691

111 kW (0.5 mJ) pulse amplification at 1.5 μm using a gated cascade of three erbium-doped fiber amplifiers

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The generation of high peak power pulses by amplification of the output from a distributed feedback diode laser is demonstrated using a cascade of three erbium-doped fiber amplifiers (EDFAs) separated by an acousto-optic gate. The optimized amplifier chain consisted of two high efficiency single-mode EDFAs pumped with 40 mW at 980 nm, followed by a multimode EDFA pumped with 1.5 W at 978 nm. At low repetition rates, peak output powers of 111 kW and energies of 0.5 mJ at 1.534 μm were obtained.

High-power and mJ energy pulses at the relatively eye-safe wavelength past 1.5 μm find applications in sensors, range finding, and Lidar. With the advent of the erbium-doped fiber amplifiers (EDFA) it is attractive to generate such pulses by simply amplifying low-power diode-laser pulses using the high gains available. Attempts to obtain high power have been reported[1] using a two-stage erbium-doped amplifier employing an optical gate, resulting in a gain and pulse energy of 49 dB and 1.05 nJ. To further increase the pulse energy into the mJ range requires the use of multimode fiber amplifiers. To date, 16 dB of amplification has been demonstrated in an erbium-doped multimode amplifier,[2] for a continuous-wave (cw) input signal of −11.84 dB m.

This letter demonstrates the combination of both single-mode and multimode fiber amplifiers in a gated cascade to generate low repetition rate, high peak power pulses. Comparable performance to a diode-pumped, Q-switched Nd:YAG laser[3] is obtained although at the more favorable wavelength of 1.5 μm. Single-mode and multimode fiber geometries were employed to optimize both amplifier gain and stored energy, taking into account the available input signal and pump power. The optimum fiber parameters were determined using an extension of a numerical model that has previously been employed for cw signal amplification.[4] As is well known in large cascaded laser amplifiers, it is essential to prevent the amplified spontaneous emission (ASE) buildup from saturating the amplifier if a large gain is required. This can be achieved by using saturable absorbers between stages, or in the case of pulse systems, to isolate the amplifiers using a synchronously timed gate. In this experiment the whole system was configured for amplification of a ~10 ns pulse and thus it was possible to use an acousto-optic modulator as the gate.

The experimental configuration is shown in Fig. 1. The first two EDFAs (EDFA1 and 2) were constructed from single-mode fiber and were designed for maximum amplification of a short, low energy pulse, typically $\approx 10^{-11}$ J. The amplifying fiber was characterized by a germano-silicate core, a numerical aperture (NA) of 0.24, cutoff wavelength of ~920 nm, and erbium absorption of 0.95 dB/m at 1.536 μm. EDFA1 and 2 used different fiber lengths[5] (25 and 60 m), separated by a polarization-independent isolator (signal insertion loss 1 dB) to suppress the backward-traveling ASE and thus prevent saturation at the input to the amplifier. The amplifiers were pumped in series using a common 40 mW 980 nm diode and, since the isolator has a very high loss at the pump wavelength, two wavelength-division multiplexing (WDM) couplers with insertion losses at the pump/signal wavelengths of 0.11 dB/0.31 dB and 0.16 dB/0.31 dB were included to provide a low-loss bypass for the pump. The resultant forward insertion losses between the two amplifiers were ~0.6 dB at the pump wavelength and ~2.1 dB at the signal wavelength. The isolation in the reverse direction was greater than 30 dB over a 50 nm bandwidth centered at 1540 nm. This configuration has given excellent results for cw, small signal amplification and can yield gain as high as 54 dB.[5] The third EDFA (EDFA3) acts as a power amplifier and had a geometry optimized for an input pulse of energy $\approx 10^{-7}$ J. To obtain mJ pulses it is obviously necessary to store energy in the amplifier of this order and this requirement determines the core volume for a given Er^{3+} concentration. The stored energy was achieved in our case by employing a multimode fiber in order to increase the core area. In addition, the NA was reduced to minimize the number of fiber modes and thus the ASE. We employed a germano-alumino-silica erbium-doped multimode fiber of length 1.7 m with an

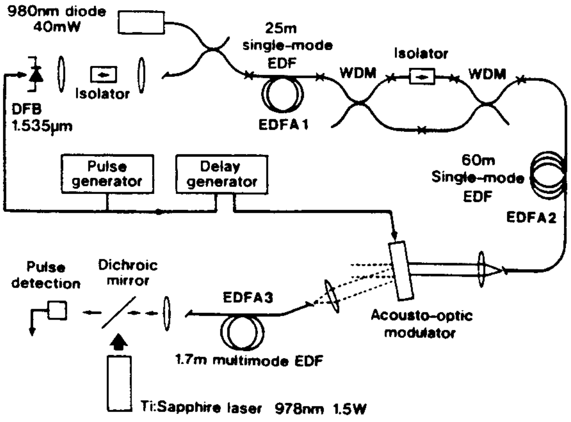

FIG. 1. Experimental setup.

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erbium concentration of 1450 ppm, numerical aperture of 0.12, and core diameter of 25 μm, which supported $\sim$20 modes at both pump and signal wavelengths. EDFA3 was pumped with 1.5 W at 978 nm from a Ti:sapphire laser. Since the fiber is multimode, in principle one of the new multistripe 980 nm diode lasers could be employed. The signal source was a DFB laser diode operating at 1.534 μm and allowed 5–500 ns pulses with a maximum peak power of 1.53 mW to be launched into EDFA1. The signal and pump source were copropagated in EDFAs1 and 2 and counterpropagated in EDFA3.

Analysis of the ASE spectra indicated that EDFAs1 and 2 exhibited a net maximum gain at 1.534 μm with a 3 dB bandwidth of 2.1 nm, while the gain of EDFA3 was centered at 1.532 μm with a 3 dB bandwidth of 4.8 nm. This slight mismatch in gain spectrum results in a small decrease ($\sim$2 dB) in unsaturated gain, but will not significantly affect the saturated pulse output.

An acousto-optic modulator (AOM) was employed between EDFA2 and EDFA3 to gate the optical signal. The output beam from EDFA2 was collimated through the AOM and the first-order defracted beam launched into EDFA3. The transmission loss was 3.4 dB and the extinction ratio of 41 dB effectively prevented any significant ASE power coupling from one amplifier to the other when the AOM was in the off state. The rise time of the optical gate was 300 ns.

The cascade amplifier was characterized for a range of parameters, including pump power, input pulse power, pulse width, and repetition rate.

The maximum output power obtained was 111 kW using a 10 ns quasisquare input pulse of peak power of 1.53 mW at a repetition frequency of 400 Hz. This output corresponds to a net amplifier gain of 78.6 dB. The launched pump powers in this case were 40 mW and 1.5 W for EDFA1/2 and EDFA3, respectively. The amplification was split such that the output peak power from EDFA2 was 88 W, corresponding to 47.6 dB gain in these two sections. The AOM was driven with a gate width of 300 ns. Owing to the coupling loss between the two EDFAs, the resultant input pulse to EDFA3 had 40 W peak power and the peak gain of EDFA3 was 34.4 dB. However, because of the high peak powers in EDFA3, the leading edge of the pulse significantly depletes the population inversion and reduces the gain available to the trailing edge (Fig. 2) showing clearly that the pulse was significantly depleting the population inversion. The average output pulse power over its 10 ns duration was 34.5 kW, giving a pulse energy of 0.35 mJ. The peak output power measured was limited by the 2 ns rise time of the 10 ns pulse. However, it is clear that significantly higher output powers should be possible for a shorter duration pulse, particularly if the small mismatch in spectral gain peak noted earlier could be eliminated.

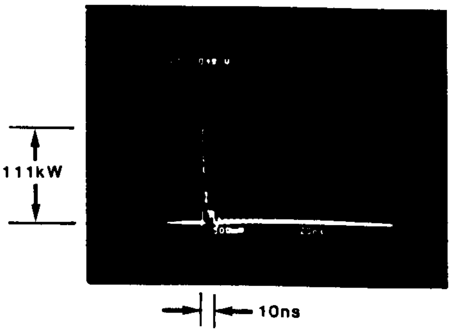

FIG. 2. 10 ns amplified pulse of 111 kW peak power (0.34 mJ).

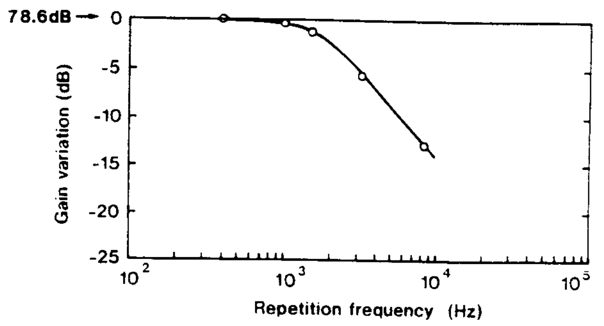

FIG. 3. Dependence of amplifier chain net gain on pulse repetition frequency. Here the input pulse width and peak power are 10 ns and 1.53 mW, respectively, while pump powers for EDFA1/2 and 3 are 40 mW and 1.5 W, respectively.

Pulse amplification was measured as a function of pulse repetition frequency and a 3 dB gain saturation was observed at a frequency of 2 kHz, as shown in Fig. 3. This relatively low frequency is a consequence of the low pump rate and the long metastable lifetime of the Er^{3+} ion in silica glasses ($\tau_f \sim 10$ ms) as well as the high pulse energy which significantly depletes the gain medium.

Figure 4 shows the dependence of net amplification of the EDFA chain on the duration of the electrical pulse employed to gate the acousto-optic modulator, which was timed synchronously such that the optical pulse experienced a minimal loss. The rise time of the AOM (10%–90% was 300 ns, which set the minimum gate width that could be employed. Increasing the gate opening resulted in an output power reduction, with a 3 dB reduction being observed for a gate opening of only 700 ns. This strong dependency on gate opening is not believed to be due to gain saturation in the third-stage amplifier, as might be expected because of the forward propagating ASE, which

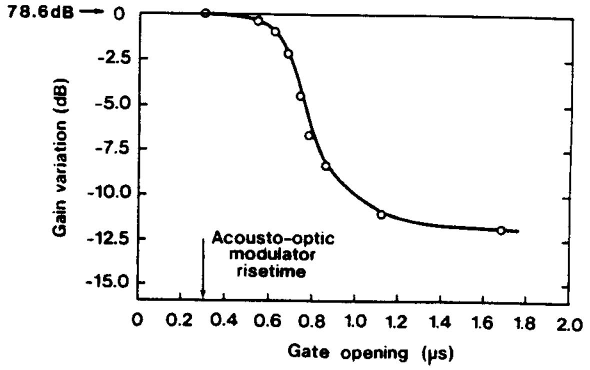

FIG. 4. Dependence of amplifier chain net gain on AOM gate opening.

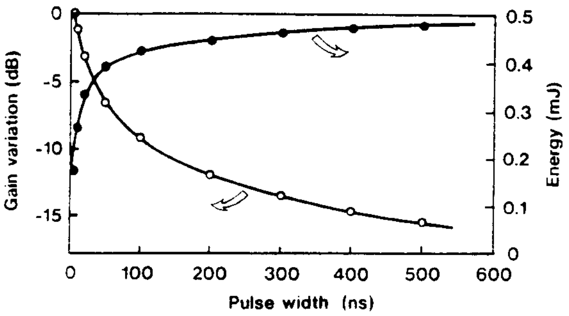

FIG. 5. Dependence of amplifier chain net gain and amplified pulse energy on input pulsewidth; here the input peak power is 1.53 mW, the repetition frequency 400 Hz, and pump powers for EDFA1/2 and 3 40 mW and 1.5 W, respectively.

we estimate to be only a few μJ for these time periods. In fact, this gain reduction is probably caused by saturation in the *second-stage amplifier* due to *backwards* propagating ASE. If this is the case, the sharp dependency on gate opening could be alleviated by incorporating between stages 2 and 3 either an isolator or a section (~ 100 m) of undoped fiber to provide a delay between the gate opening and the backwards ASE entering stage 2.

Figure 5 plots the dependence of the output pulse energy and time-averaged gain as a function of input pulse width in the range 5–500 ns at a constant repetition rate of 400 Hz. The average gain is seen to decrease by 16 dB with increasing pulsewidth. However, this is accompanied by an increase in output pulse energy, which can approach 0.5 mJ for a 500 ns pulse width. Figures 6(a) and 6(b) show the dependence of gain characteristics on both the first- and second-stage pump powers. In both cases the gain was saturated, indicating the system was well optimized.

Theoretical simulations of the system response have been carried out employing an extension of a cw model[4] and parameters representative of the fibers employed. Considering a 10 ns input pulse with 2 ns risetime and 1.53 mW peak power, we predict a peak output power of 155 kW and total energy of 0.46 mJ, which is in reasonable agreement with the experiment. Further, we predict peak output powers of 900 kW for a 100 ps input pulse in the same configuration, or a 10 ns, 1 MW pulse when a third multimode power amplifier pumped by a 10 W diode is added to the chain.

In conclusion, by employing a cascade of three EDFAs separated by an acousto-optic gate we have amplified a 10 ns, 1.53 mW pulse from a DFB laser to a peak power of 111 kW (0.34 mJ). It is predicted that peak output powers up to 1 MW should be achievable.

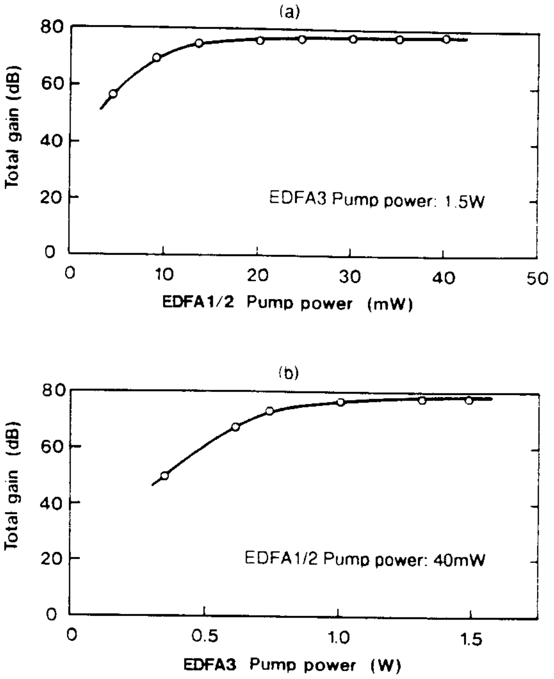

FIG. 6. Dependence of amplifier chain net gain on (a) EDFA1/2 pump power with EDFA3 pump power of 1.5 W and (b) EDFA3 pump power with EDFA1/2 pump power of 40 mW. In this case the input pulse width and peak power were 10 ns and 1.53 mW, respectively, and the repetition rate was 400 Hz.

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