230-mW Diode-Pumped Single-Frequency Er : Yb Laser at 1.5 μm

S. Taccheo, G. Sorbello, *Student Member, IEEE*, P. Laporta, G. Karlsson, and F. Laurell

***Abstract*—We report on a diode-pumped Er : Yb laser able to generate a single-frequency output power in excess of 200 mW at both 1.53 μm and 1.56 μm and over 300 mW in multimode operation. The tuning characteristics of the source are reported and discussed. The relative intensity noise presents in all configurations a peak value lower than −92 dB/Hz and its level decreases below −160 dB/Hz for frequencies higher than 8 MHz.**

***Index Terms*—Diode-pumped laser, erbium-ytterbium laser, optical fiber communications, single-frequency laser, tunable laser.**

I. INTRODUCTION

EFFICIENT single-frequency lasers in the 1.5-μm region are of great interest for optical communications, eye-safe measurements and ranging, and spectroscopy. In particular, there is a strong need in both digital and analog optical transmission for high-power tunable single-frequency lasers [1]. In fact, an output power level in excess of 100 mW makes unnecessary booster amplification and avoids the related system sensitivity degradation due to amplified spontaneous emission generated in the signal slot. These sources may be exploited as well for the definition of an absolute frequency standard at 1.5 μm by locking a frequency-doubled oscillator to metrology standards such as Rb and K absorption lines [2], and for high-resolution spectroscopy. Narrow-linewidth dual- and single-frequency lasers are also suitable to generate stable electric signals ranging from hundreds of gigahertz to terahertz [3], [4].

Despite the vast efforts devoted to power scaling of narrow-linewidth single-frequency sources at 1.5-μm wavelength, currently available devices exhibit output powers generally well below the 100-mW level. Among InGaAsP distributed feedback lasers (DFB), which are nowadays the dominant sources for optical communication systems, the highest power commercial devices provide a few tens of milliwatts with ~MHz linewidth, the 100-mW level being demonstrated only at the laboratory level [5]. As far as solid-state erbium-based sources are concerned, the single-mode erbium fiber laser [6], [7] is limited by the amount of pump power that can be coupled into the fiber, while bulk Er–Yb:glass lasers generally suffer from pump-induced thermal stress [8]. However solid-state laser sources easily achieve far better linewidth (<50 kHz) compared to DFB laser offering advantages for applications such as coherent optical detection. Very recently, we demonstrated an output power in excess of 100 mW from a tunable, linearly polarized, single-frequency Er–Yb laser using a new glass base [9]. Comparable results were also obtained by using a similar design with a monolithic cavity [10].

In this letter, we present results on the power scaling of our Er–Yb glass laser up to a value of 230 mW that represents, to the best of our knowledge, the highest output power for a single-frequency solid-state laser at 1.5 μm. This output power level was achieved by using a new glass host able to support high pump intensity and by an upgraded pumping scheme employing two cross-polarized 1-W 980-nm laser diodes. We also report the tuning characteristics of this source using different optimized output coupler for obtaining different oscillating wavelengths, and we present and discuss the relative intensity noise (RIN) properties of the oscillator, which turns out to be an excellent candidate for many applications including analog optical communications and frequency doubling. In particular, the peculiar amplitude noise spectrum of such a solid-state laser offers a negligible noise compared to DFB laser in the frequency band of interest for common antenna television (CATV) applications.

II. EXPERIMENTAL SETUP

The compact laser cavity consists of a 1-mm-thick flat-flat erbium-doped and ytterbium-codoped phosphate glass disk and a 10-mm radius of curvature output coupler. One face of the glass disk forms one end of the resonator and is coated for high reflection ($R > 99.9\%$) at 1550 nm and for high transmission ($T > 92\%$) at 980-nm pump wavelength. The other face is antireflection coated ($R < 0.1\%$) at the laser wavelength. To enhance the optical gain coefficient and to allow operation above 1565 nm, the erbium concentration was increased by 50% with respect to other active media previously used [7] up to $\sim 1.5 \times 10^{20}$ ion/cm^3, while the ytterbium concentration ($\sim 2 \times 10^{21}$ ion/cm^3) was kept almost unchanged. The use of a new glass base (Kigre QX–Er) makes it possible to sustain much higher thermal loads with improved resistance to pump induced thermal stress. To achieve single-frequency operation and coarse spectral control, an uncoated 100-μm-thick BK7-etalon is inserted in the laser resonator. The 10-mm radius of curvature output coupler is glued to a piezoelectric transducer for fine cavity tuning and for linewidth dithering. The pumping scheme, together with the experimental setup, are shown in Fig. 1. Two broad-area 1-W 975-nm InGaAs laser diodes, coupled by a polarizing beam-splitter, produce an almost circular 45-μm pump beam waist. The reshaping and focusing optical systems is composed by a triplet with focal length $f = 8$ mm and a pair of

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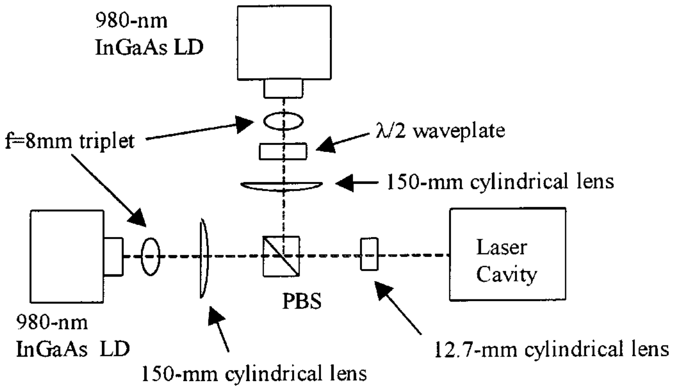

Fig. 1. Experimental setup. PBS: polarizing beam splitter; LD: laser diode.

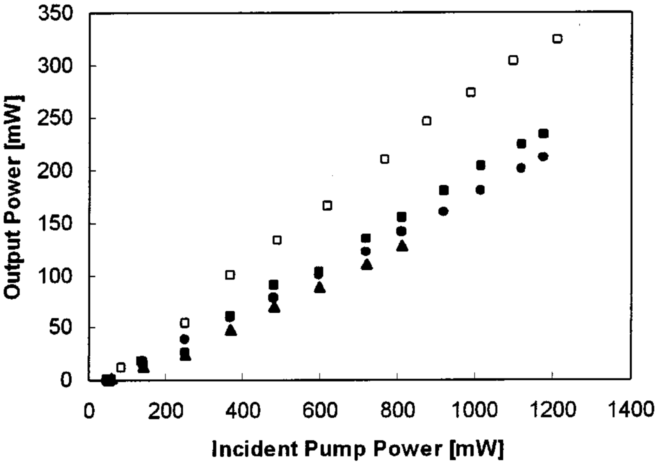

Fig. 2. Output power versus incident pump power. (□) multimode operation, 2% output coupler; (■) single-frequency operation at 1535.9 nm, 2% output coupler; (●) single-frequency operation at 1558.4 nm, 1% output coupler; (▲) single-frequency operation at 1567.5 nm, 0.5% output coupler.

cylindrical lenses with focal lengths $f = 150$ mm and $f = 12.7$ mm to reduce the source astigmatism and circularize the pump beam in the active material. All the optics are antireflection coated to minimize backreflections at 980 nm. The maximum available pump power incident on the active material disc is ~1.2 W. We did not observe any pump RIN modification induced by the backreflections and, therefore, no optical isolators on the pump paths were used.

III. EXPERIMENTAL RESULTS

Fig. 2 shows the output power characteristics of the Er–Yb laser for various output coupler transmission values and two different operating regimes. Empty squares refer to multimode operation obtained using a 2% output coupler. Over 300 mW output power was achieved at 1.2-W incident pump power with ~70 mW pump power threshold and 27% slope efficiency. The output beam was circular and diffraction limited ($M^2 < 1.05$), and we were able to couple into a standard single-mode optical fiber about 75% of the output power. We plan to further reduce the coupling losses to less than 0.5 dB. The high single-pass gain value (about 12%) obtained suggests that this laser can be operated with higher output coupling values in order to further increase the slope efficiency. The measured oscillating bandwidth was about 2.8 nm, corresponding to ~12 equally spaced longitudinal modes. Ultrastable terahertz beat frequency generation is therefore possible by a suitable external spectral filtering of two longitudinal modes [3]. In fact, even in the absence of any cavity length control, in a laboratory environment (temperature variations within a few degrees) a mode-spacing frequency stability $\Delta\nu/\nu$ better than 10^{-7} may be readily achieved.

The insertion of a 100-μm-thick uncoated etalon allows for robust single-frequency operation. Fig. 2 shows the output power versus incident pump power curves corresponding to three different wavelengths across the laser tuning range, namely 1535.9 nm (squares), 1558.4 nm (circles), and 1567.5 nm (triangles), obtained by using the 2%, 1%, and 0.5% output coupler transmission, respectively. Note that the red-shift of the lasing wavelength with the decreasing cavity losses is related to the erbium laser three-level scheme where the round-trip gain is a balance between emission and absorption spectra weighted by the respective populations: lower losses correspond to a lower population inversion and, therefore, to a higher gain at longer wavelengths where absorption cross section is minimum [8]. The best result, 230 mW output power with 21% slope efficiency, is achieved at 1535.9 nm, close to the erbium peak gain, and represents, to the best of our knowledge, the highest output power in single-frequency operation so far obtained from a diode-pumped erbium glass laser at 1.5 μm [10]–[12]. A slight lowering of this performance is observed when the laser wavelength is red shifted by lowering the output coupler transmission. For laser operation at 1558.4 nm, a 19% slope efficiency with over 200 mW output power is achieved. Fig. 2 shows that for laser operation at 1567.5 nm, the maximum single-mode output power is limited to 127 mW (at ~800 mW pump power). This effect is due to the presence of a second longitudinal mode, which appears by further increasing the pump power. We notice that, although a linearly polarized output beam is readily achievable by inducing a slight isotropic stress in the glass disk (e.g., by using a pump beam with a small ellipticity), the polarization state is stable but not as reproducible as when it is obtained by using a Polarcor etalon [9]. In all cases, the laser linewidth was measured to be narrower than 10 kHz. For those applications where linewidth-related nonlinear phenomena, such as the stimulated Brillouin scattering in an optical fiber, may be detrimental, the laser linewidth can be broadened by phase modulation of the laser field using the piezoelectric transducer acting on the resonator length.

Fig. 3 shows the tuning characteristic of our source. For the sake of clarity, only the wavelengths corresponding to an output power in excess of 90 mW are indicated in the figure. The use of output couplers with different transmission values makes it possible to choose a few wavelength intervals across the broad erbium gain band [8]. The particular oscillating wavelength inside these intervals is then selected by tilting the etalon. The piezoelectric transducer allows fine cavity tuning with a frequency tuning resolution of ~1 MHz. A continuous tuning interval between 1532 nm and 1538 nm is observed using the 2% output coupler. With the 1% output coupler the tuning interval splits up into two regions, from 1547 nm to 1551 nm and from 1556 nm to 1559 nm. The 0.5% output coupler allows a reduced tuning

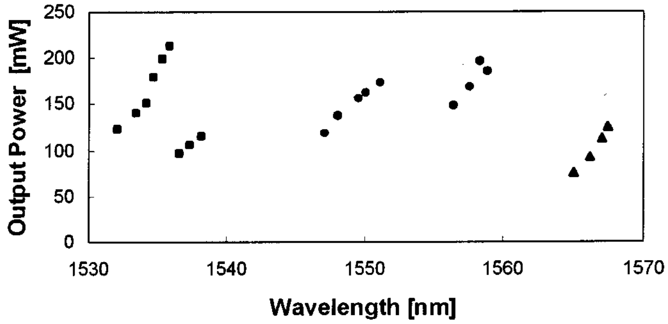

Fig. 3. Output power versus oscillating wavelength: squares refer to 2% output coupler transmission; circles to 1% output coupler; crosses to 0.5% output coupler. The data refer only to wavelengths with high output power level.

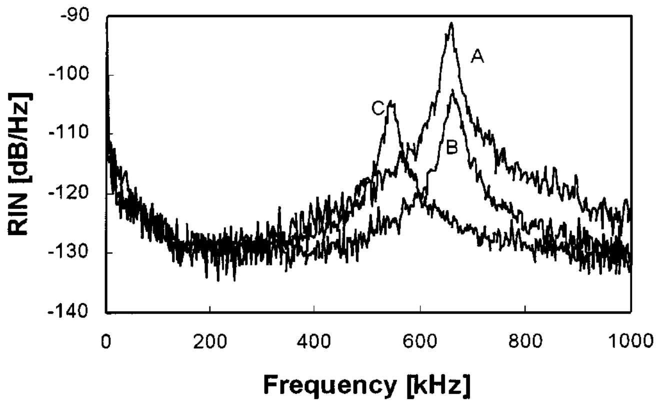

Fig. 4. Laser RIN spectra for (a) 2%, (b) 1%, and (c) 0.5% output coupler transmission. The electronic noise floor is about −135 dB/Hz.

interval of about 2.5 nm from 1565 nm to 1567.5 nm. In the first case, the 6-nm tuning interval is limited by the free spectral range of the etalon; in the other cases, the low finesse of the uncoated etalon becomes the limiting factor. Note that a much broader tuning range was achieved at lower pump power levels. In fact, by using the above-mentioned three output couplers, we were able to span the 1528.5–1570.2-nm wavelength range with robust single-frequency operation and with an output power exceeding 10 mW across the whole interval. The lowest single-frequency output power occurs at around 1543 nm, due to the unfavorable balance between the absorption and the emission cross sections.

The RIN properties of the Er–Yb laser were also investigated. Fig. 4 shows the RIN curves measured in single-frequency operation at the maximum pump power for the different configurations above discussed. The RIN peaks at the relaxation oscillation frequency are located at around 600 kHz, well below the modulation band of interest for CATV analog transmissions, with values of −92 dB/Hz, −102 dB/Hz, and −104 dB/Hz for the three wavelengths of 1535.9 nm, 1558.4 nm, and 1567.5 nm, respectively. The better RIN performance at lower coupling losses is due to reduced impact of pump fluctuations on low inverted erbium–ytterbium laser [13]. For frequencies higher than ~2 MHz, the RIN curves flatten at a constant level of ~ −135 dB/Hz, which is the limiting sensitivity due to electronic noise of the spectrum analyzer. By assuming a −40 dB/Hz slope after the peak in agreement with previous experimental results [13], the real laser RIN is expected to decreases below −160 dB/Hz for frequencies higher than ~8 MHz.

IV. CONCLUSION

We have demonstrated and characterized a diode-pumped single-frequency Er : Yb laser able to generate over 200 mW output power at both 1.53 μm and 1.56 μm, with tuning intervals of a few nanometers. Extended tunability over a broad wavelength interval, from 1528.5 to 1570.2 nm, has been achieved with reduced output power. In all operation conditions, the relative-intensity noise peak at the relaxation oscillation frequency of ~600 kHz is below −92 dB/Hz. This compact high-power source is a promising candidate for optical communication systems, metrology standards, and high-resolution spectroscopy in the spectral window around 1.5 μm.

REFERENCES

[1] M. R. Phillips, "Amplified 1550-nm CATV lightwave system," in *Proc. Optical Fiber Communication Conf.*, ser. OSA Tech. Dig. Washington, DC: Opt. Soc. Amer., 1998, pp. 85–86.

[2] V. Mahal, A. Arie, M. A. Arbore, and M. M. Fejer, "Quasiphase-matched frequency doubling in a waveguide of a 1560-nm diode laser and locking to the rubidium D^2 absorption lines," *Opt. Lett.*, vol. 21, pp. 1217–1219, 1996.

[3] P. V. Mamyshev, S. V. Chernikov, and E. M. Dianov, "Generation of fundamental soliton trains for high-bit-rate optical fiber communication lines," *IEEE J. Quantum Electron.*, vol. 27, pp. 2347–2355, Oct. 1992.

[4] G. D. Bartolini, D. K. Serkland, W. L. Kath, P. Kumar, D. W. Anthon, and D. L. Sipes, "A highly-stable, 59 GHz soliton source at 1550 nm," in *Proc. Ultrafast Electron. Optoelectron.* ser. OSA Trends Opt. Photon, Nuss and Bowers, Eds. Washington, DC: Opt. Soc. Amer., 1997, vol. 13, pp. 23–26.

[5] T. R. Chen, W. Hsin, and N. Bar-Chaim, "Very high power InGaAsP/InP distributed feedback lasers at 1550 nm wavelength," *Appl. Phys Lett.*, vol. 72, no. 11, pp. 1269–1271, 1998.

[6] K. Hsu, W. H. Loh, W. L. Dong, and C. M. Miller, "Efficient and tunable Er/Yb fiber grating lasers," *J. Lightwave Technol.*, vol. 15, pp. 1438–1441, Aug. 1997.

[7] M. Ibsen, E. Rønnekleiv, G. J. Cowle, M. O. Berendt, O. Hadeler, M. N. Zervas, and R. I. Leming, "Robust high power (>20 mW) all-fiber DFB lasers with unidirectional and truly single-polarization outputs," in *Conf. Proc. Lasers and Electro-Optics*, ser. OSA Tech. Dig. Washington, DC: Opt. Soc. Amer., 1999, pp. 245–246.

[8] S. Taccheo, P. Laporta, and C. Svelto, "Widely tunable single-frequency erbium–ytterbium phosphate glass laser," *Appl. Phys. Lett.*, vol. 68, no. 19, pp. 2621–2623, 1996.

[9] S. Taccheo, S. Longhi, and P. Laporta, "20-dBm tunable single-frequency erbium–ytterbium bulk laser," in *Proc. Eur. Conf. Optical Communication*, vol. 1, 1998, Paper TuB14, pp. 219–220.

[10] T. L. Boyd, D. Klemer, P.A. Leilabady, J. Noriega, and M. Pessot, "A 1.55-μm solid-state laser source for DWDM applications," *J. Lightwave Technol.*, vol. 17, pp. 1904–1908, Oct. 1999.

[11] A. Diening, E. Heumann, G. Huber, and O. Kuzmin, "High-power diode-pumped Yb,Er : LSB laser at 1.56 nm," in *Conf. Proc. Lasers and Electro-Optics*, ser. OSA Tech. Dig. Washington, DC: Opt. Soc. Amer., 1998, vol. 6, pp. 299–300.

[12] P. Thony and E. Molva, "1.55 nm-wavelength CW microchip lasers," in *Advanced Solid-State Lasers*. ser. OSA Trends in Optics and Photonics, S. A. Payne and C. R. Pollock, Eds. Washington, DC: Opt. Soc. Amer., 1996, vol. 1, pp. 296–300.

[13] S. Taccheo, P. Laporta, O. Svelto, and G. de Geronimo, "Theoretical and experimental analysis of intensity noise in a codoped erbium–ytterbium glass laser," *Appl. Phys. B*, vol. 66, no. 1, pp. 19–26, 1998.