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Short pulse high power fiber laser systems

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Abstract: We review the rapid recent progress in the development of short pulse high-power fiber laser and amplifier devices. Use of cladding pump technology now provides a route to compact and efficient laser and amplifier systems with high beam quality and high output powers. A new Yb-fiber CPA system incorporating a CFBG stretcher with both 2nd and 3rd order dispersion is presented for high pulse energy applications. In addition, a simplified Yb-fiber parabolic amplifier system is also shown to be suitable for producing higher average powers, here up to 25 W.

1. Introduction

There is an increasing demand for high-power ultrashort-pulse laser systems for industrial and scientific applications. Fiber laser technology is emerging as an attractive option for pulsed systems – not least due to the fact that during the past few years, the favourable heat-dissipation geometry of fibers has enabled tremendous increases in the average continuous wave output powers that can be reached. Powers of up to 1.4kW in a single transverse mode have now been achieved, and multi-mode systems are now approaching the 10kW regime. Furthermore, the broad gain bandwidths of Er and Yb doped fibers can support ultrashort ~100 fs pulses. However, due to nonlinear effects, the creation of practical high power pulsed fiber systems still requires new amplification techniques and the development of new fiber components. In this paper we report our recent results on a high pulse peak power CPA system incorporating chirped fiber bragg gratings (CFBGs), and a high average power parabolic amplifier system, both based on Yb fiber amplifiers and operating at 1.06 microns.

2. Yb fiber CPA system incorporating a CFBG with 3rd order dispersion compensation

Milli-Joule energy pulses may be generated in fiber amplifiers using the technique of chirped pulse amplification (CPA) [1], in which ultrashort pulses from an oscillator are stretched to several hundred picoseconds duration before amplification, and recompressed at the output of the amplifier by a matching compressor. This reduces the peak powers in the amplifier below the threshold for nonlinear pulse distortion, allowing for amplification to much higher pulse energies. Pulse stretching may be done with bulk gratings, but in the interests of moving as close as possible to an all-fiber system, we use a chirped fiber Bragg grating (CFBG). Due to the high pulse energies bulk gratings must still be used for the compressor. The bulk grating compressor inevitably has a large 3rd order phase term in addition to the 2nd order dispersion. In order to achieve femtosecond pulse durations both these terms must be matched in the pulse stretcher.

Here, we present for the first time, to our knowledge, an Yb fiber CPA system using a CFBG with both 2nd and 3rd order dispersion. The CFBGs presented here have acceptance bandwidths of up to 18nm and were produced using a scanning technique previously developed to produce precision gratings for telecommunication applications [2, 3]. A CFBG with 2nd and 3rd order dispersion matched to a bulk grating has previously been demonstrated in a CPA system at 1550nm[4], but the maximum energy and minimum pulse duration will be limited using Er compared to Yb amplifiers. A CFBG that matched the diffraction grating compressor dispersion was presented recently operating at a wavelength of 1.05μm [5]. However, in that study no amplification was implemented and the recompressed pulses had poor contrast.

Fig. 1 shows the schematic of our CPA system. Our femtosecond mode-locked Yb fiber oscillator (developed in-house) [6] produces ~30pJ pulses with a 50 MHz repetition rate. The pulses are centered at 1055 nm with a spectral FWHM of 18.6nm with an autocorrelation FWHM of ~110fs. The pulses were stretched with the CFBG and then passed through two single-mode (5μm core) core-pumped Yb doped fiber amplifiers. Electro-optic and acousto-optic modulators were used to reduce the repetition rate and filter ASE between amplifier stages. Power amplification took place in a 9m length, cladding pumped, Large Mode Area fiber with a core diameter 16.5μm, doped with 7000 ppm Yb^{3+} ions, and a cladding diameter of 200μm. The fiber, which was effectively single mode in operation, was pumped from opposite ends with 915nm and 975nm pump diodes. Fig. 2a) shows the power output of the final stage amplifier as a function of pump power - the slope efficiency was ~70%. The maximum average power achieved before compression was 17 W. Fiberised and free-space polarization controllers were distributed through the system as necessary.

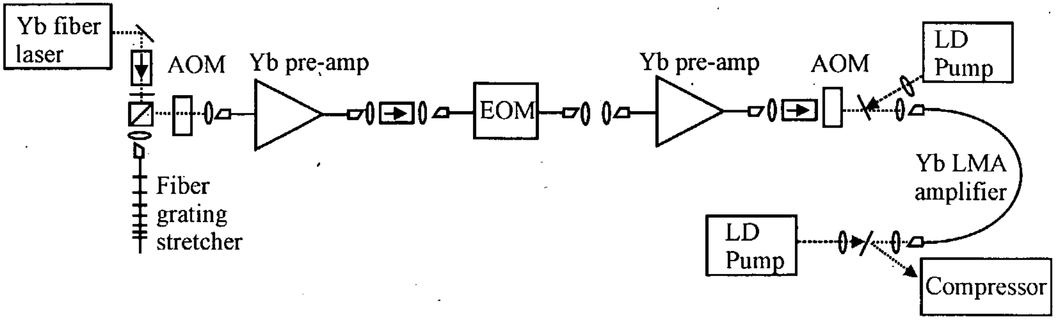

Fig 1. Schematic of CPA system. (AOM,EOM=Accousto/Electro-optic modulator, LD=laser diode, LMA=large mode area fiber.)

The group delay response and the reflectivity of the gratings reported in this paper were measured by a an RF phase-delay measurement technique. Fig. 2b) shows the reflection spectrum and delay as a function of wavelength for a CFBG centered at 1053nm with an acceptance bandwidth of 18nm. The solid curve through the delay data is a fit to 2^{nd} and 3^{rd} order dispersion, giving values of D x length = 44.65±0.4 ps/nm ($\beta_2 = \left(\partial^2\phi/\partial\omega^2\right) = -26.4$ ps^2/rad), and dD/dλ x length = 1.48±0.2 ps/nm^2 ($\beta_3 = \left(\partial^3\phi/\partial\omega^3\right) =$ 0.545 ps^3/rad^2) closely matching the values for our 1500 lines/mm reflection grating compressor.

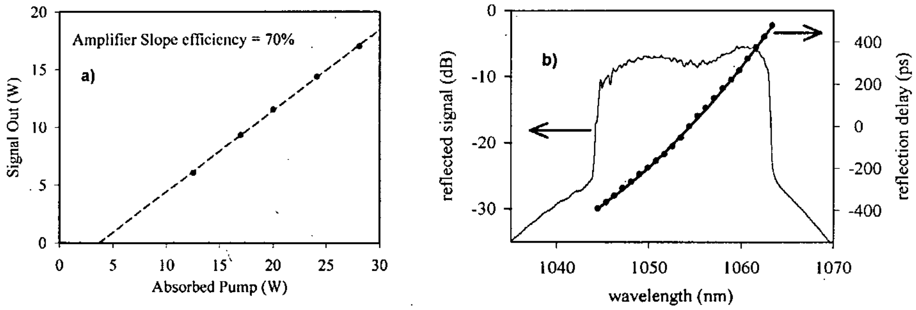

Fig 2. a) Power performance of CPA system LMA amplifier. b) Reflection spectrum and measured delay as a function of wavelength for an 18nm CFBG. The solid curve through delay data is a fit to 2^{nd} and 3^{rd} order terms.

The bandwidth of the amplifiers was considerably less than the spectral bandwidth of the seed laser, and we stretched the pulses with a relatively narrow band grating (7 nm) in order to avoid distortions due to gain narrowing effects. Fig. 3a) shows the autocorrelation of the recompressed output pulses.

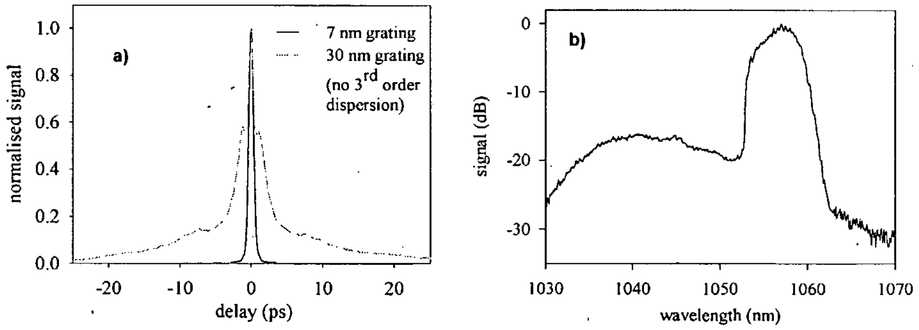

Fig 3. a) Autocorrelation after recompression (demonstrates importance of higher order dispersion compensation), and b) the spectrum of the pulses from CPA system.

The output pulse width is estimated at ~500 fs. Fig. 3a) also includes an autocorrelation of a pulse through the same system which was stretched with a 30 nm bandwidth grating which had only 2^{nd} order dispersion. It can be seen that uncompensated 3rd order dispersion has resulted in a substantially broader autocorrelation (~3 ps) with a broad pedestal. Fig. 3b) shows the spectral output of the final amplifier with the 7nm grating. The bandwidth of the output pulse is ~5nm ($\Delta\nu\Delta\tau$ ~0.7). Pulse energies from the system were limited to <10 μJ because the fiber amplifiers were not optimized for maximum gain and minimum nonlinearities, but clearly with a more optimal choice of fiber this system has the potential to reach similar pulse energies to those previously achieved using fiber amplifiers and bulk stretchers. The minimum duration of our pulses was limited by the bandwidth of our amplifier.

3. Parabolic amplifier system

It has been shown that high power pulses in a fiber amplifier with normal dispersion evolve towards parabolic pulses with a linear chirp, which enables recompression to short durations despite significant self-phase modulation in the fiber [7]. Recently we reported a system with average power of >25 W, and pulse energies of 410 nJ from an all Yb^{3+} -fiber oscillator and amplifier system [8]. The setup was a simplified version of the CPA system, without stretcher and pulse-gating components, and therefore having a much more compact compressor. The output of the amplifier system is shown in Fig. 4. It can be seen that the spectrum of the pulses broadens at higher energies. The spectral bandwidth of the high energy pulses was ~20 nm. The measured autocorrelations correspond to pulse durations of ~160 fs at low energy and ~110 fs at 410 nJ. The autocorrelations demonstrate that the pulses did not have large pedestals and that the pulse quality was good ($\Delta\nu\Delta\tau$ ~0.6) for pulses with energies up to 410 nJ. The system also produced pulses at higher average powers of up to 40 W without the onset of significant Raman scattering, but for these higher energy pulses the nonlinear spectral broadening exceeded the amplifier bandwidth, and the quality of the recompressed pulses was reduced.

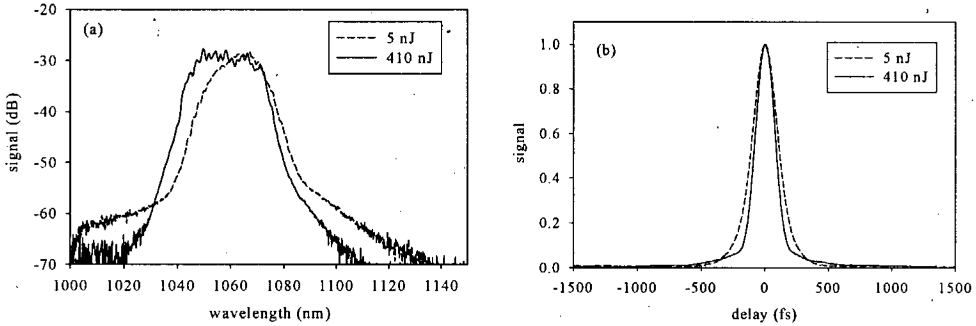

Fig. 4. (a) spectra and (b) autocorrelations of low (5 nJ) and high (410 nJ) energy pulses from parabolic amplifier system.

4. Summary

In summary, we have presented the first demonstration of an Yb-fiber CPA incorporating CFBG stretcher with both 2nd and 3rd order dispersion to match the bulk compressor. We also presented a high average power (25 W) parabolic scheme. These systems highlight the potential of fiber technology for the development of practical high-power ultrashort-pulse fiber-based lasers for future industrial and scientific uses.

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