P-TL
Accepted

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83 W single-frequency narrow-linewidth MOPA using large-core erbium-ytterbium co-doped fiber

C. Alegria[1,3], Y. Jeong[1], C. Codemard[1], J. K. Sahu[1,2], J. A. Alvarez-Chavez[2], L. Fu[1], M. Ibsen[1], J. Nilsson[1,2]

1: Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, United Kingdom

2: Southampton Photonics, Inc., 3 Wellington Park, Hedge End, Southampton SO30 2QU, United Kingdom

3: Phone +44 23 8059 3139, fax +44 23 8059 3142, email ca@orc.soton.ac.uk

Abstract

We demonstrate a continuous-wave (CW) single-frequency, narrow-linewidth, laser at 1550 nm with an output power of 83 W using a master-oscillator power amplifier configuration. A seed from an all-fiber DFB-laser with a linewidth of 13 kHz was polarization scrambled and boosted through a chain of amplifiers in an all-fiber configuration. The last amplification stage consisted of a highly efficient cladding-pumped large-core erbium-ytterbium co-doped fiber which helped increase nonlinear thresholds.

Keywords: Lasers, Optical fiber lasers, Optical fiber amplifiers, Optical fiber applications

Introduction:

The output power of fiber lasers and amplifiers has been growing at a high rate. The availability of high power pump sources including multi emitter diodes, diode bars and stacks together with the development of efficient fiber designs and fabrication methods, has driven fiber laser and amplifier technology to compete with its solid state "bulk" counterparts. In particular, the high conversion efficiency of ytterbium (Yb^{3+}) doped fibers has allowed the demonstration of lasers operating at 1 μm with output powers of 500 W [1] and 400 W [2] and with diffraction limited beam quality (M^2 close to 1). These lasers have applications in industry (cutting, engraving and soldering), medicine, and defense, to mention just a few. Additionally, the eye-safe operation of erbium (Er^{3+}) lasers and amplifiers around 1.5 to 1.6 μm has attracted attention for applications in areas such as range finding, sensors, biotech and free space and satellite communications. Lasers with output powers in excess of 100 W operating in the 1550 m region have been reported in the recent literature [3, 4]. These lasers are composed of multi-frequency lines, with linewidth restricted only by a wide gain spectrum, or the bandwidth of a wavelength selective filter. Some applications, however, require single-frequency operation with linewidth of the order of a few kilohertz to a few megahertz. As it is practically impossible to select a single longitudinal mode of a high power fiber laser cavity, mainly due to the long cavity length and operating power which is many times above threshold, a master-oscillator – power-amplifier configuration (MOPA) is commonly used. Typically a low power single-frequency seed is amplified through several stages until the desired output power is reached. One of the main difficulties in achieving high output powers when amplifying signals with narrow linewidth is the advent of nonlinear effects. When the laser linewidth is narrower than the Brillouin gain bandwidth (approximately 50 MHz), this becomes the predominant limitation to achieve higher output powers. In order to increase the SBS threshold several methods have been reported in the literature such as, applying strain to the fiber [6], a temperature distribution along the fiber [7], a longitudinal variation in the dopant concentrations [8] or in the core radius [9], among others. However, the most basic approach is to increase the effective mode area and to reduce the length of the fiber. Recently a 100 W single-frequency MOPA was demonstrated at a wavelength of 1064 nm in Yb-doped fibers using this approach [5].

In this paper we describe the amplification of a 1552 nm, narrow linewidth (13 kHz) cw Er:Yb all-fiber DFB-laser up to an output power of 83 W using an all-fiber configuration. The first two amplification stages used commercial single mode fiber amplifiers boosting the signal up to 2 W. The last amplifier stage consisted of a cladding pumped Er:Yb large-core fiber which helped avoiding nonlinear effects, in particular stimulated Brillouin scattering (SBS). The large-core fiber was spliced to the single mode fiber using a standard fusion splicer allowing, in this way, for a compact, all-fiber design.

Experiments:

The experimental setup for the full MOPA chain is shown in figure 1. The single-frequency seed consisted of a cw DFB fiber laser with a linewidth of 13 kHz and an output power of 10 mW, which was polarization-scrambled using a commercial polarization controller, before being amplified. The "low power" amplifier chain was built using a Nortel amplifier to boost the signal to 18 dBm followed by a high-power amplifier from Southampton Photonics, which boosted the signal to an output power of 2 W. A 2 by 2 1% tap was inserted at the output of the second amplifier in order to monitor both the forward power and any light propagating backward from the last amplifier stage due, e.g., to Rayleigh scattering or SBS.

The last amplification stage used cladding pumped large-core Er:Yb doped fiber which was designed and fabricated in-house using standard MCVD and solution doping [10]. 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 Er and Yb, was centered in the preform, and had a numerical aperture of 0.2 and background losses lower than 0.1 dB/m. Finally, the fiber was coated with a low refractive index polymer which provided the outer cladding for the double-clad structure with an inner-cladding NA of 0.48. The small signal pump absorption was around 4.5 dB/m at the wavelength of 975 nm. The total length of fiber used in the last amplification stage was L=3.5 m.

The pump was launched into the inner cladding and was counter-propagating to the signal. The pump source consisted of a high power diode stack at 975 nm which was focused onto the large-core fiber. The output end of the fiber was angle-polished to avoid signal back-reflection and consequent instabilities in the high power amplifier. A dichroic mirror with high reflectivity (HR) around 1550 nm and high transmission (HT) at the pump wavelength was used to extract the forward propagating signal. A second dichroic mirror with HR at 1 μm and HT at the pump wavelength was inserted to protect the pump source from any spurious 1 μm laser radiation (Figure 1). The low-power amplification stage had a single mode fiber (SMF) output which was spliced to the large-core fiber using a standard fusion splicer. As the large-core fiber had a core diameter close to 30 μm it was tapered down in order to match the SMF. The splice loss was less than 0.5 dB. Afterwards, the splice region was covered in high index gel so that the SMF was protected from unabsorbed multimode pump light. As the pump beam was propagating mostly in the cladding, this method proved to be very effective in protecting the SMF from damage. When the high index gel is not applied to the splice area, the residual pump power is enough to burn the SMF coating, thus destroying the fiber. The slope efficiency of the amplifier was ~34% relative to the launched pump power as shown in Figure 2. The linewidth of the laser was measured using the delayed self-heterodyne technique (using a 35 MHz frequency shifter) with a delay line of around 58 km providing a resolution around 2 kHz. Figure 3 shows the traces taken from an RF spectrum analyzer before amplification and after signal amplification to an output power of 60 W. Before amplification the DFB was connected directly to the linewidth measurement system and stabilized in order to get the low noise measurement shown in Figure 3. The 60 W signal linewidth was measured through a 50 m patch cord that connected different labs, which made the measurement noisy. Despite this, it can be clearly seen that there was no broadening of the laser linewidth after the amplification. Figure 4 shows the amplifier spectrum measured using an optical spectrum analyzer (OSA), with a resolution bandwidth (RBW) of 0.5 nm, for different launched pump power levels. It is observed that the amplified spontaneous emission (ASE) builds up significantly in the shorter wavelength region (around 1535 nm) when the pump power is increased. Due to the highly multi-moded fiber core of the final amplifier, the ASE can be propagated and amplified in higher order modes which are not saturated by the signal. The percentage of power in the single-frequency line compared to the integrated ASE spectrum was 98.0%, 97.1% and 96.8%, for pump powers of 50 W, 100 W and 200 W, respectively.

After characterizing the source at around 60 W output power, we tried to increase the output power of the single-frequency source. A maximum output power of 83 W with an M^2 of 2.0 was reached, when launching 250 W of pump power into the fiber. We explain the non-diffraction limited characteristics as due to the mode field mismatch between the large-core fiber and SMF at the splice point, leading to multimode excitation. Also, a central dip in the core refractive index profile, which is characteristic to the large-core Er:Yb fiber, may cause a donut shaped fundamental mode and subsequently raise its M^2 value. When trying to increase the pump power above 250 W, the large-core Er:Yb co-doped fiber failed. We believe that the failure mechanism was due to degradation of the fiber coating which is thought to originate from the high thermal load of Er:Yb co-doped fibers. This argument was supported by a similar maximum output power obtained when this fiber was used in a laser configuration. The power-handling should improve if the outer cladding is replaced by a better low-index coating or by a glass. A better heatsink may also improve the power-handling.

For optical sources with narrow linewidth which are orders of magnitude below the Brillouin gain linewidth (~50 MHz), SBS is the dominant nonlinear effect [11]. However, the large 30 μm diameter core together with the short fiber length used in our experiment helped to increase the threshold for undesirable nonlinear effects as SBS and SRS (stimulated Raman scattering). In fact, it was estimated that the nonlinear product power-length for this fiber was around 297 W m [11]. Assuming an effective radius of 15 μm the SBS power threshold is around 84 W in 3.5 m of this fiber. However, as the signal is amplified from 2 W, we can estimate roughly that the threshold increases to at least 168 W which is still much higher than the 83 W output power obtained in this experiment. This estimate is obtained by making the rough approximation that the signal is linearly increasing along the amplifier length, bringing the average power along the amplifier to half and consequently the SBS threshold doubles. More accurate estimates can be made by using a numerical model as presented in [13]. Furthermore, as the pump absorption is quite high (~4.5 dB/m) about 98% of the pump is absorbed, causing a temperature distribution along the fiber core [12] which is known to increase the SBS threshold via an effective broadening of the Brillouin gain [7]. In general, though, the Brillouin gain coefficient and the gain bandwidth are not well characterized in this kind of fibers, making accurate predictions of the SBS threshold difficult.

Conclusions:

We presented a high power single-frequency all-fiber laser system with a linewidth of 13 kHz and M^2 of 2.0 at a wavelength of 1552 nm. The laser comprised a single-frequency fiber DFB-laser seed source that was amplified through three amplification stages up to a power of 83 W (cw). The final amplifier stage consisted of a diode-stack cladding-pumped large-core Er:Yb doped fiber with 400 μm outer diameter and a 30 μm core which led to high nonlinear thresholds. The linewidth of the 13 kHz single-frequency seed was not broadened after the three amplification stages and there was no sign of SBS. Due to its "eye-safe" nature, this laser could have applications in range finding, sensing or satellite communications which require high power radiation.

Acknowledgement: This work is supported in part by DARPA under Contract MDA972-02-C-0049.

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Figure Captions:

Fig. 1 : Experimental setup of the high power MOPA chain.

Fig. 2 : Output power of the single-frequency laser relative to the launched pump power.

Fig 3. : Linewidth measurement using a self-heterodyne technique before amplification and after amplification to an output power of 60W.

Fig 4. : Amplifier spectrum at different pump power levels measured with an optical spectrum analyzer.

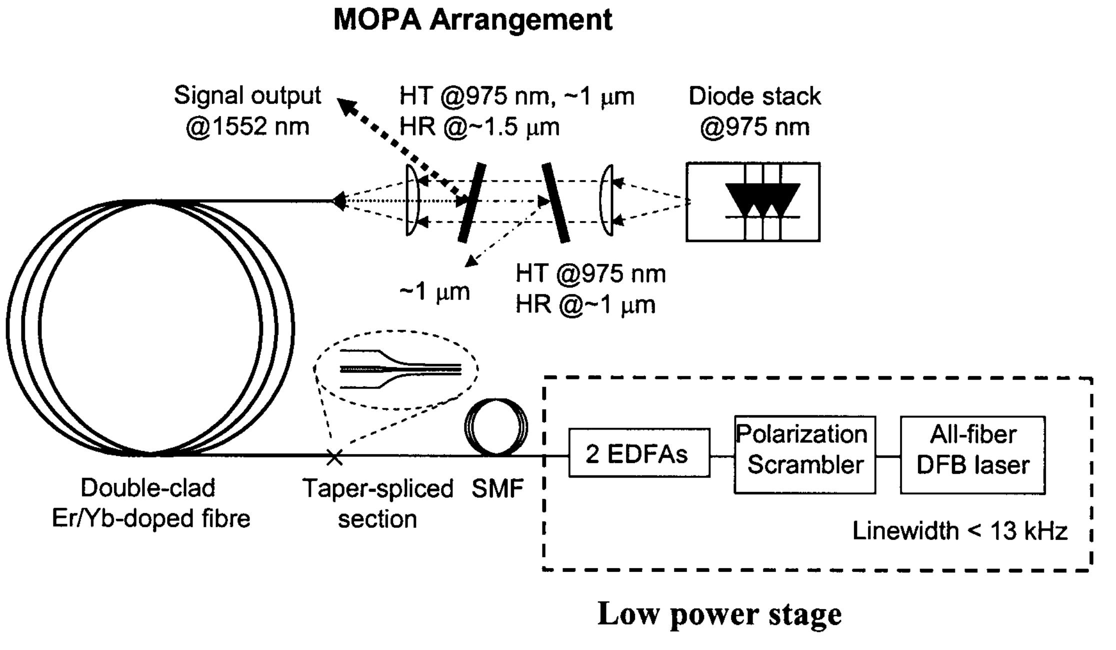
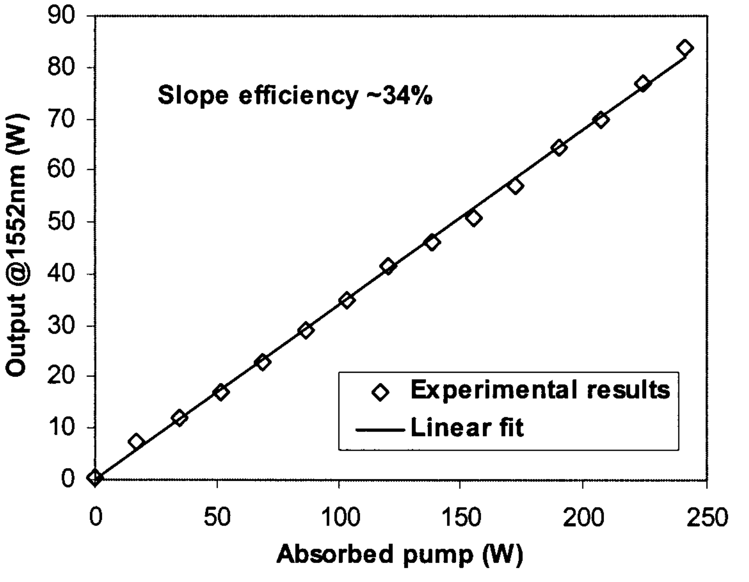
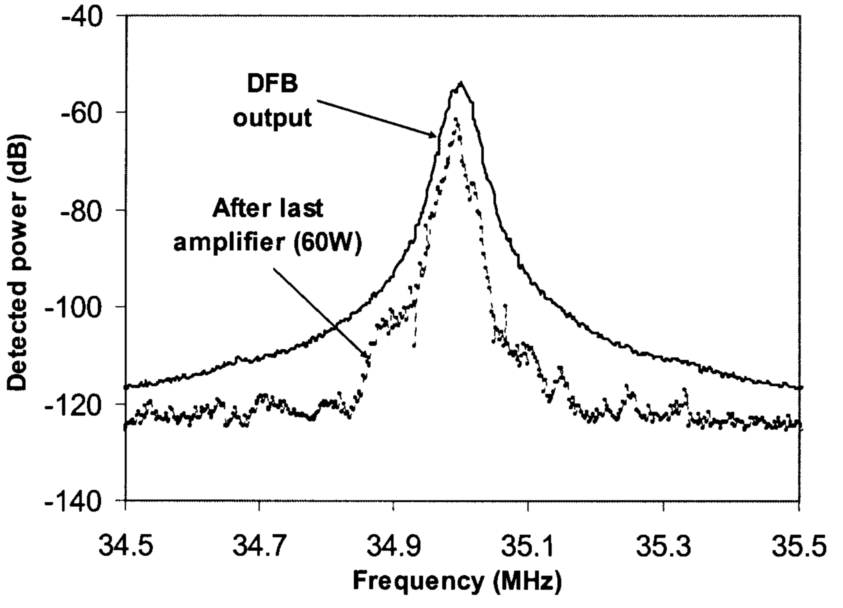

MOPA Arrangement
Signal output
@1552 nm
HT @975 nm, ~1 μm
HR @~1.5 μm
Diode stack
@975 nm
~1 μm
HT @975 nm
HR @~1 μm
2 EDFAs
Polarization
Scrambler
All-fiber
DFB laser
Linewidth < 13 kHz
Double-clad
Er/Yb-doped fibre
Taper-spliced
section
SMF
Low power stage

Fig. 1



Slope efficiency ~34%
Experimental results
Linear fit
Output @1552nm (W)
Absorbed pump (W)
0
10
20
30
40
50
60
70
80
90
0
50
100
150
200
250

Fig. 2



-40
-60
-80
-100
-120
-140
Detected power (dB)
DFB
output
After last
amplifier (60W)
34.5
34.7
34.9
35.1
35.3
35.5
Frequency (MHz)

Fig. 3

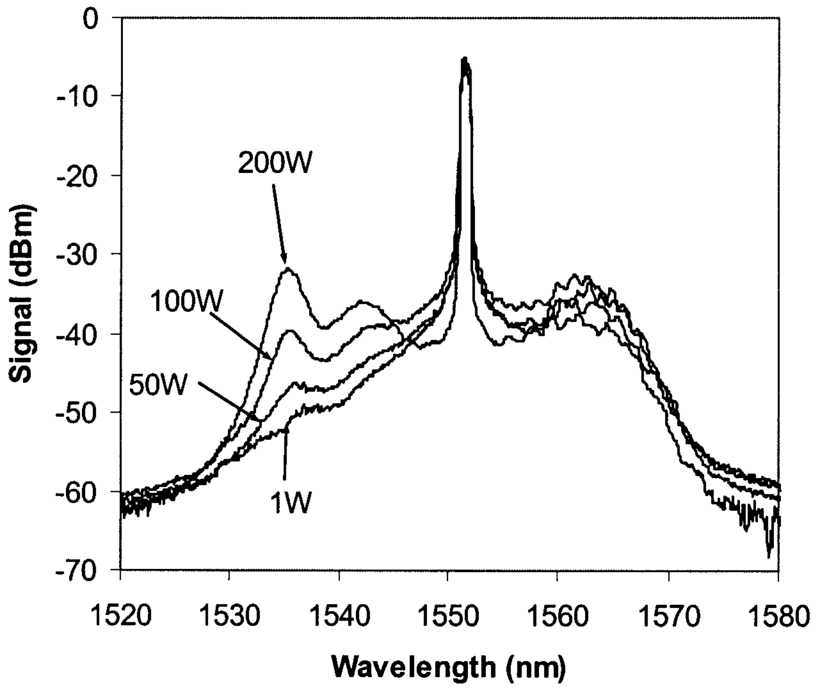

0
-10
-20
-30
-40
-50
-60
-70
Signal (dBm)
200W
100W
50W
1W
1520
1530
1540
1550
1560
1570
1580
Wavelength (nm)

Fig. 4