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Femtosecond pulse amplification in cladding-pumped fibers

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Received June 8, 1995

Femtosecond pulse amplification in a cladding-pumped fiber amplifier is demonstrated for the first time to our knowledge. Using a cladding-pumped erbium-doped fiber power amplifier and a passively mode-locked fiber seed oscillator in conjunction with an all-fiber chirped-pulse amplification system, we obtain 380-fs near-bandwidth-limited pulses with an average power of 260 mW. The pulse repetition rate is varied between 5 and 50 MHz, and pulse energies as high as 20 nJ are generated. © 1995 Optical Society of America

Since the first demonstration of passive mode locking in fiber oscillators,[1,2] fiber lasers have developed steadily toward being compact and highly reliable sources of femtosecond pulses.[3] Despite extensive efforts in this area by many research groups, fiber lasers have to date not been considered serious alternatives to femtosecond solid-state lasers in most nonlinear optics applications because of their intrinsic power limitations. However, the commonly held notion that fiber lasers are limited to low powers is wrong. By use of double-clad fiber structures,[4] efficient and simple brightness conversion from high-power large-area multimode laser diode pump sources into a single diffraction-limited fiber mode can be obtained, and in fact cw output powers as high as 5 W have recently been so acheived.[5]

We show here that the high power levels that can be generated with cladding-pumped fiber lasers may in principle be utilized in the femtosecond regime by employing the chirped-pulse amplification technique.[6-8] Moreover, by construction of an all-fiber chirped-pulse amplification circuit[9] based on chirped fiber Bragg gratings[10] (FBG's) and by insertion of a cladding-pumped power amplifier in the final stage(s) of the amplification circuit, a very compact system design may be preserved.

To take advantage of our internally manufactured femtosecond erbium fiber oscillator (IMRA IM-150-FS), we developed a system based on erbium as the gain medium. Though previous research on cladding pumping the 1.55-μm transition in Er^{3+} has utilized Yb^{3+} codoping,[11] here we employed a singly doped double-clad Er fiber (Er^{3+} doping level 1000 parts in 10^6).[12] The reason is that codoped erbium fibers have limitations in the femtosecond regime owing to their narrow bandwidths induced by their large phosphate content. As the singly erbium-doped fiber is phosphate free, a large bandwidth for the power amplifier can be obtained; in addition the elimination of the codopant also ensures a high pumping efficiency.

The refractive-index profile of the double-clad erbium power amplifier is shown in Fig. 1. The fiber core has a diameter of ≈ 5 μm and a numerical aperture NA of ≈ 0.12, whereas the inner cladding has a diameter of 25 μm and an equivalent NA of ≈ 0.18. The use of such a small inner cladding ensures full inversion of the amplifier with a high-power pump source and a high effective absorption cross section without the use of Yb^{3+} as a codopant. Further, the double-clad structure minimizes the nonlinearity of the power amplifier by preserving a large core diameter for the fundamental mode. In this way a high Al_2O_3 doping level, which is required to prevent clustering of heavily Er^{3+}-doped silicate fibers, can be employed without raising the NA of the fundamental mode. In fact the $1/e$ intensity spot diameter at the signal wavelength was estimated to be ≈ 10 μm in this fiber.

The power amplifier was pumped with two polarization multiplexed master oscillator–power amplifier (MOPA) laser diodes delivering a total pump power of 1.75 W at 980 nm, of which as much as 1.15 W was launched into the power amplifier. The coupling efficiency was limited only by the losses in the isolators employed to prevent feedback into the MOPA's and by the imperfect coating of the polarization multiplexer, as the cladding-pumping scheme ensures nearly perfect input coupling even with pump beams that are not perfectly diffraction limited.

The experimental setup of the full system is shown in Fig. 2. The fiber seed oscillator was derived from an environmentally stable Kerr-mode-locked fiber laser[13]

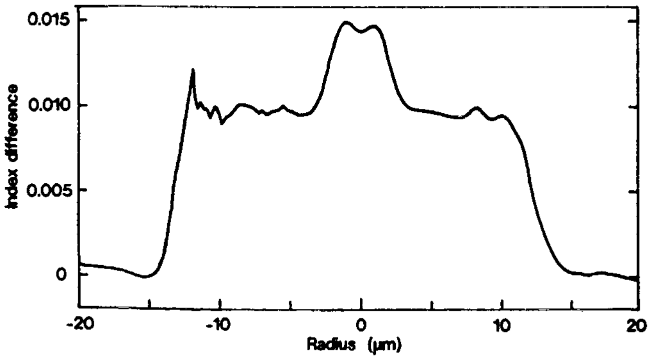

Fig. 1. Refractive-index profile of the Er^{3+}-doped double-clad fiber.

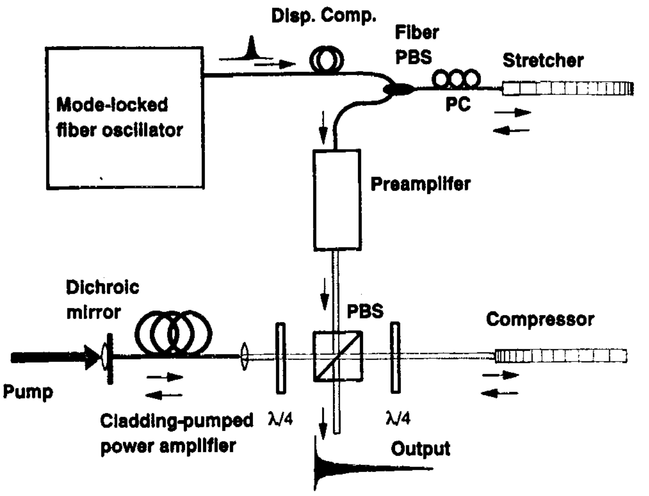

Fig. 2. Setup of the high-power femtosecond fiber laser system. PBS's, polarization beam splitters; PC, polarization controller.

that generated bandwidth-limited 200-fs pulses at a wavelength of 1558 nm with pulse energies of 10 pJ at a stable repetition rate of 5 MHz. By employing passive harmonic mode locking[14] we increased the repetition rate and the average output power to 50 MHz and 500 μW, respectively. Note, however, that we could vary the repetition rate between 5 and 50 MHz (in steps of 5 MHz) by simply changing the pump power to the oscillator between 15 and 90 mW at 980 nm. In this case, pulse bunching was prevented by an optimization of the polarization state in the fiber; however, various stable repetition rates could be obtained[15] without a change in the polarization state.

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 peak reflectivity >99% was used to stretch the pulses to a width of ~50 ps. Because of the small bandwidth of the FBG and the high loss of the all-fiber polarization beam splitter, the pulse energy emerging from the pulse stretcher was only 3 pJ. To operate the power amplifier in saturation we used a preamplifier, which produced a gain of 16 dB and boosted the average signal power to 20 mW, of which 10 mW was coupled into the power amplifier.

To extract the maximum power from the power amplifier we operated it in a double-pass configuration, and the length was optimized to 3.8 m by use of multiple cutbacks. The measured output power as a function of input power of the power amplifier operating with the broad-bandwidth seed signal of 10 mW average power is shown in Fig. 3. A slope efficiency of 40% was obtained, which gave a maximum signal power of 420 mW. We verified that the pump light was multimode and the signal light was single mode by imaging the amplifier output on a vidicon camera. Moreover, we measured a coupling efficiency of 90% (corrected for reflection losses) of the amplifier signal output into a standard single-mode fiber.

After recompression in a negatively chirped FBG, similar to the first one, an average output power of 260 mW was obtained, limited by the 90% reflectivity of the grating and the presence of some uncoated optics. Note that coupling between the various optical beams was efficiently performed by a polarization beam splitter and quarter-wave plates where appropriate. To compensate for any residual second-order dispersion after recompression, we could insert a short section of high-dispersion fiber in front of the preamplifier.

At a repetition rate of 50 MHz a pulse energy of 5.2 nJ was thus generated. We obtained much higher pulse energies by simply operating the oscillator at a lower repetition rate; however, the nonlinearity of the present system limited the maximum extractable pulse energy to ~20nJ.

Autocorrelation traces and the corresponding pulse spectra for 2-, 5-, and 12-nJ pulses are shown in Fig. 4. The FWHM pulse widths for the 2- and 5-nJ pulses are 380 fs, and for the 12-nJ pulse the FWHM pulse width is ≈370 fs, assuming a sech^2 pulse shape. The corresponding time–bandwidth products are near 0.5 for the three cases. The spectral widths (≈11 nm) of the pulses indicates that gain narrowing in the amplifier does not pose a severe limit on the obtainable pulse width, which is in line with the low overall gain of ≈35 dB of the system.

However, some significant spectral reshaping is evident from the pulse spectra and the relatively large time–bandwidth products, which in fact are caused by a variety of effects. We showed previously[9] that by employing two identical oppositely oriented FBG's the effects of longitudinal grating irregularities on the dispersion characteristics can be compensated. However, a nonuniform reflection profile is not compensated for. In fact, the resulting spectral nonuniformities of the amplified pulses are even enhanced as a result of gain narrowing. Further, a nonuniform reflection profile can also cause irregularities in the stretched pulses, which may lead to an early pulse breakup in the power amplifier because of modulational instability. Finally, self-phase modulation in the system also poses a limit on the available pulse quality and energy.

The nonlinear phase delay of the system can be obtained by adding the contribution from the power amplifier and the fiber lead (7 cm) in front of the FBG. Assuming an effective propagation length of 3.8 m in the power amplifier and 40-ps pulses with an

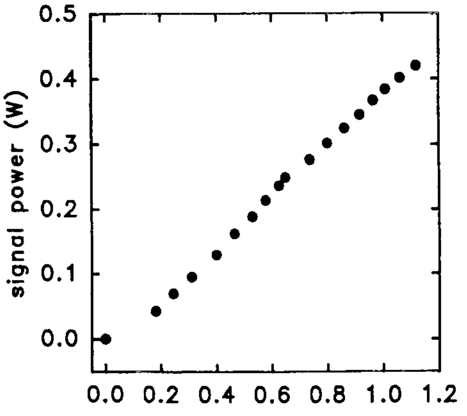

Fig. 3. Signal output power versus launched pump power of the cladding-pumped Er^{3+}-doped power amplifier.

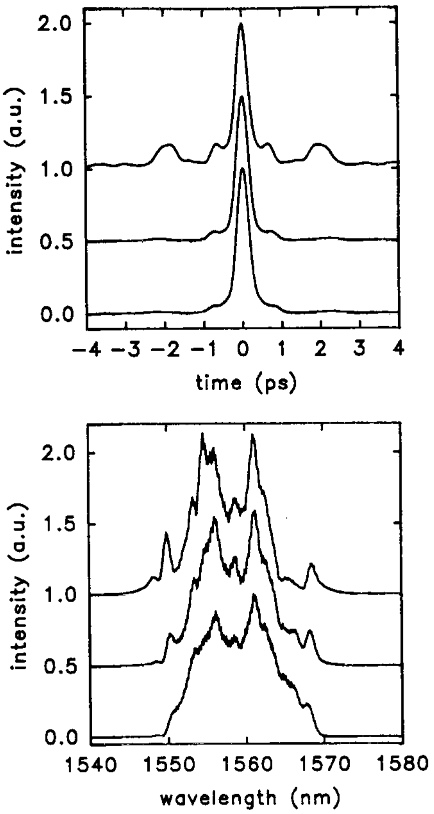

Fig. 4. Autocorrelation traces (top) and corresponding pulse spectra (bottom) of the generated 12-, 5-, and 2-nJ pulses (top to bottom).

energy of 8.4 nJ, we obtain a nonlinear phase delay of 0.44π. Similarly, assuming 380-fs pulses with an energy of 5.0 nJ, the nonlinear phase delay in the fiber lead is calculated to be 0.48π. At a pulse repetition rate of 50 MHz, the combined nonlinear phase delay is thus $\approx\pi$, which explains the relatively good quality of the autocorrelation traces up to a pulse energy of 5 nJ.

Finally, we have also performed initial experiments with broad-area diode lasers to replace the MOPA's. Using a 2.5-m length of Er^{3+}/Yb^{3+} double-clad fiber as a power amplifier and a single 1-W broad-area pump diode operating at 973 nm, we obtained a signal power of 100 mW, limited at this time by the imperfect wavelength overlap between oscillator and amplifier. However, by use of improved diode coupling schemes and longer and improved chirped FBG's, this new technology should eventually permit the construction of compact and robust femtosecond fiber lasers generating average powers in excess of 10 W.

In conclusion, we have demonstrated femtosecond amplification in a cladding-pumped fiber for the first time to our knowledge. We have shown that cladding-pumped femtosecond fiber lasers can produce average powers that are truly competitive with those of conventional solid-state lasers.

We are indebted to K. Sugden and I. Bennion for manufacturing the fiber gratings. We are also grateful to M. L. Dennis and M. Frankel for providing us with the dispersion-compensating fiber.

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