Linewidth Controlled 50-W Output Polarization Maintaining Fiber Laser

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ABSTRACT Optical fiber amplification technology, which had made vast progress in Erbium doped fiber amplifiers (EDFAs) for communication applications, has recently increased dramatically its optical output at the 1.0-μm wavelength by means of cladding pumping techniques using Ytterbium (Yb) doped fibers. As the fiber laser technologies including optical parts for fiber amplifiers and pumping semiconductor lasers have advanced year by year, fiber lasers have developed into superior laser oscillators in terms of controllability in wavelength, linewidth and state of polarization, as well as of output power. This paper reports on the basic configuration of fiber lasers, discusses their wavelength and linewidth control, and presents the characteristics of a polarization-maintaining fiber laser of all-fiber configuration that has achieved an optical output of 50 W at 1083-nm wavelength.

1. INTRODUCTION

Optical fiber amplification technology, which had made vast progress in Erbium doped fiber amplifiers (EDFAs) for communication applications, has recently increased dramatically the optical output at the 1.0-μm wavelength by means of cladding pumping techniques, in which pumping light is guided into the cladding of pumping fiber [1)~4)]. In the single-mode fiber lasers, owing to the core and clad configuration, any lightwave other than that of core guided modes in the employed fiber is difficult to be transmitted, so that the output light forms stable transverse modes in accordance with the index profile. This constitutes a major advantage when the output power of a fiber laser is used in combination with an external wavelength converter. However, when application to wavelength conversion is assumed, the wavelength stability, linewidth and polarization state of light source must be taken into consideration in the design, and this presents an important aspect different from using the fundamental laser wavelength directly. In this paper, the basic operation of fiber laser will be presented together with the design of a fiber laser with wavelength, linewidth and polarization state control for use in wavelength conversion application, and output performance up to 50 W of a fiber laser.

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2. BASIC CONFIGURATION

Figure 1 shows the cross-section of a cladding mode pumping fiber. The mode field diameter of this fiber is 6 μm for single-mode operation at 1.0-μm wavelength, and the silica cladding is coated with a fluorine resin having a lower refractive index for guiding the pumping light. Figure 2 shows the configuration of the fiber laser studied here. The pumping light with a wavelength of 915 nm where Yb exhibits a broad absorption peak was employed, taking wavelength controllability into account. The light output from the pumping semiconductor laser chip is coupled to a multi-mode fiber with a core diameter of 105 μm and an NA of 0.22, and is subsequently guided into the cladding of a Yb-doped fiber. The laser cavity

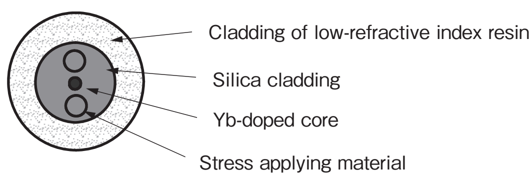

Figure 1 Polarization maintaining double-clad Yb-doped fiber.

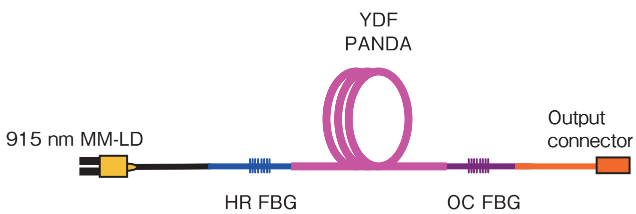

Figure 2 Basic configuration of clad-pumped fiber laser.

consists of a high-reflectivity fiber Bragg grating (HR FBG) with a reflectivity higher than 99%, and an output coupler FBG (OC FBG) with a reflectivity of around 10%, and lases at a wavelength that is determined by the reflected lightwaves from the FBGs. An FBG is configured by generating periodic interference fringes directly on a fiber glass, taking advantage of structural defects in silica.

The center wavelength λ_B, reflection bandwidth $\Delta\lambda$ and reflectivity R_B of an FBG can be designed as follows.

$$\lambda_B = 2n\Lambda$$

$$n = \frac{n_3 + n_2}{2}$$

$$\Delta\lambda = \left[\frac{2\Delta n \eta}{\pi}\right]\lambda_B$$

$$\Delta n = n_3 - n_2$$

$$R_B \approx \tanh^2\left[\frac{\pi\eta L \Delta n}{\lambda_B}\right]$$

where, n_2 is the refractive index of the FBG where the index is increased due to UV irradiation, n_3 is the refractive index of fiber core, Λ is the grating writing interval on the FBG, η is the confining coefficient in the core, and L is the grating writing length.

Since the grating is written directly on the silica glass of a fiber, the FBG shows a thermal wavelength shift as the fiber elongates or contracts due to the linear expansion of silica glass. In order to obtain high wavelength stability by compensating for temperature changes, use of a temperature compensation package shown in Figure 3 is effective, which can eliminate elongation and contraction of an FBG caused by temperature changes. Stabilization techniques for the lasing wavelength of a fiber laser will be presented in the next Section.

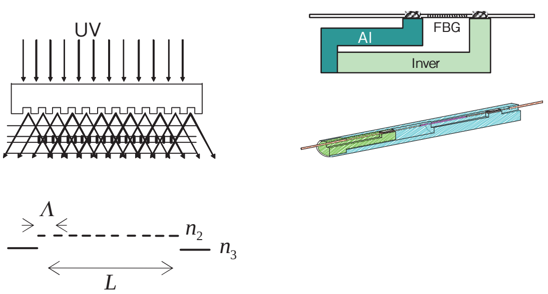

Figure 3 Basic structure of FBG and temperature compensation package.

3. CHARACTERISTICS OF FIBER LASER WITH 6-W OUTPUT

A fiber laser stabilized in wavelength was fabricated by using temperature-compensated FBGs. Figure 4 shows the reflection spectrum of an FBG written on a polarization maintaining fiber, where two reflection peaks 0.3 nm apart exist since the two optical axes in the fiber perpendicular to each other have two different refractive indexes. We have realized single polarization lasing by making the peak position of the HR on the short-wavelength side overlap with that of the OC on the long-wavelength side.

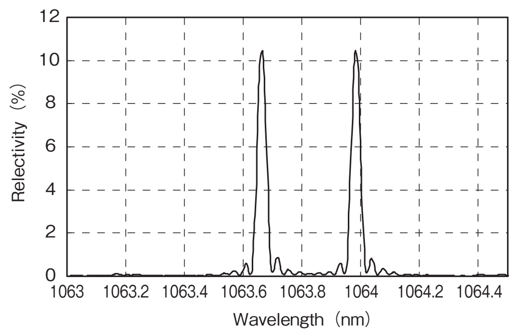

Figure 4 Reflection spectrum of FBG written on a polarization maintaining fiber.

Figure 5 shows the lasing spectrum of this fiber laser; Figure 6 the pumping current vs. optical output and its temperature dependence; and Figure 7 the pumping current vs. lasing efficiency. While a conversion efficiency from pumping light power to laser output power of 60% or higher has been obtained including the optical loss produced by inner optical parts, this rather low efficiency

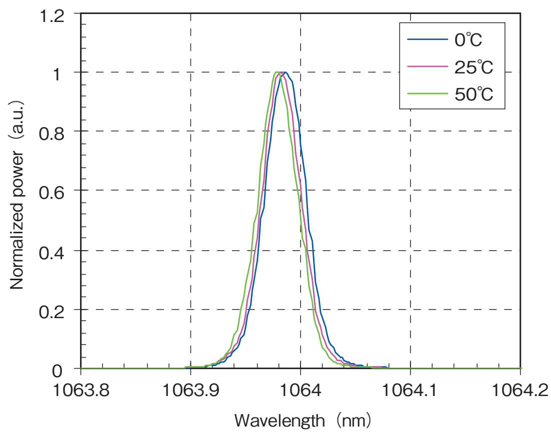

Figure 5 Lasing spectrum at 6-W output.

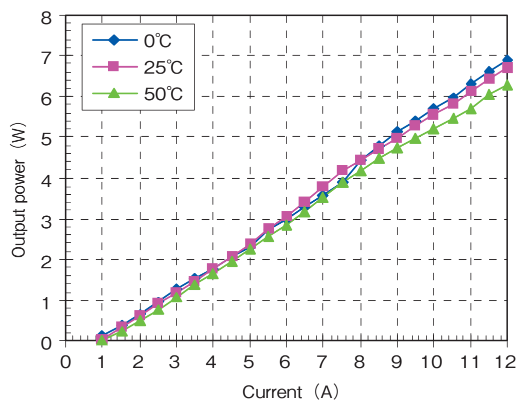

Figure 6 Pump current vs. output power characteristics.

results from the use of a slightly shorter lasing fiber to improve the controllability of laser linewidth.

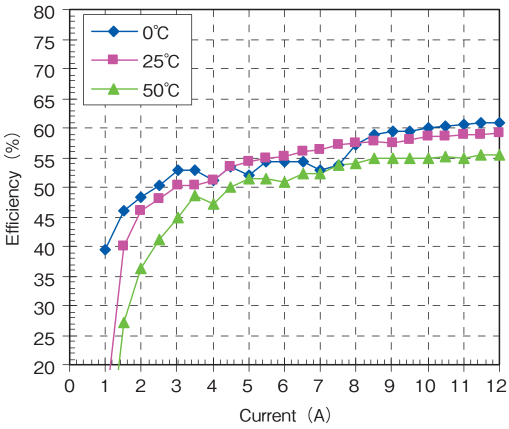

Figure 7 Pump current vs. efficiency.

The temperature dependence of the center wavelength was, as shown in Figure 8, 7 pm or less for a temperature range of 0 ~ 50°C at 6-W output, and the linewidth was found as about 35 pm. Such wavelength precision is suitable for wavelength conversion applications using second harmonic generation (SHG) devices. Figure 9 shows the appearance of this fiber laser with 6-W output, accommodated in a compact casing measuring 100 mm x 100 mm x 16 mm.

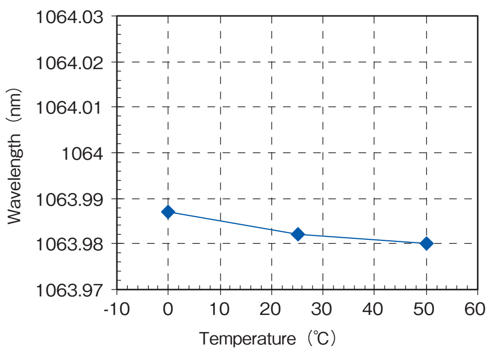

Figure 8 Temperature dependence of center wavelength.

Figure 9 Appearance of compact single polarization fiber laser.

4. FURTHER OUTPUT POWER ENHANCEMENT AND LINEWIDTH EXPANSION

The output power of a fiber laser can be increased by using additional pumping light sources, or even when gain saturation is reached, by increasing the length of lasing fiber.

Figure 10 shows an example configuration of a fiber laser with high output power by CW operation. To efficiently guide the light from multiple pumping semiconductor lasers into the cladding of a lasing fiber, a fused-fiber type optical component called tapered fiber bundle is used; specifically, the 10-W class pumping light sources of 915 nm in wavelength are each guided from the pumping ports counting 36 in total into the cladding of a Yb-doped double clad lasing fiber of 40 m in length. In this configuration, the cavity consists of an HR FBG having a reflectivity of 99% or higher with a center wavelength of 1085 nm--- where the gain peak of Yb-doped fiber is located ---and an OC FBG having a reflectivity of about 10%. As shown in Figure 11, the output power of this laser is 250 W at a total pumping power of 366 W, and the conversion efficiency from pumping light is 68%.

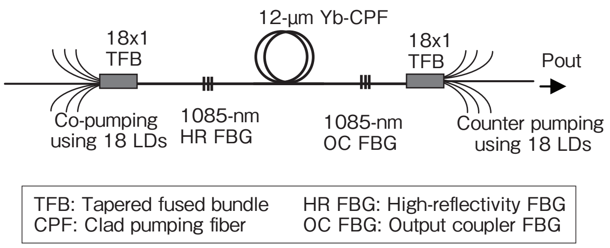

Figure 10 Configuration of CW fiber laser.

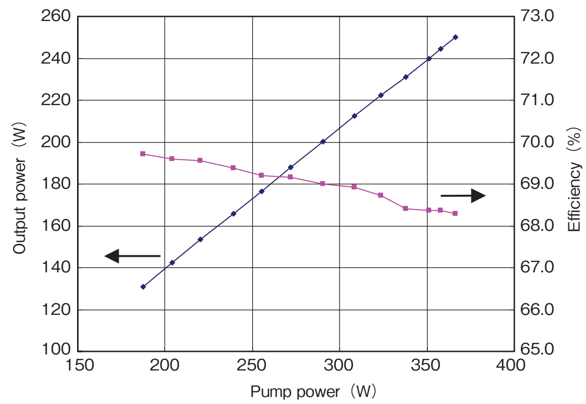

Figure 11 Output power and efficiency of CW fiber laser.

Since the cavity length of this laser is very long--- as long as 40 m ---so that the longitudinal mode spacing, which is calculated from the allowed resonating modes determined in number by the integral multiple of the wavelength, becomes very narrow--- about 0.1 pm. And since the amplification bandwidth of the Yb-doped fiber is very broad exceeding 100 nm, the lasing spectrum or linewidth of this laser is limited by the wavelength bandwidth of the cavity.

Figure 12 shows the reflection spectrum of an FBG designed to be equivalent to the one used in this laser, indicating that the half bandwidth of wavelength is about 100 pm.

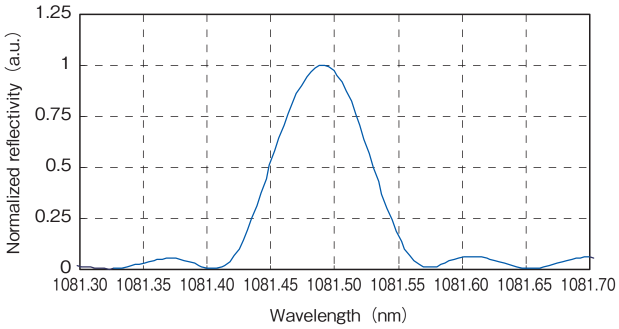

Figure 12 Reflection spectrum of an equivalent FBG.

On the other hand, Figures 13 and 14 show the lasing spectrum of this laser up to 250-W output. It can be seen that the spectrum has expanded more than ten times the wavelength bandwidth of the FBG, and that the spectrum width expands further as the output power increases. Since the longitudinal mode spacing is 0.1 pm as mentioned before, about 1000 longitudinal modes are generated in the bandwidth of the FBG, i.e., 100 pm. It is considered that since these longitudinal modes originally

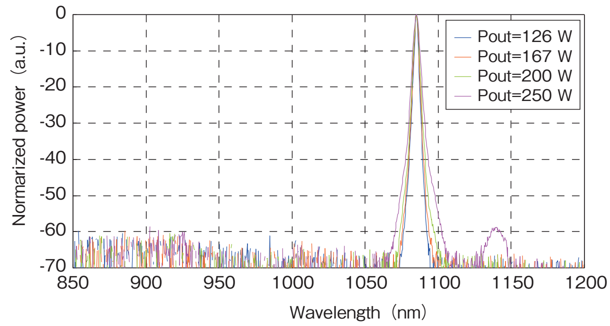

Figure 13 Output spectra of CW fiber laser.

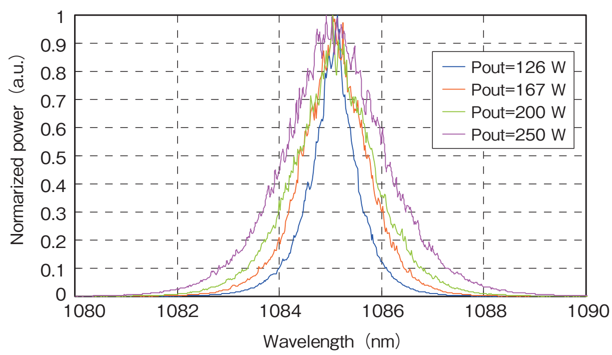

Figure 14 Output spectra of CW fiber laser (enlarged view).

have a very narrow linewidth individually, they expand in linewidth due to self phase modulation (SPM) as they propagate in the glass medium of fiber. Incidentally, the lasing peak due to Raman scattering can also be observed at around 1140 nm.

5. 50-W OUTPUT POLARIZATION MAINTAINING FIBER LASER

Although the output power of fiber lasers can be increased by using changed laser configurations as mentioned before, their linewidth also grows as the output power increases due to wavelength expansion caused by SPM. Moreover, their center wavelength tends to shift to the longer wavelength side due to the fact that the core temperature of FBGs slightly increases, irrespective of temperature compensation using a temperature-compensated package, as the high-power lasing light passes through the FBG. Since the linewidth is required to be controlled below 200 pm for high-efficiency wavelength conversion, to satisfy this requirement, we have employed a master oscillator and power amplifier (MOPA) configuration, in which the output from a fiber laser designed to produce a relatively low output power is amplified by postpositioned fiber amplifiers. As shown in Figure 15, the number of postpositioned optical amplifiers is three in total.

Figure 16 plots, against output power, the lasing

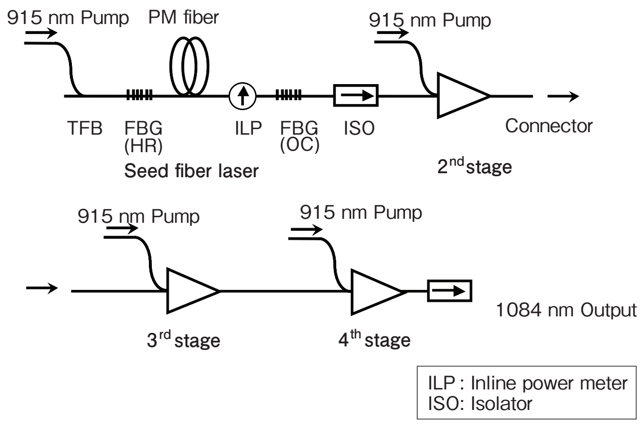

Figure 15 Configuration of 50-W polarization maintaining fiber laser.

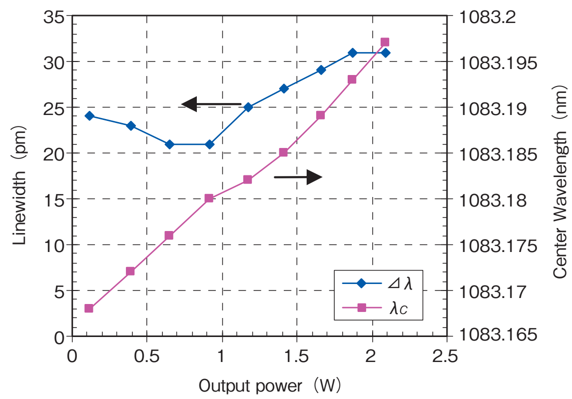

Figure 16 Lasing wavelength and linewidth of the first-stage seed laser.

wavelength and the linewidth FWHM of the seed laser at the first-stage. The output power of the seed was limited to some 2 W maximum to ease the control of the laser linewidth.

Figures 17 and 18 show the output power and linewidth at the second- and third-stage amplifiers, respectively. Figure 19 shows the output characteristics vs. pumping power at the last stage, and Figure 20 the linewidth vs. output power. The center wavelength was 1083.151 nm, constant at every output power.

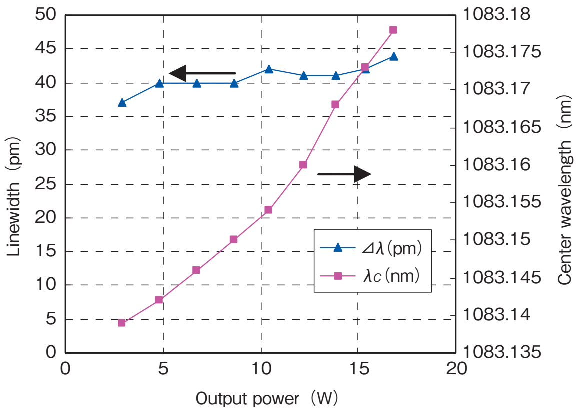

Figure 17 Output characteristics of the second-stage amplifier.

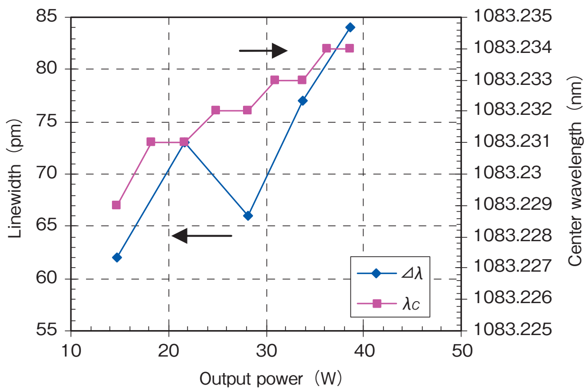

Figure 18 Output power and linewidth of the third-stage amplifier.

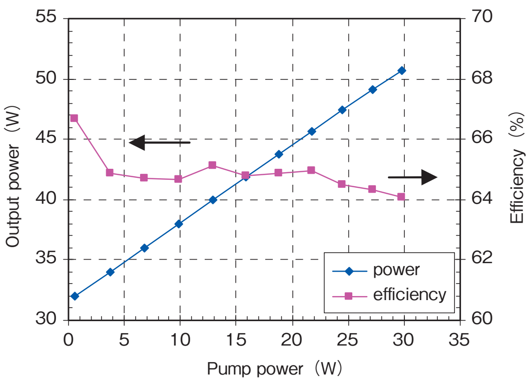

Figure 19 Output power and efficiency vs. pumping light power at the fourth-stage amplifier.

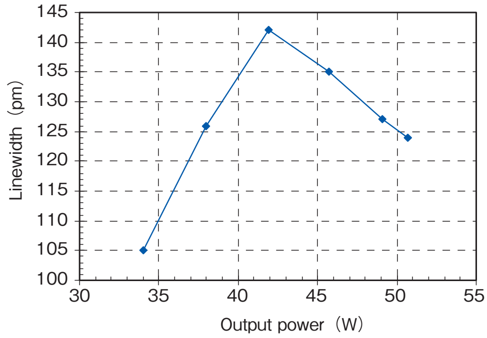

Figure 20 Linewidth vs. output power.

6. CONCLUSIONS

By taking advantage of wavelength stabilizing techniques for FBG, we have been successful in developing a fiber laser that achieves, at a wavelength of 1064 nm, a high-level of temperature as well as long-term stability in terms of linewidth and wavelength. Moreover, using a fiber amplifier of MOPA configuration, we have succeeded in obtaining a polarization-maintained output power of up to 50 W at a wavelength of 1083 nm, while controlling its linewidth below 200 pm.

It is known that, when this laser is combined, a 532-nm green light can be easily generated, in a postpositioning manner with an SHG device based on periodically poled lithium niobate (PPLN), and that a conversion efficiency of around 30% is usually obtained.

Since the wavelength of this laser is very stable without using a special control means, it is expected that applications will expand further. Work is now underway to investigate its applications in the 1030 ~ 1180 nm range, which takes advantage of the very wide gain bandwidth of Yb at 1.0 μm, since this range corresponds to the fundamental wavelength for the 500 ~ 600 nm range that is difficult to be generated directly using semiconductor lasers.

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