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Efficient wavelength-tunable operation of tandem-pumped Yb fiber lasers

Y. J. Jung[1] · **M. J. Jeon**[1,2] · **H. Jeong**[2] · **J. W. Kim**[1]

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Abstract Highly efficient operation of double-clad Yb fiber lasers with fixed-wavelength and wavelength-tunable resonator configurations tandem-pumped by tunable Yb fiber lasers is reported. When wavelength selection was achieved using volume Bragg gratings in an external feedback cavity, the tandem-pumped Yb fiber laser produced maximum output powers of 7.0, 6.8, and 6.4 W at 1070 nm, corresponding to slope efficiencies of 88.2, 87.8, and 89.5%, for pump wavelengths of 1020, 1025, and 1030 nm, respectively. The wavelength-tunable fiber laser employing volume Bragg gratings and diffraction gratings was tuned from 1055 to 1112 nm with a linewidth of ~0.3 nm (FWHM), which was in good agreement with the calculated gain spectra. Optimization of tandem-pumped Yb fiber lasers and the prospect for further improvement in performance are considered.

1 Introduction

Fiber lasers and amplifiers are now one of the most attractive laser configurations for many application areas, especially industry and defense, due to their outstanding characteristics including their ability to produce multi-kilowatts of continuous-wave (cw) output power with high efficiency, good beam quality, compactness, and reliability [1–5]. However, power scaling over ~3 kW, while preserving the near-diffraction-limited beam quality, is rather challenging with conventional direct diode pumping at 915 or 976 nm since the induced thermal effects accompanied by nonlinear optical effects cause degradation of the beam quality and catastrophic damage of the fiber at high-power levels [6, 7]. Employing a long length of the active fiber is a relatively straightforward way to mitigate thermal problems but at the expense of increased nonlinear scattering. On the other hand, a short length of fibers for reducing nonlinear scattering exacerbates the undesirable thermal effects. In order to alleviate thermal problems without elevating nonlinear scattering, in-band pumping one fiber laser or amplifier with another one, i.e., tandem pumping, has been attracting much interests over the years since the quantum defect (QD), the main heat source in the lasing process [8], can be significantly reduced. For example, the QD of Yb fiber lasers at 1080 nm becomes 5.6% for tandem pumping at 1020 nm, which is nearly half the value of conventional diode pumping at 976 nm. Thus, tandem pumping can allow the fiber laser to achieve a much higher output power without thermal problems in comparison to conventional diode pumping. It is also known that tandem pumping can reduce the unsaturated gain of unwanted higher order modes in multimode fiber lasers, leading to better beam quality and less self-pulsing [9]. Moreover, the use of a large-core fiber helps to reduce the nonlinear effects since their thresholds increase in proportion to the core area. In addition, it is expected to relieve photodarkening in an aluminosilicate Yb-doped fiber as a result of the decreased Yb^{3+} excitation level [10]. Due to these advantages, tandem pumping has demonstrated excellent performances in various high-power fiber lasers including Yb-doped fiber lasers at ~1080 nm pumped by Yb fiber lasers at ~1020 nm [11–17], Er-doped fiber lasers at ~1580 nm pumped by Er,Yb fiber lasers at ~1535 nm [18, 19], and

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✉ J. W. Kim
jwk7417@hanyang.ac.kr

1 Department of Applied Physics, Hanyang University ERICA, Ansan, Gyeonggi 426-791, Republic of Korea

2 Korea Institute of Industrial Technology, Cheonan, Chungnam 330-825, Republic of Korea

Tm- or Ho-doped fiber lasers at ~2100 nm pumped by Tm fiber lasers at ~1950 nm [20, 21]. It is well-known that a record single-mode output power of 20 kW was achieved in a tandem-pumped Yb fiber laser [22]. Although tandem pumping is very promising for power scaling of Yb fiber lasers, many scientific and technical details have yet to be published.

In this paper, we report fixed-wavelength and wavelength-tunable operation of an Yb fiber laser tandem-pumped by a tunable Yb fiber laser. The fixed-wavelength fiber laser yielded cw outputs of 7.0, 6.8, and 6.4 W at 1070 nm, corresponding to slope efficiencies of 88.2, 87.8, and 89.5%, for pumping at 1020, 1025, and 1030 nm, respectively. The wavelength-tunable Yb fiber laser could be tuned from 1055 to 1112 nm using both the diffraction grating and the volume Bragg grating and successfully achieved laser operation with the minimum quantum defect of 2.4%. We investigate the dependence of the laser performance on the pumping and laser wavelengths in detail and compare them with the calculated gain spectra and numerical simulations.

2 Experiments and results

The tandem-pumped Yb fiber laser configurations used in our experiments are shown in Fig. 1. The pump light was provided by a diode-pumped tunable Yb fiber laser constructed in-house. The Yb fiber pump laser (YFPL) employed a double-clad multimode (MM) Yb fiber supplied by nLight (Yb1200-20/125DC). This fiber had an Yb-doped core with a diameter of 20 μm and a numerical aperture (NA) of 0.08 surrounded by an octagonal-shape pure silica inner-cladding with a diameter of 125 μm. The latter was coated with a low refractive index polymer outer-cladding yielding a high NA of 0.48 for the inner-cladding pump guide. The peak cladding absorption coefficient at 976 nm was ~25.8 dB/m and, hence, a relatively short fiber length of ~1 m was selected for our experiments. Two fiber-coupled diode lasers wavelength-stabilized at 976 nm were used to pump the Yb fiber via a (2 + 1) to 1 pump/signal combiner. Feedback for lasing was provided by the ~3.6% Fresnel reflection from a perpendicularly cleaved facet at the output end of the fiber and, at the opposite end, by a simple external feedback cavity containing a collimating lens with a 100 mm focal length and a diffraction grating with 300 lines/mm. The fiber end facet that was adjacent to the external cavity was angle-cleaved at ~10° to suppress broadband feedback. Under this configuration, the lasing wavelength could be selected from 1017 to 1052 nm, as shown in Fig. 2a, with a linewidth (FWHM) of ~0.3 nm.

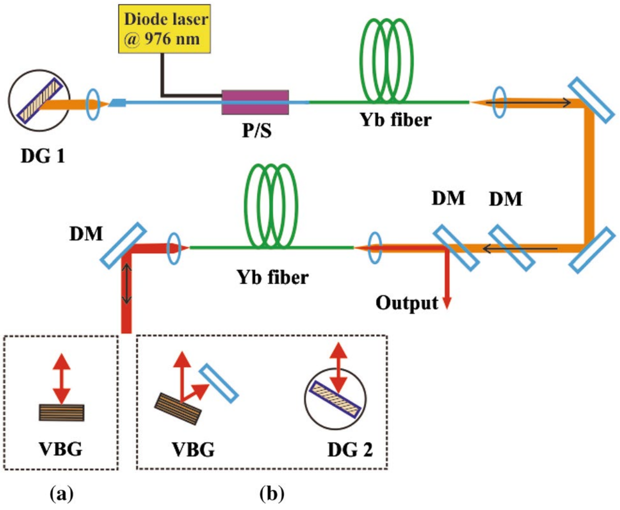

Fig. 1 Schematic of the tandem-pumped Yb fiber laser configuration for **a** fixed-wavelength operation and **b** tunable operation

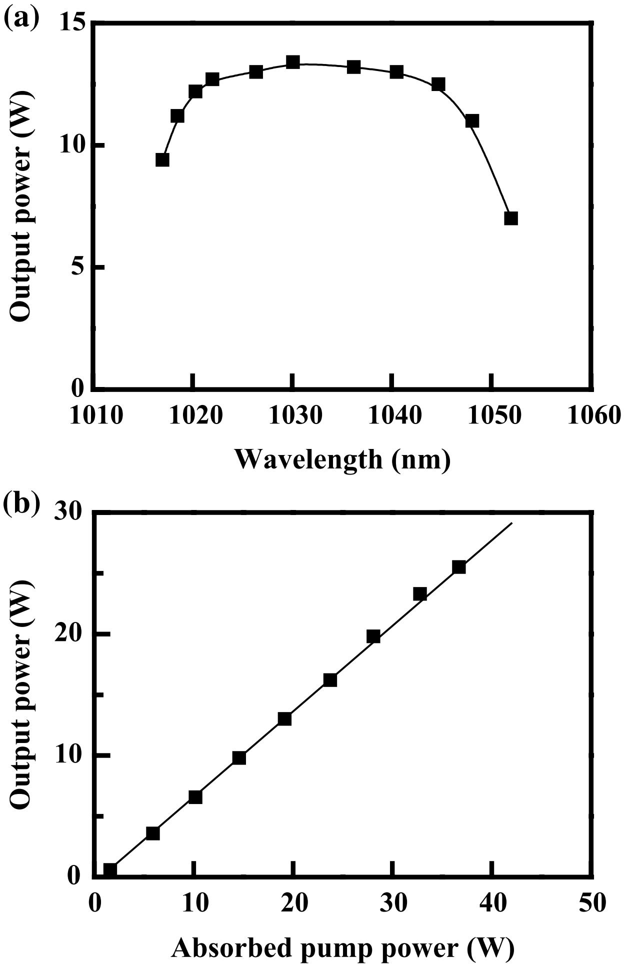

Fig. 2 **a** Yb fiber pump laser output power versus operating wavelength and **b** laser output power versus absorbed pump power for fixed-wavelength Yb fiber lasers at 1030 nm

The laser output power as a function of the absorbed pump power is shown in Fig. 2b. The Yb fiber laser generated a maximum output power of 25.5 W at 1030 nm for an absorbed pump power of 30.4 W, corresponding to a slope efficiency of 72.1%. We selected three wavelengths, 1020, 1025, and 1030 nm, for tandem pumping in our experiments. The YFPL output was collimated and then launched into the signal Yb-doped double-clad fiber.

The tandem-pumped Yb fiber signal laser (YFSL) employed the same MM Yb fiber used in the pumping source. The length of the fiber was ~16 m and the cladding absorption efficiencies for the pump light at 1020 nm, 1025, and 1030 nm were calculated to be 92.6, 86.9, and 76.5%, respectively, using the absorption data provided by nLight. In order to separate the pump and signal beams, two dichroic mirrors with high reflectivity (HR > 95%) at the lasing wavelength (1050–1100 nm) and high transmission (T > 90%) at the pump wavelength (1010–1040 nm) were inserted before the YFSL. In the fixed-wavelength YFSL, a simple external cavity design was employed and feedback for lasing was provided by a volume Bragg grating (VBG) aligned with the grating vector parallel to the beam direction. The VBG used in our experiments had a clear aperture of 5 × 5 mm and a thickness of 2 mm. Both end facets of the VBG were antireflection coated at the lasing wavelength (1.0–1.1 μm). The peak reflectivity was 95% at 1070 nm with a FWHM bandwidth of <1 nm.

Using this configuration, the fixed-wavelength YFSL yielded maximum output powers of 7.0, 6.7, and 6.3 W at 1070 nm for an absorbed pump power of 10.2 W at 1020 nm, 9.2 W at 1025 nm, and 9.1 W at 1030 nm, respectively (see Fig. 3). The slope efficiencies with respect to the absorbed pump power were 88.2, 87.8, and 89.5% for pump light wavelengths of 1020, 1025, and 1030 nm, respectively, showing that the lasing performance did not depend on the pump wavelength. The beam qualities were measured to be 2.3–2.5, but it is expected to be enhanced after stripping of the cladding mode.

Tunable operation of the YFSL was demonstrated by employing the modified external feedback cavity design with the VBG and the reflective diffraction grating (Fig. 1b). For the VBG, the shortest lasing wavelength achieved was 1055 nm for pump wavelengths of 1020 and 1030 nm, as shown in Fig. 4(a). The output power levels are 3.0–4.1 W for 1020 nm and 1.6–3.6 W for 1030 nm, which were slightly lower than the output powers of 4.5 W (1020 nm) and 4.1 W (1030 nm) obtained in the fixed-wavelength configuration due to the double reflection from the VBG in the tunable feedback cavity. The reflective diffraction grating with 300 lines/mm blazed at 1 μm was also used for tunable operation and Fig. 4b shows the

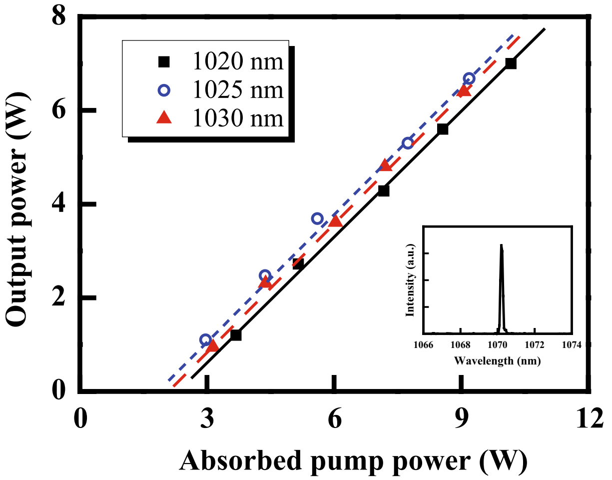

Fig. 3 Yb fiber signal laser output power versus absorbed pump power in the fixed-wavelength configuration using the VBG pumped at 1020, 1025, and 1030 nm. The inset is the output spectrum of the output at 1070 nm

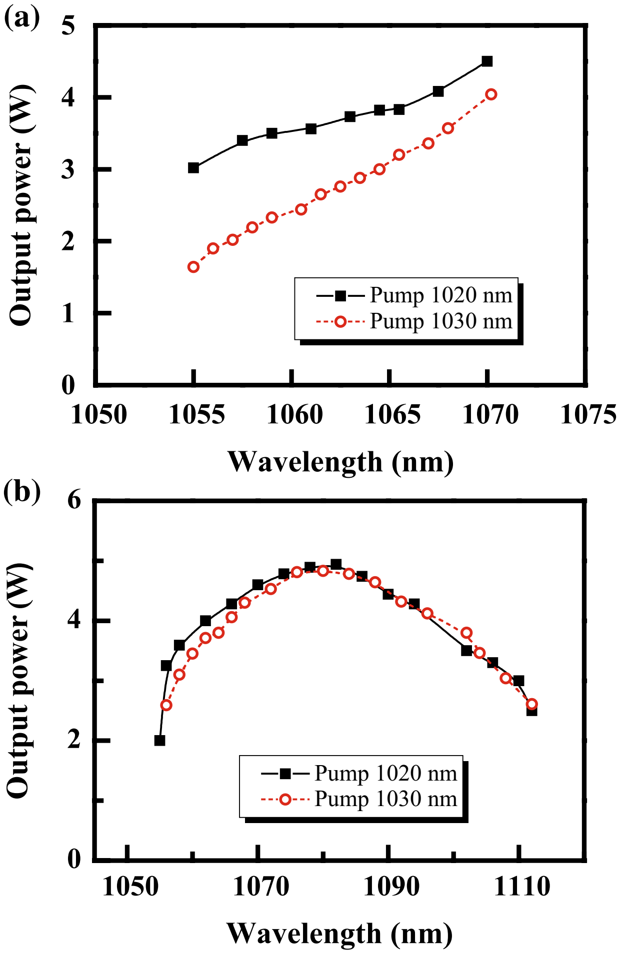

Fig. 4 Yb fiber signal laser output power versus operating wavelength in the wavelength-tunable configuration using **a** the VBG and **b** the diffraction grating

experimental results. The lasing wavelength could be tuned from 1055 to 1112 nm for pumping at 1020 and 1056 to 1112 at 1030 nm, which has little dependence on the pump wavelength. The minimum quantum defect achieved in the experiments was 2.4%, which was nearly one-fourth of the value for conventional diode pumping at 976 nm, implying the possibility of efficient lasing with a very small heat density. Although the same Yb fiber was used for both the YFPL and YFSL, the different tuning ranges can be understood by the gain curve of the Yb fiber due to the Yb^{3+} excitation level. The gain G$_{\mathrm{dB}}$ (in dB) can be calculated from the cross-section spectra using the following equation [[23]:

$$G_{\mathrm{dB}}(\lambda_{\mathrm{p}}) = 4.343\,L N_0 \Gamma\left[\left(\sigma_a(\lambda_{\mathrm{p}}) + \sigma_e(\lambda_{\mathrm{p}})\right) n_2 - \sigma_a(\lambda_{\mathrm{p}})\right], \tag{1}$$

where λ_p is the pump wavelength, L is the fiber length, N_0 is the concentration of Yb^{3+} ions, Γ is the overlap of the pump power distribution with the Yb-doped region (the ratio between the core and cladding areas), σ_a and σ_e are the absorption and emission cross-sections, respectively, and n_2 is the fraction of excited Yb ions. The fiber parameters (N_0, σ_a, and σ_e) were provided by nLight. The fraction of the excited Yb^{3+} ions, n_2, is the only variable in Eq. (1) when the fiber and the pump wavelengths are determined. If the gain is broadened homogenously in the fiber, n_2 is independent of the pump wavelength [10]. However, the pump power distribution along the fiber causes inhomogeneous broadening effects of the gain, especially in a cladding-pumped fiber, leading to the wavelength-dependence of n_2 [23, 24]. The Yb^{3+} excitation level along the fiber was numerically calculated with the aid of the commercial software RP Fiber Power (RP Photonics Consulting GmbH). Although n_2 decreases along the fiber for the end-pumping configuration due to the higher absorption at the pumping end, we used the maximum value of n_2 for Eq. (1) in order to investigate the differences of the gain spectrum due to the pump wavelength. The calculated maximum values of n_2 were 2.7% and 2.0% at pump wavelengths of 1020 and 1030 nm, respectively, confirming the very small value of n_2 for tandem pumping. Figure 5 shows the theoretical gain spectra of the used Yb fiber for each pump wavelength using the calculated n_2. The shortest wavelengths of the positive gain are 1055 and 1058 nm for pumping at 1020 and 1030 nm, respectively, which are in a very good agreement with the experimental values (see Fig. 4). For diode pumping at 976 nm, the shortest wavelength was calculated to be ~994 nm with the n_2 value of ~30.0%, as shown in Fig. 5, which was much shorter than the experimental value of the YFPL, ~1017 nm. This discrepancy can be attributed to the rapid decay of n_2 along the active fiber for the diode pumping with high absorption. The value of n_2 becomes <3% at the position of 0.6 m, less than 10% of the maximum value, for the pump wavelength of 976 nm. Thus, the actual value of n_2 in the latter part of the fiber is much smaller than the theoretical expectation (~30%), resulting in laser operation at a longer wavelength. For tandem pumping at 1020 and 1030 nm, n_2 is calculated to be ~0.6% even at the position of 16 m, which is very uniform along the fiber.

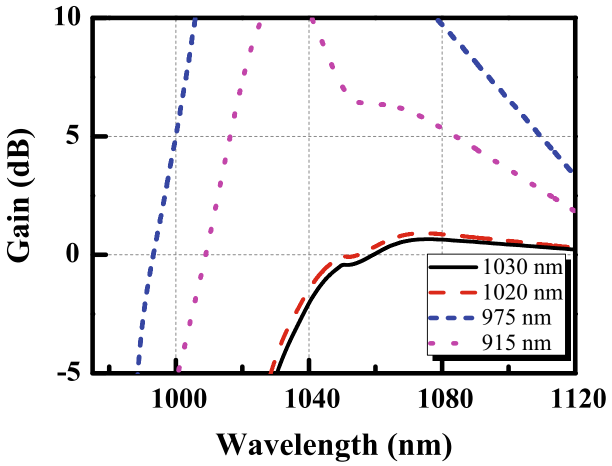

Fig. 5 Theoretical gain spectra of the Yb fiber for pump wavelengths of 915, 976, 1020, and 1030 nm. The Yb^{3+} excitation level, n_2, was theoretically calculated at each wavelength

Table 1 summarizes the experimental and calculated results for tandem pumping at 1020 and 1030 nm. For the same length of fiber, i.e., ~16 m, the calculated slope efficiencies are nearly the same for both pump wavelengths, which were in good agreement with the experimental values, since the smaller QD for pumping at 1030 nm was compromised by a slightly lower gain (see Fig. 5), compared to pumping at 1020 nm. Table 1 also shows the calculated results of the Yb fiber length required for cladding absorption of 20 dB and the expected slope efficiency at each pumping wavelength. As shown in Table 1, the necessary length of the Yb fiber is much longer for pumping at 1030 nm than it is at 1020 nm, resulting in a noticeable decrease in the slope efficiency even for the smaller quantum defect. These results can be attributed to the significantly increased background loss and reabsorption loss caused by the longer length of the Yb fiber. Moreover, a longer fiber exacerbates the nonlinear effects limiting the obtainable maximum power. Therefore, we can conclude that tandem pumping at 1020 nm is preferable for power scaling of the Yb fiber laser overcoming the conventional diode pumping.

Table 1 Summary of the theoretical and experimental results for tandem-pumped Yb fiber lasers using a MM Yb fiber (nLight, Yb1200-20/125DC)

	Wavelength (nm)	Theory	Experiment
Slope efficiency (lasing at 1070 nm, fiber length: ~16 m)	1020	92.5%	88.2%
	1030	92.4%	89.5%
Shortest lasing wavelength (fiber length: ~16 m)	1020	1054 nm	1055 nm
	1030	1059 nm	1056 nm
Fiber length for 20 dB absorption and the corresponding slope efficiency	1020	27.7 m	
		88.6%	
	1030	48.1 m	
		85.4%	

3 Conclusion

We have demonstrated the highly efficient, wavelength-tunable operation of tandem-pumped Yb-doped fiber lasers for different pump wavelengths in fixed-wavelength and wavelength-tunable cavity configurations using a VBG and a diffraction grating. The Yb fiber laser wavelength-fixed by the VBG produced maximum output powers of 7.0, 6.8, and 6.4 W at 1070 nm, corresponding to slope efficiencies of 88.2, 87.8, and 89.5%, for pumping wavelengths of 1020, 1025, and 1030 nm, respectively. Tunable operation was demonstrated over 57 nm from 1055 to 1112 nm, which was in good agreement with the theoretical gain spectra at the given pump wavelengths. Moreover, our results indicate that pumping at a shorter wavelength is preferable for tandem pumping since it allows us to use a shorter length of fiber, having a smaller background loss, lower cost, and reduced nonlinear scattering. Therefore, it is confirmed that the tandem-pumping laser configuration enables highly efficient laser operation with a very small quantum defect in the cladding-pumped Yb fiber laser configuration, offering a promising route for very high-power operation that is superior to the conventional diode pumping configuration.

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