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Wideband tunable high power narrow linewidth erbium-ytterbium doped fiber laser using compression-tunable fiber Bragg grating

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ABSTRACT

We demonstrate a high power erbium-ytterbium co-doped large-core fiber laser with narrow linewidth, an M^2 value of 1.7 and a broad tuning range. The fiber was cladding-pumped by a diode stack emitting at 975 nm. The laser had a linewidth around 0.16 nm and was tuned from 1533 nm to 1566 nm by compression-tuning a fiber Bragg grating. Output powers in excess of 30 W were obtained over the entire laser tuning range which was limited by the low gain at wavelengths shorter than 1533 nm and by the grating fabrication wavelength at 1566 nm. The laser slope efficiency was ~30% and the threshold ~3.3 W. Our results underline the capability for efficient, broad-band, high-power operation of large-core Er-Yb doped fibers and demonstrate compatibility with telecom components like standard single-mode fibers and fiber Bragg gratings.

Keywords: Fiber laser, high power, tunable laser, optical fiber

1. INTRODUCTION

Cladding-pumped fiber lasers and amplifiers have attracted growing interest due to the high output powers and wavelength ranges achieved using this technology. Benefiting from improvements in fiber design and fabrication and the availability of reliable pump diode sources (including multi-emitter diode sources, diode bars and diode stacks), the output powers of cladding-pumped fiber laser systems have grown rapidly, over recent years. Ytterbium (Yb^{3+})-doped lasers and amplifiers operating around 1.1μm take advantage of high pump to signal conversion efficiencies to operate at high output powers [1,3], which have already reached the kW level from single-fiber devices. Erbium-ytterbium co-doped cladding pumped lasers operating at wavelengths in the 1.5-1.6 μm region also attracted interest, in particular due to their "eye-safe" operation and telecom compatibility. Even though they have lower conversion efficiencies compared to lasers operating at 1.1 μm they found applications in several areas such as range finding, LIDAR, free space and satellite optical communications, medical, research among others. Continuous-wave (CW) output powers in excess of a hundred watt, which presented a broad wavelength spectrum, have been reported at a wavelength around 1.55μm [4-6].

Widely tunable and narrow-linewidth laser systems are of great interest because they have a number of useful applications such as wavelength-division multiplexing (WDM) in communication systems, research, spectroscopy, etc. For high performance in these applications, higher power levels, compact designs, broad tuning ranges as well as narrow linewidths are desired. However, power-scaling of narrow-linewidth fiber lasers is often limited by non-linear effects. In particular, the narrow-linewidth (but not single-frequency) together with a relatively long fiber with a small core diameter (typically <10 μm) leads to a low threshold power for stimulated Raman scattering (SRS), which degrades the laser performance and can limit the maximum output power achievable [7]. On the other hand, when working with single-frequency lasers (typically with linewidths narrower than 50 MHz), stimulated Brillouin scattering is the dominant non-linear effect. Therefore, for power-scaling of narrow-linewidth sources, a careful design of the laser system is required in order to suppress the effect of SRS or SBS, for example, by using a short fiber with a large core and a

-sufficiently broad linewidth sot that SBS can be avoided. Several tunable lasers operating in the 1.5 – 1.6 μm wavelength range have been reported in the literature [8-11]. High power tunable laser operation was achieved by Laroche et. al. [10] in the L-band. In their setup they used a cladding pumped Er/Yb co-doped fiber pumped at 940 nm by two beam-shaped diodes, with and external bulk grating to achieve up to 29 W of output power in the L-band with a linewidth of 0.6 nm, which was composed of several narrow lines. By rotating the external grating they were able to tune the laser from 1561 nm to 1627 nm. Using a similar setup, Nilsson et al. [11], reported high power tunable laser in the C-band with a maximum output power of 6.7 W and a linewidth of 0.25 nm. In both these cases, the laser cavity was built using free space optics which results in a bulky setup.
In this paper, we report a compact, widely tunable, Er/Yb co-doped fiber laser, generating up to 43 W of CW output power and operating at a wavelength range from 1532 nm to 1567 nm with a linewidth of 0.16 nm (FWHM) and a good spatial beam quality ($M^2 < 1.7$). We used a cladding pumped Er-Yb large-core fiber which increases the nonlinear thresholds of stimulated Raman scattering (SRS). The large mode area fiber was spliced to the single mode fiber using a standard fusion splicer allowing, in this way, for a compact, all-fiber design for the laser cavity. The tuning range was limited at short wavelengths by the intrinsic Er-Yb gain spectrum and at long wavelengths by the original fabrication wavelength of the Bragg grating which could be extended until 1580 nm using an appropriate grating.

2. EXPERIMENTAL SETUP

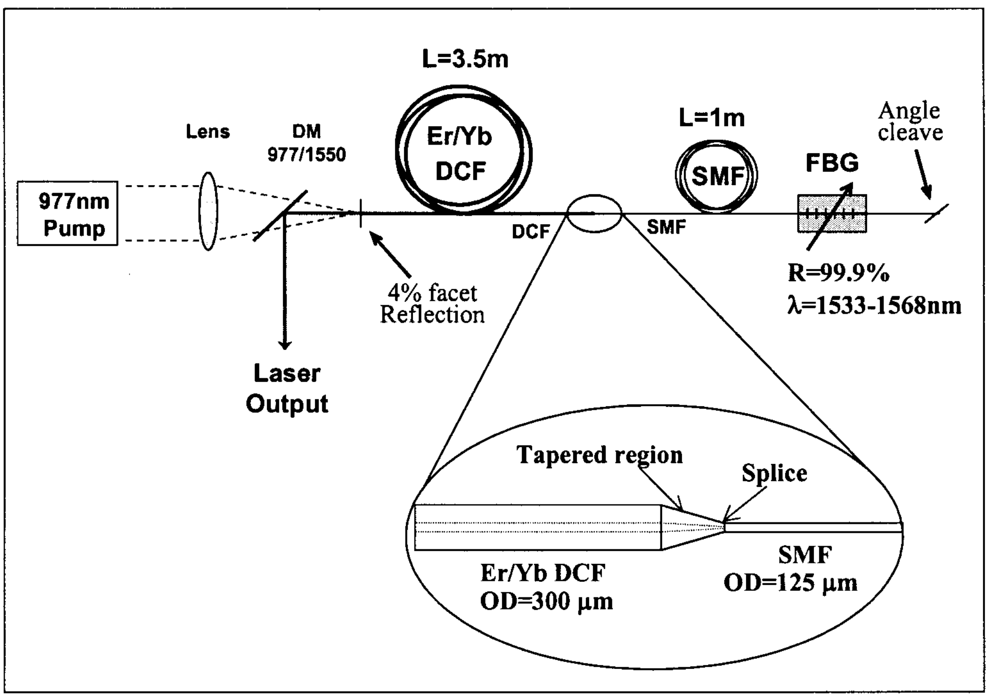

Figure 1: Experimental setup of the tunable laser source.

The experimental setup for the tunable laser is shown in Figure 1. The tunable laser used a cladding pumped large core Er/Yb doped fiber which was designed and fabricated in-house using standard MCVD and solution doping [14]. The fiber preform was milled in a D-shape in order to increase pump absorption, with an outer diameter for the long and short section of respectively, 400 μm and 360 μm, after the pull. The phosphosilicate core was co-doped with erbium (Er^{3+}) and ytterbium, had a numerical aperture of 0.2 and was centred in the preform. Finally, the fiber was coated with a low refractive index polymer which provided the outer cladding for the double-clad structure with an NA of 0.48. The pump was launched in the inner cladding and the fiber small signal absorption was around 4.5 dB/m at the pump wavelength of 975 nm. A fiber length of L=3.5 m was used in the experiments.

The laser cavity was formed by the 4% Fresnel reflection from a perpendicularly cleaved facet at one end of the Er/Yb doped fiber and by a 99.9% reflectivity fiber Bragg grating at the other end. The grating was written in a standard single mode fiber which was spliced to the doped fiber. In order to achieve the best fundamental-mode matching from the single-mode fiber to the large core doped fiber, the last was tapered to a suitable diameter. A 1m long single mode fiber section was included in the cavity in order to eliminate higher order modes propagating in the fiber and therefore achieve and improved beam quality. Furthermore, it is known that a tapered region in the large-core fiber within a laser cavity provides higher losses to higher order modes improving the selection of the fundamental mode, which enhances the beam quality [13]. The Er-Yb doped fiber was pumped by a diode stack at 975 nm, launched directly into the active fiber through the perpendicularly cleaved fiber faced in an end-pumping scheme. This facet also served as the output coupler. A dichroic mirror (DM) with high reflectivity at ~1.5 μm was used to separate the pump radiation at 975 nm from the output of the tunable laser around 1550 nm. A second DM with high reflectivity at ~1.1 μm was inserted between the pump and launch end to filter out possible laser emission at 1.1μm from excited Yb^{3+} ions, which could otherwise damage the pump source. Finally, the pump-launching end of the fiber was held in a temperature-controlled metallic V-groove that was designed to prevent thermal damage to the fiber coating by any non-guided pump power or by the heat generated in the laser cycle itself.

The critical point of this laser configuration was the large-core to SMF splice section. The SMF had a standard high refractive index coating for cladding-mode stripping. Thus the pump power that remained unabsorbed after the large-core fiber section, propagating in the inner cladding as well as any signal power lost from the core would largely be absorbed by the coating of the SMF. This could potentially damage the SMF. To minimize the risk of damaging the SMF fiber a somewhat overlength 3.5-meter piece of Er/Yb fiber was used which, at an absorption rate of 4.5 dB/m, yielded a total of ~15.7 dB of pump absorption. The unabsorbed pump power was only a few watts. As a result, there was no thermal damage observed in the SMF section due to the unabsorbed pump beam with 140 W of launched pump power, even without any additional cooling unit for the SMF.

The laser wavelength was scanned using an in house technology which relies on compression tuning the fiber Bragg grating [8,12]. Using this technique, tuning ranges of up to 110 nm at 1550 nm were demonstrated. By combining this technique with high power laser technology, a compact tunable laser with high output power and wide tuning range could be achieved. An all-fiber configuration would be possible by changing the pumping scheme to side-pumping.

3. RESULTS

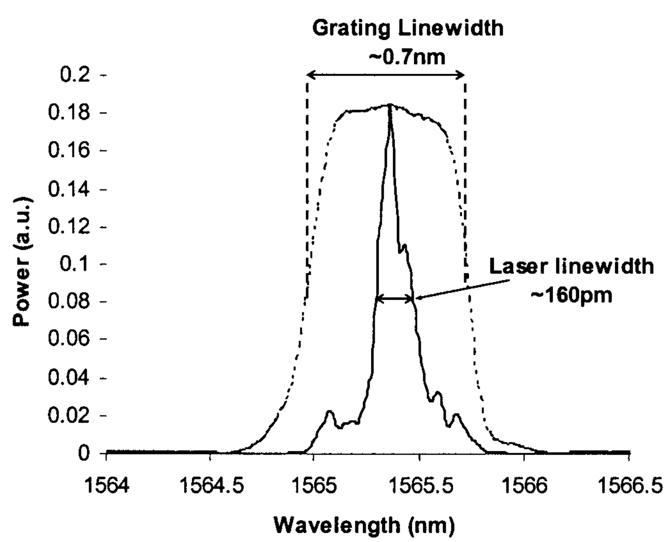

Figure 2: Comparison of the bandwidth of the grating and the laser linewidth.

The incorporation of a fiber Bragg grating in the laser cavity provides a wavelength selective feedback into the cavity restricting the laser operation to the bandwidth of the grating. To ensure that no additional feedback was introduced into the cavity, the single mode fiber end was angle cleaved in order to avoid back-reflections. This suppresses spurious lasing at other wavelengths. The grating reflection spectrum is shown in Figure 2 (dashed line) which has bandwidth of 0.7 nm (FWHM). In comparison, the laser radiation (solid line) is much narrower with a linewidth of only 160 pm due to the multiple pass amplification and consequent linewidth narrowing of the laser radiation. On the other hand, the laser linewidth is still much larger than the linewidth of the SBS gain spectrum, rendering this effect insignificant. The experimental results for the laser linewidth, shown in Figure 2, were obtained for an output power of 20 W using an optical spectrum analyzer (OSA) with 50 pm resolution bandwidth.

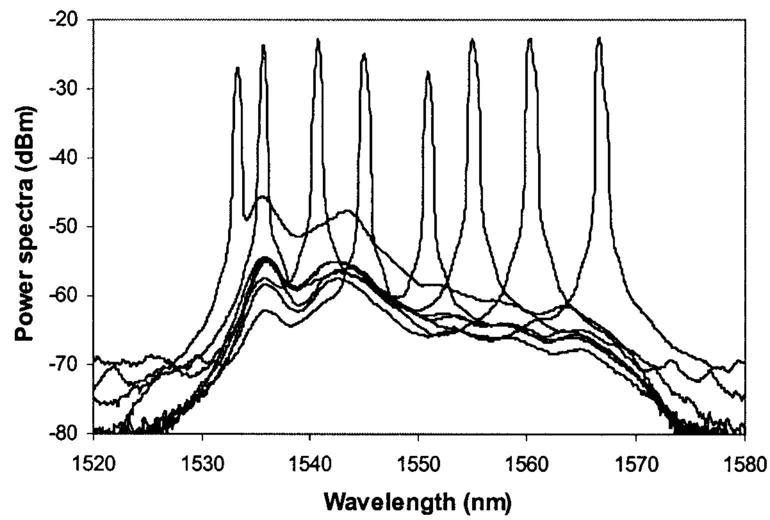

Figure 3: Spectra of the tunable laser for different grating wavelengths.

The fiber Bragg grating was fabricated at a wavelength of 1566 nm and compression-tuned by 33 nm until a wavelength of 1533 nm. Figure 3 shows the laser spectra for the different grating wavelengths with an output power of around 20 W, measured using an optical spectrum analyzer (OSA) with a resolution bandwidth (RBW) of 0.5 nm. The short-wavelength tuning range was limited to 1533 nm by the reduction in the gain at lower wavelengths. At these wavelengths, the signal power would not be enough to suppress the ASE and the laser would become unstable and prone to self-pulsing, which would damage the laser. Already 1533 nm it can be observed in Figure 3 that the ASE build-up is quite significant. The limitation for operating the laser at wavelengths higher than 1566 nm is only due to the grating fabrication wavelength. As the Er-Yb gain spectrum extends until close to 1580 nm, if the grating was fabricated at this wavelength, the laser tuning range would be about 45 nm. Nevertheless, the results shown in Figure 3 illustrate the potential of this tunable laser configuration.

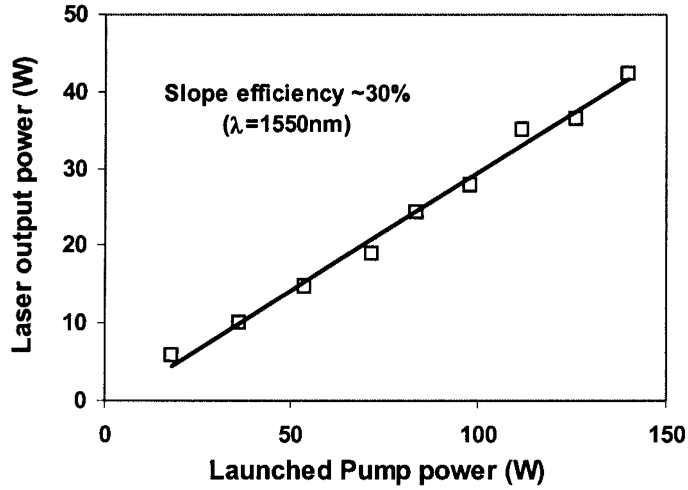

Figure 4: Slope efficiency of the laser for a wavelength of 1550 nm

The measurement of the laser slope efficiency and threshold at a wavelength of 1550 nm was ~30% and ~3.3 W, respectively. Figure 4 shows the laser output power for different launched pump powers. As most of the power was absorbed the launched pump power is nearly the same as the absorbed pump power. It can be seen that the laser efficiency is quite high if we take into account that the intrinsic quantum efficiency for the laser is around 62.9% and that some power is lost by imperfect transfer of energy from the Yb^{3+} ions to the Er^{3+} ions and ASE at 1μm. In fact, it was measured that the parasitic emission at ~1.1 μm arising from Yb^{3+} ion excitation was relatively low (< 2 W in the output laser beam) even at the highest output level.

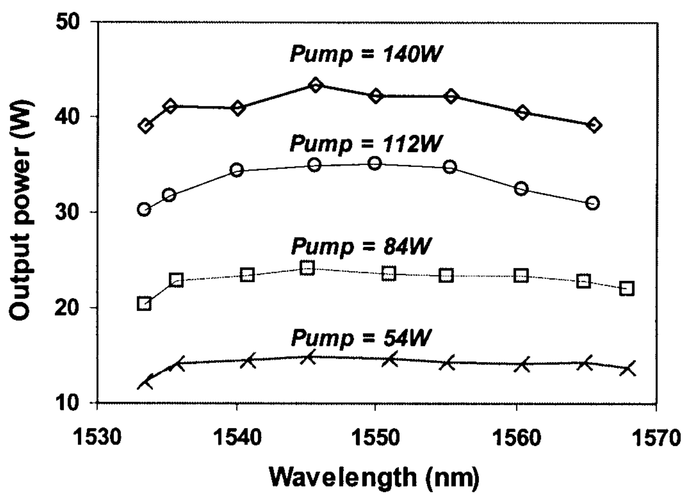

Figure 5: Measured output power of the laser as function of the wavelength for different pump power levels.

Finally, the output power of the laser was measured for different wavelengths and pump powers. These results are shown in Figure 5. It is observed that the laser output power spectrum is very flat across the wavelength range from 1533 nm to 1566 nm. Output powers in excess of 39 W were obtained for the whole tuning range with a maximum of 43 W at 1545 nm.

We did not increase the laser output power because we feared that the increased pump power could potentially damage the large-core to SMF splice region. At the moment work is in progress to optimize the splice region by minimizing the splice losses in the fundamental mode and finding effective methods of removing the pump light, which would allow us to reach higher output powers for the tunable laser.

4. CONCLUSIONS

We demonstrated a compact, high power erbium-ytterbium co-doped large-core fiber laser with an M^2 value of 1.7. The laser had a linewidth around 0.16 nm and was tuned from 1533 nm to 1566 nm by compression-tuning of a fiber Bragg grating. Output powers around 40 W were obtained over the entire tuning range which was limited by the low gain at wavelengths shorter than 1533 nm and by the fabrication wavelength of the grating at 1566 nm. By using a grating fabricated at 1580 nm, a broader tuning range would be obtained. The laser slope efficiency was ~30% which is good for a Er-Yb co-doped fiber that has a low quantum efficiency and can suffer from inefficient energy transfer from the Yb^{3+} to the Er^{3+} ions. The output power was limited by the power handling of the large-core to SMF splice region. Even tough no damage occurred, we did not increase the pump power in order not to risk damaging the splice region.

Our results underline the capability for efficient, broad-band, high-power operation of large-core Er-Yb doped fibers and demonstrate compatibility with telecom components like standard single-mode fibers and fiber Bragg gratings. This device could be useful for WDM free-space optical communications, research purposes, medical applications and others.

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