Diode-pumped high-average power femtosecond fiber laser systems

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The recent progress in femtosecond laser technology is currently driven by the prospect of fully diode pumped systems, which promise the eventual replacement of the well-established Ti:sapphire laser in the field of ultrafast optics. Apart from more traditional diode-pumped solid-state lasers, fiber-based systems have received an increasing amount of attention due to the uniquely compact assemblies possible with fiber lasers. However, to date fiber lasers have replaced Ti:sapphire- based systems only in areas, were low power levels are required, such as the injection seeding of regenerative amplifiers[1]. Here, we show that fiber lasers can also produce power levels and pulse widths that are sufficient for the pumping of optical parametric oscillators (OPOs) and amplifiers (OPAs).

The key to generating high average powers from fiber laser based systems is to employ double-clad fibers as amplifiers[2], as double-clad fibers allow a uniquely simple method for brightness conversion from high-power multi-stripe diode arrays. Self-phase modulation in the amplifiers is then minimized by employing an all-fiber chirped pulse amplification technique based on chirped fiber Bragg gratings (FBGs)[3].

Femtosecond amplifier systems need to be seeded with ultra-fast oscillators; preferred are erbium oscillators, where one typically has two options. Either passively modelocked systems operating at their fundamental cavity round-trip time in short lengths of fibers or passive harmonically modelocked systems in long lengths of fibers[4] can be employed. Fundamentally modelocked oscillators allow the generation of pulses at repetition rates between $\approx 1 - 50$ MHz with pulse widths between 1 psec - 100 fsec and pulse energies between $\approx 6 - 300$ pJ, giving average seed powers between $\approx 0.006 - 15$ mW. At a seed power level of 15 mW, a single fiber power amplifier can in principle be used to generate a power level of about 2 W.

In this work, however, for experimental convenience we preferred employing harmonically modelocked fiber lasers, as they allow the construction of femtosecond oscillators with adjustable repetition rates anywhere between 25 and 500 MHz (with the present state of the art). However, due to the intrinsic jitter ($\approx$100 psec) of passive harmonically modelocked oscillators they are at present not suitable for the pumping of OPOs. In Fig. 1 we show the optical spectrum (30 nm FWHM) of a harmonically modelocked laser operating at 150 MHz, which produced 200 fsec (1.8×bandwidth-limited) pulses with a pulse energy of 30 pJ. Nearly the full bandwidth of the oscillator pulses can be preserved in an amplification process, as also shown in Fig. 1, where we used an Er/Yb co-doped double-clad amplifier[5] pumped by a 1 W diode array (operating at 980 nm). By a careful selection of the oscillator and amplifier gain spectrum 300 pJ pulses with a bandwidth of 28 nm were generated, where the average output power was 50 mW. Currently we are developing a system pumped by an array of

1 W diode lasers pig-tailed to a fiber bundle, which should allow an increase in the pulse energies by a further order of magnitude.

We have demonstrated that self-phase modulation in the amplifiers can be minimized by employing an all-fiber chirped pulse amplification system. The experimental set-up of such a system is shown in Fig. 2. For pulse stretching and compression we employed a 5 mm long positively chirped FBG with a bandwidth of ≈ 15 nm centered at ≈1.555 μm, a dispersion of +3.40 ps^2 and a reflectivity of ≈ 90%. Here the oscillator was similar to the one described above and operated at 50 MHz and thus the first chirped FBG stretched the oscillator pulses to a width of about 50 psec. Due to coupling losses and some residual reflections in the system we had to employ a pre-amplifier between the oscillator and the power amplifier. The power amplifier was a singly-doped double-clad Er fiber (Er^{3+} doping level = 1000 ppm)[6], which has ≈1.7 times the optical bandwidth (≈43 nm) of an Er/Yb co-doped fiber. Using a pump power of 1.15 W delivered from two MOPA diode lasers, an output power of 420 mW was generated before compression in the second chirped FBG. After recompression an average output power of 260 mW was obtained and thus the pulse energy is 5.2 nJ.

The autocorrelation trace and the corresponding pulse spectrum are shown in Fig. 3. The FWHM pulse width is 380 fsec assuming a $sech^2$ pulse shape. The corresponding time-bandwidth product is ≈0.5. Some spectral re-shaping is evident, which in fact is caused by grating non-uniformities and the onset of nonlinear spectral re-shaping at this pulse energy. We calculated the nonlinear phase delay of the pulses in the present system to be around π by solving the rate equations of the power amplifier for the signal-power distribution along the fiber. A further reduction in the nonlinearity of the amplifier is possible by simply reversing the direction of the pump light. The present system is capable of generating 400 fsec pulses with pulse energies of 20 nJ with an average power of about 1 W. Power levels well in excess of 1 W and even shorter pulses should be possible by employing longer and more uniform chirped FBGs.

In conclusion we have described some of the fundamental design principles and performance limitations of high-average power femtosecond fiber laser systems. We believe that these systems are competitive with conventional femtosecond solid-state lasers.

References

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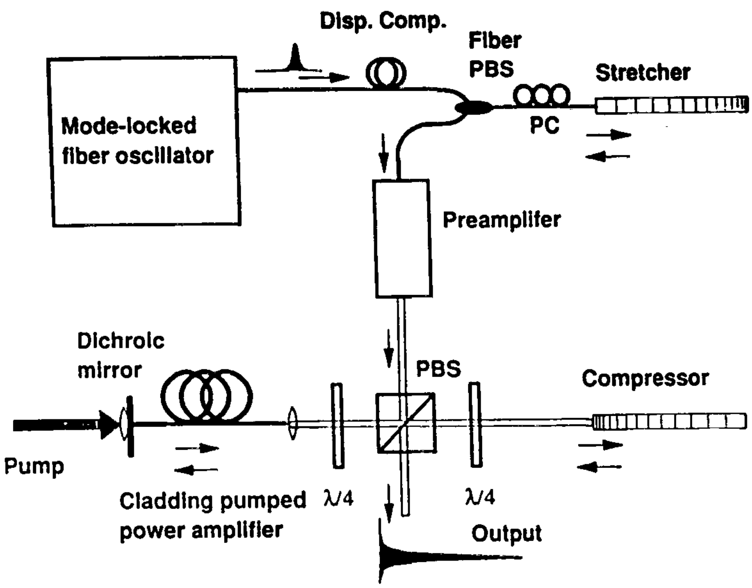

Fig.2) Experimental set-up for an all-fiber chirped-pulse amplification system employing chirped fiber gratings and cladding-pumped fiber amplifiers.

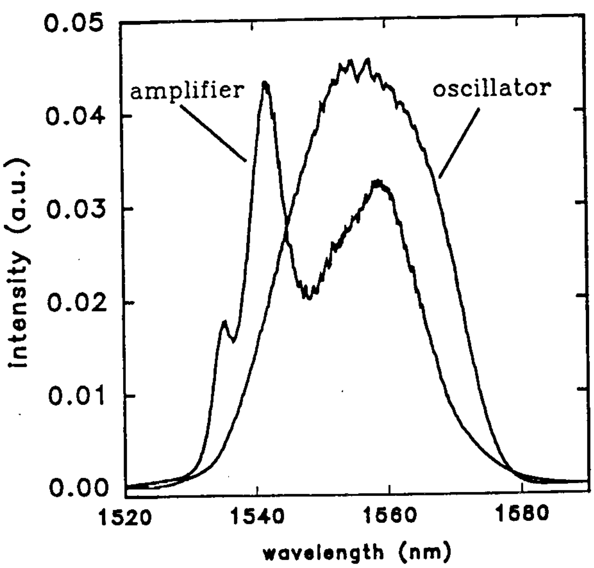

Fig. 1) Spectrum of a passive harmonically modelocked Er-fiber oscillator amplified in a cladding-pumped Er/Yb fiber amplifier.

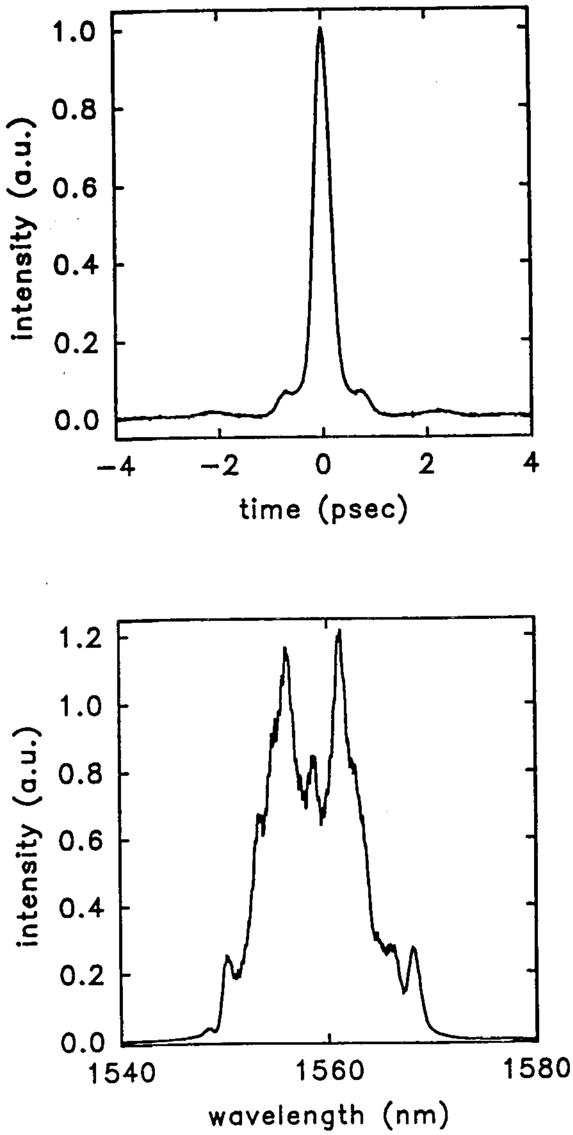

Fig. 3) Autocorrelation and spectrum of 5.2 nJ, 380 fsec pulses generated with the all-fiber chirped pulse amplifications system. The average systems output power is 260 mW.