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Abstract: Picosecond pulses at gigahertz repetition rates from two different passively mode-locked VECSELs are amplified to high powers in cascaded ytterbium doped fiber amplifiers. Small differences in pulse durations between the two VECSELs led to amplification in different nonlinear regimes. The shorter 0.5 ps pulses could be amplified to 53 W of average power in the parabolic pulse regime. This was confirmed by excellent pulse compression down to 110 fs. The VECSEL producing longer 4.6 ps pulses was amplified in an SPM dominated regime up to 200 W of average power but with poor recompressed pulse quality.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (060.4370) Nonlinear optics, fibers.

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1. Introduction

The development of high average power picosecond and femtosecond fiber-based sources emitting in the 1-μm wavelength range has attracted much interest in recent years. Outstanding properties such as high efficiency and excellent heat dissipation characteristics have led to a rapid increase of average power and energy achievable in a nearly diffraction limited beam from compact and robust Yb-doped fiber amplifiers and lasers. Thus fiber based sources are progressively replacing their bulk counterparts. Picosecond pulses at high average powers are useful in numerous application areas including micromachining, nonlinear frequency conversion, and fundamental science. High-power fiber-based picosecond and femtosecond sources are typically based on master oscillator – power amplifier (MOPA) designs that use mode-locked fiber lasers [1] and solid state lasers [2], or gain-switched laser diodes [3] as seed lasers.

Despite all their remarkable properties, high-power short pulse fiber lasers suffer from the onset of unwanted nonlinear effects which in turn limit the maximum output power and degrade output pulse shape and duration. An initial controlled broadening of the pulse prior to amplification in a fiber amplifier followed by subsequent recompression can be used to mitigate against these effect. This technique, called chirped pulse amplification (CPA), is typically used to achieve the highest possible pulse energy and peak power whilst maintaining the input pulse duration after recompression of the amplified pulses. The fiber based CPA configuration has enabled the generation of femtosecond pulses with 1mJ of energy [4] and also average powers of ~100 W [5] from Yb-doped fiber amplifiers.

An alternative technique relies on the direct fiber amplification of ultra-short pulses to high peak power and high average power. In this case, after fiber amplification the short pulses accumulate a large amount of chirp due to self-phase modulation, which is then employed to compress the output pulse using a grating pair. This technique is very simple and very suitable for generating high peak powers at high average power. Furthermore, it allows efficient and clean pulse compression to durations that are generally much lower than those achievable via the more complex CPA scheme. The compression efficiency depends directly on the linearity of the generated chirp. The optimal condition is satisfied when the pulses are short enough and of adequate energy to undergo the required balanced interplay of dispersion, self-phase modulation (SPM), and gain in the fiber amplifier. This leads to parabolic shaped output pulses with a perfectly linear chirp [6]. The parabolic amplification regime has led to the recent demonstrations of high-power femtosecond fiber lasers involving seed sources producing sub-picosecond pulses with repetition rates at tens of MHz [1, 7, 8].

A passively mode-locked (ML) optically-pumped vertical-external-cavity surface-emitting semiconductor laser (VECSEL) capable of generating pulses at GHz repetition rate around 1 μm appears very suitable as a seed source for fiber amplifiers to achieve these types of amplification regimes at high repetition rates. VECSELs produce near-transform-limited ps and sub-ps pulses in near diffraction limited beams with extinction ratios and output powers suitable for high-gain fiber amplification to high powers. They are also inherently wavelength selectable, robust and compact, which are additional features that make them ideally compatible with fiber amplifier.

Here we report on the experimental demonstration of fiber amplification of ps and sub-ps pulses with a repetition rate in the GHz range produced by passively ML-VECSELs. Two fiber MOPA systems seeded by two different VECSELs were designed to investigate amplification to high average power in different nonlinear regimes, where the effects of the nonlinearities produce vastly different results. A first MOPA seeded by relatively long 4.6 ps pulses generated in excess of 200 W of average power with strongly chirped, 5.8 ps long,

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pulses. This condition where pulses mainly undergo the effects of SPM led to a large pedestal when the pulses were compressed to the femtosecond range. This was due in practice to nonlinearities of the chirp at the edge of the pulses. However the amplification of 500 fs long seed pulses produced by a different VECSEL resulted in the generation of parabolic pulses at 53 W average power. These linearly chirped pulses could then be compressed to 110 fs with excellent quality. We compare and discuss these different regimes and scope for further power scaling.

2. Experimental setup

The master oscillators we describe are ML-VECSELs which used gain structures and external cavity designs similar to those described in [9], with repetition rates around 1 GHz. The gain chips employed 6 InGaAs/GaAs quantum wells above a GaAs/AlGaAs DBR, optically pumped by the 830-nm output of a fiber-coupled diode, absorbed into the barrier layers. Pulses of 4.6 ps duration at 1055 nm were generated using the low-temperature MBE-grown single-quantum-well SESAM described in [10]. The 1043 nm, 500 fs, ML-VECSEL used optical Stark-effect mode-locking with a specially-designed MOCVD-grown SESAM [9].

Figure 1 illustrates the whole MOPA with seed source and fiber amplifiers. The pulses produced by the VECSEL are launched into a fiberized isolator and are then preamplified by one or two YDFAs (Yb-doped fiber amplifiers) to a power level sufficient to saturate the final high-power fiber amplifier stage. The preamplified beam is brought into free space, collimated and passed through a half-wave plate for partial polarization control and a free-space single-polarization isolator. It is then launched into the final-stage, power, amplifier through a lens. The power amplifier consists of a double-clad large mode area (LMA) Yb-doped fiber (YDF) with a D-shaped 400 μm thick inner cladding. The fiber is pumped through its output end by a diode stack source emitting around 975 nm. Dichroic mirrors placed at both fiber ends separate the signal from the pump beam.

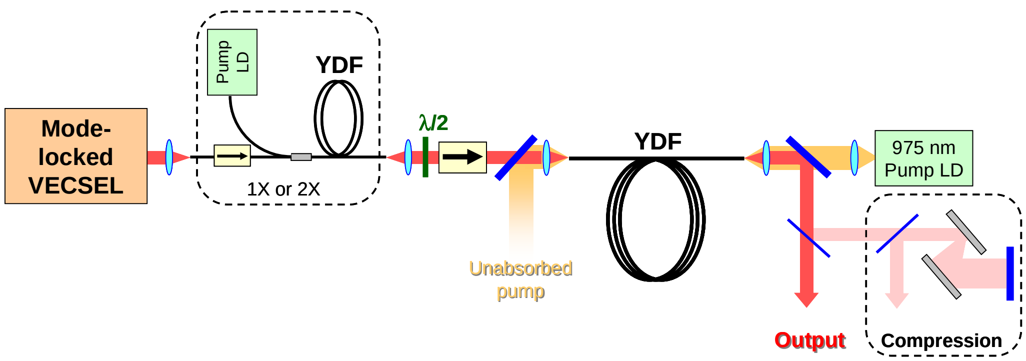

Fig. 1. Set-up of high-power high repetition rate picosecond - femtosecond fiber source. YDF: Yb-doped fiber; LD: laser diode; $\lambda/2$: half-wave plate.

Average powers, and optical spectra and intensity autocorrelation traces are measured at the output of the high-power YDFA. A fraction of the energy is also extracted to investigate the temporal compression characteristics with a reflection bulk grating compressor composed of a pair of 830 lines/mm gratings with variable spacing.

3. SPM-dominated regime of amplification

We first construct a MOPA operating in a SPM-dominated regime of amplification. The advantage of this regime is that it places relatively few constraints on the fiber and pulse parameters, allowing these, for example, to be selected for the highest average output power. The ML-VECSEL chosen for this experiment produced 4.6-ps pulses at 910 MHz and with 8 mW of average power. The wavelength was 1055 nm and the linewidth 0.45 nm, corresponding to a time-bandwidth product ($\Delta\tau\Delta\nu$) of ~ 0.56. The pulses were amplified to

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2 W of average power by cascaded 6- and 8-m long single-mode cladding-pumped YDF preamplifiers. The signal is then launched into the final-stage cladding-pumped YDF, fabricated in-house, with a length of 12 m, a core diameter of 25 µm and a numerical aperture NA < 0.05 providing a large effective area as well as excellent beam quality ($M^2 < 1.1$) when the fundamental mode is selectively excited.

The power amplifier generated more than 255 W of average output power for 350 W of launched pump power. The corresponding slope efficiency was 76% as shown in Fig. 2(a) The output beam was spectrally and temporally characterized up to 200 W of average output power. Instabilities precluded reliable measurements at higher powers. As the power increases the level of amplified spontaneous emission (ASE) rises and severe spectral broadening caused by SPM is also observed with linewidth up to 9 nm (Fig. 2(c)). The spectral shape is typical for the regime where SPM dominates over dispersion due to the relatively long pulses.

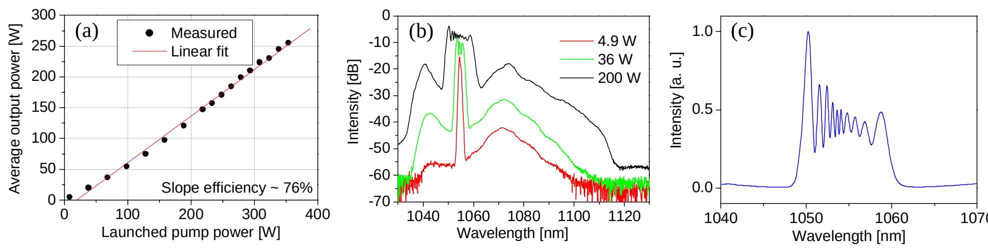

Fig. 2. Characteristics of MOPA seeded with 4.6 ps pulses. (a) Power conversion characteristics of final-stage amplifier, (b) output spectra at various output powers (resolution 0.2 nm) and (c) spectrum at 200 W in linear scale (resolution 0.1 nm).

There is still a small increase in pulse duration as a result of dispersion of the spectrally broadened pulse. Figure 3(a) illustrates this by comparing the autocorrelation trace of the seed and the amplified signal. At 200 W the fiber MOPA produces 5.8 ps pulses, assuming a $sech^2$ pulse shape. This corresponds to a peak power of 38 kW, which is sufficiently low to keep stimulated Raman scattering (SRS) at a low level. Thanks to the significant spectral broadening induced by SPM, these pulses can be compressed down to an autocorrelation time of 430 fs. Figure 3(b) shows the autocorrelation trace of the compressed pulse. There is a significant pedestal due to nonlinearities in the chirp along the pulse as expected in the SPM dominated amplification regime with non-parabolic pulses. In order to reach the parabolic amplification regime it is necessary to use shorter seed pulses, and this is the topic of the next section.

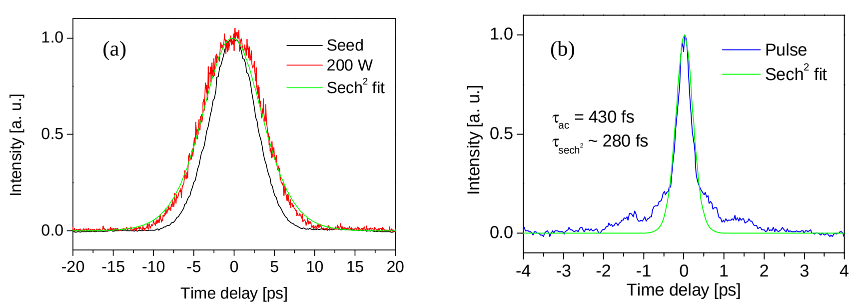

Fig. 3. Autocorrelation traces of (a) uncompressed and (b) compressed pulses at output of MOPA. The MOPA was seeded by 4.6 ps long pulses which were amplified to 200 W of average output power.

4. Parabolic pulse amplification

In a normal dispersion fiber amplifier, the pulse shape converges faster to parabolic shape during fiber propagation when shorter seed pulses are employed [11]. However, shorter pulses

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also increase the peak power, and make it more difficult to reach high average powers before SRS becomes a problem. An attractive feature of ML-VECSELs is the ability of producing pulses short enough for parabolic pulse amplification at gigahertz repetition rate. To demonstrate this, and to investigate the power scalability in the parabolic pulse regime, we next used a VECSEL producing 500 fs pulses at 1.1 GHz as a master oscillator. The laser linewidth was 2 nm meaning that the hyperbolic secant-shaped pulses were nearly transform-limited. These shorter pulses are created by a faster SESAM. This functioned at around 1040 nm, which is still within the YDFA gain bandwidth. The fiber MOPA includes one preamplifier composed of a 2 m long cladding-pumped YDF with 20 μm core and 128 μm cladding (Coractive HPA-Yb-20-02). The YDF was forward-pumped by a 915 nm laser diode launched through the end of the YDF via a lens. The use of the short fiber with a large core and a relatively small inner cladding ensured minimum pulse distortion by fiber nonlinearities and dispersion. It also shifted the gain of the YDFA to shorter wavelengths, as is typical for systems with ground-state absorption of the signal [12]. Thus the YDFA was well suited to amplification at 1040 nm. After transmission through the free-space isolator shown in Fig. 1, the amplified pulses with an average power of 1.3 W and a duration of about 0.8 ps were launched into the YDF of the final-stage amplifier. This was an 8 m long polarization maintaining (PM) double-clad YDF fabricated in-house with a mode-field diameter of 16 μm and a birefringence of 3.5×10^{-4}. This fiber was chosen for its effective area, which is suitable for obtaining appropriate amounts of SPM, with sufficient pump absorption and without significant SRS. The use of a polarization-maintaining fiber (operating on a single birefringence axis) eliminates any polarization fluctuations that may affect autocorrelation measurements. A half-wave plate was used to align the seed beam polarization axis to the slow axis of the PM-YDF. At 1.1 GHz repetition rate the required energy level to reach the parabolic pulse amplification regime in this fiber dictates a watt-level average power [13] which is also sufficient to saturate the final-stage amplifier.

The signal was amplified up to 53 W of average power with 100 W of launched pump power as reported in Fig. 4(a). The power evolution is slightly nonlinear due to the power dependence of the pump wavelength, and hence of the pump absorption. At maximum output power the pump diode emitted near 973 nm where the Yb absorption is reduced. Note that the need to keep the YDF short to overcome ground-state absorption of the 1040 nm signal also reduced the pump absorption, to values between 57 and 79%, depending on the pump power. This explains the relatively low amplifier efficiency. The output beam quality was measured to be approximately 1.1 times diffraction limited.

Output spectra measured at different average powers are shown in Fig. 4(b)-(c). Starting with a seed with spectral width of 2 nm, the spectrum dramatically broadens to a bandwidth exceeding 15 nm at maximum power. The rapidly decreasing wings of the spectra are characteristic of parabolic amplification. As the power increases, the spectrum broadens asymmetrically due to the limited gain bandwidth at lower wavelengths.

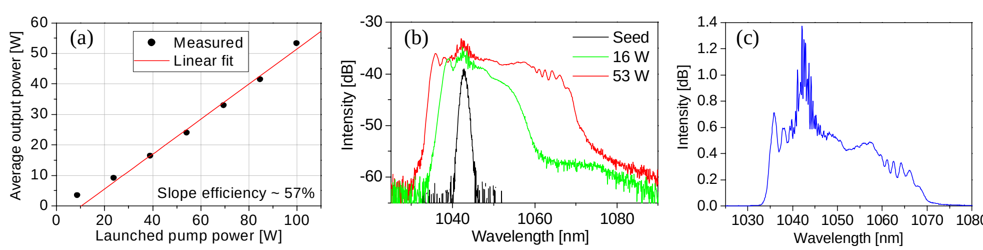

Fig. 4. Characteristics of MOPA seeded with 0.5 ps pulses. (a) Power conversion characteristics of final-stage amplifier, (b) output spectra at different output powers (resolution 0.2 nm) and (c) linear spectrum at maximum power (resolution 0.2 nm).

We also observed temporal broadening of the output pulses, which is typical of self-similar parabolic amplification in normally dispersive fibers. Autocorrelation measurements of the

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output pulse width at full width half maximum (FWHM) reveal an increase to between 2.2 ps and about 4.8 ps at minimum and maximum output power respectively (see Fig. 5(a)). The 4.8 ps pulses were compressed by the grating compressor down to an autocorrelation width of 170 fs. This corresponds to a pulse duration of 110 fs FWHM assuming a $sech^2$ pulse shape. The $sech^2$ pulse shape is a common approximation [1, 8] to the Bessel shape derived in [11]. The duty cycle becomes 10^{-4} and the time-bandwidth product 0.47, close to the transform-limited value. Moreover the autocorrelation trace depicted in Fig. 5(b) emphasizes the excellent quality of the compressed pulses with very low pedestal, as opposed to the compression of the longer non-parabolic pulses described in the previous section. This reveals the high linearity of the chirp before compression, characteristic of parabolic pulses.

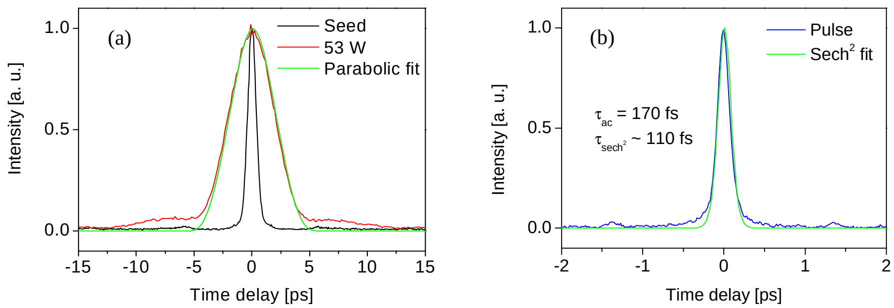

Fig. 5. Autocorrelation traces of (a) uncompressed and (b) compressed pulses at output of MOPA.

The laser system generated 48 nJ per pulse with picosecond range duration. Further power scaling was prevented by the absence of gain below 1035 nm which limited the final bandwidth of the pulses. This could be improved by using a similar ML-VECSEL with emission wavelength near 1070 nm.

5. Conclusion

In summary, we have investigated high-power fiber amplification of picosecond pulses at gigahertz repetition rates in two nonlinear regimes. A first demonstration employed long pulses amplified to 200 W of average power. There was significant SPM relative to the linear dispersion effects. Thus the pulses did not reach the parabolic regime, and there were nonlinearities in the chirp which severely degraded the pulse compression in a subsequent Treacy grating compressor. The second experiment involved the fiber amplification of shorter sub-picosecond pulses in which normal dispersion and SPM generate parabolic shaped pulses with linear chirp leading to excellent pulse compression.

The novel combination of VECSEL and high-power Yb-doped fiber amplifiers opens up a new route towards the development of high brightness, high average power, gigahertz, femtosecond pulsed sources emitting in the 1-1.1 micron wavelength range.

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