizer and the angle of the polarizer. The polarization extinction ratio of output light is 26 dB. The linear-polarization operation is confirmed and this is enough for stable frequency-doubling.

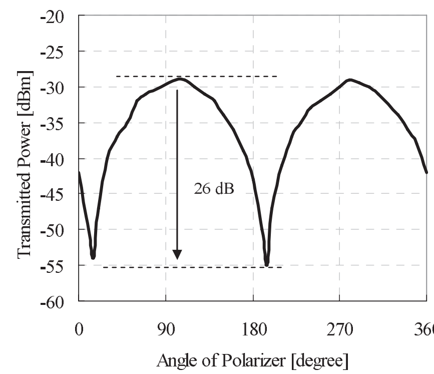


**Fig. 20** Relationship between transmitted power thorough polarizer and angle of polarizer.

## 6. Conclusion

We reviewed our work on Yb-HS-SPBGFs for linearly-polarized single-cavity fiber lasers oscillating above 1160 nm and introduced the high-power and high-efficient linearly-polarized single-cavity fiber laser oscillating at 1180 nm using the fabricated Yb-HS-SPBGF. Two Yb-HS-SPBGFs were fabricated by the stack-and-draw or pit-in-jacket method. Fiber attenuation in the Yb-HS-SPBGF fabricated by the pit-in-jacket method was 19 dB/km at 1180 nm, which was much lower than that of the Yb-HS-SPBGF fabricated by the stack-and-draw method. The ASE suppression in the large gain wavelength range was confirmed. The pit-in-jacket method is better way to fabricate the low-loss Yb-HS-SPBGF. Linearly-polarized single-cavity fiber lasers oscillating at 1180 nm using fabricated Yb-HS-SPBGFs were demonstrated. No parasitic lasing was observed in the fiber lasers. The 10.8-W output power at 1180 nm and 56% slope efficiency were achieved in the fiber laser using the low-loss Yb-HS-SPBGF. Higher output power can be achieved by increasing the pump power. The fabricated fiber laser is a good candidate as a seed laser to realize a compact and high-power yellow-orange frequency-doubling laser.

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