Operation of Erbium-Doped Fiber Amplifiers and Lasers Pumped with Frequency-Doubled Nd:YAG Lasers

M. C. FARRIES, P. R. MORKEL, R. I. LAMING, T. A. BIRKS, D. N. PAYNE, AND E. J. TARBOX

Abstract—**An optical amplifier consisting of an erbium-doped germanosilicate fiber optically pumped at 532 nm is described. Negligible excited-state absorption at 532 nm allows efficient pumping, enabling a gain of 34 dB at 1536 nm to be obtained for only 25 mW of pump power. The pulsed pump source produces negligible noise on the small signal if the pump repetition rate is above 10 kHz. Pulsed laser operation is achieved by pumping a Fabry-Perot erbium doped fiber laser with a frequency doubled Q-switched Nd-YAG laser. Pulses of 0.9-W peak power and 280-ns duration at 1.538µm were obtained.**

Introduction

Since the early demonstrations of optical amplification in rare-earth-doped fibers [1], erbium-doped fibers have generated much interest as optical amplifiers in the third telecommunications window around 1.53 µm [2], [3]. We report very high small-signal gain (34 dB) from an erbium-doped-fiber amplifier optically pumped at a wavelength of 532 nm using a power level easily obtainable from diode-pumped frequency-doubled mini-YAG lasers. Erbium doped fiber amplifiers with gains of this size offer a practical alternative to conventional optoelectronic repeaters. The all-optical amplifier may be used as a power amplifier, optical repeater and a preamplifier in conventional, coherent, and wavelength division multiplexed systems.

Demonstrations of erbium-doped fiber amplifiers to date have employed impractical gas/dye laser pump sources or very high powered semiconductor laser diodes with limited lifetimes. It is therefore important to consider all possible pump sources; the frequency doubled Nd-YAG laser being a practical contender.

This efficient solid state pump source may also be employed to pump a fiber laser. The gain modulation obtained by Q-switching the pump laser may be used to considerable advantage in order to achieve short intense pulses from the fiber laser. The erbium system is particularly suited to gain modulation because the long (15-ms) fluorescence lifetime enables low pump repetition rates to be used. Short pulses at this wavelength have many applications including OTDR for telecommunications fiber testing and optical range finders.

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Suitable Pump Sources

Published results to date have shown gains as high as 29 dB [2], [3], but have employed impractical argon-ion (514.5 nm) or argon/dye lasers (665 nm) as pump sources. Moreover, these pump wavelengths both possess a degree of pump excited-state absorption (ESA) [4], [5]. ESA occurs when the highly populated inverted metastable level responsible for the gain at 1.53 µm is depleted by pumping to an unfortunately located higher energy level (Fig. 1). It results in reduced gain and pumping efficiency.

An ideal pump band should show substantial ground-state absorption with zero ESA to ensure all pump absorption is associated with signal gain. From a practical standpoint the pump source should ideally be compact and solid-state, i.e., a semiconductor laser diode or a diode-pumped mini-YAG. An absorption band in erbium-doped silica fibers exists around 810 nm, but the presence of strong ESA at these wavelengths reduces its attractiveness. Direct pumping using an 807-nm laser diode has recently been achieved [6] using a very high NA (0.3) fiber design in order to maximize the pump intensity in the fiber core. The presence of ESA gives relatively poor pumping efficiency resulting in less gain than previously achieved [2], [3].

A possible pump source is a frequency doubled Nd-YAG laser operating at 532 nm. Such sources pumped by semiconductor diodes are available with average output powers of 40 mW. The amplifier experiments reported here used only 25-mW average power at 532 nm. There is negligible excited state absorption in Er^{3+} doped fibers at this wavelength because there is no level above the metastable level corresponding to an excitation by light at 532 nm (Fig. 1). For high second harmonic conversion efficiency the pump laser was operated mode-locked for amplifier experiments and q-switched for laser experiments. We show later that the long lifetimes of the energy

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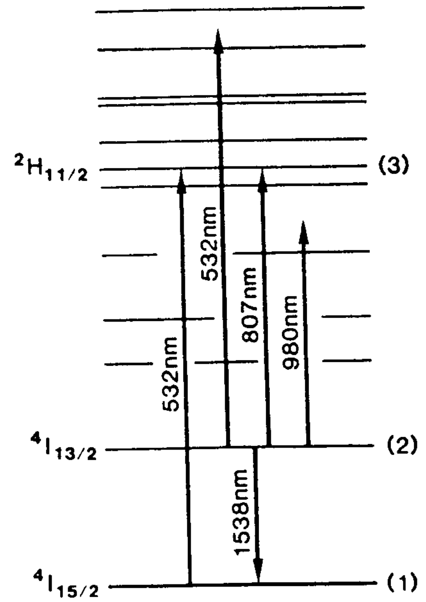

Fig. 1. Simplified energy level diagram of Er^{3+} in silica.

levels of Er-doped silica smooth any noise that might have been introduced on to the signal by a modulated pump source.

Amplification

Fig. 2 shows a schematic of the experimental amplifier setup. The pump source used was a mode-locked Nd:YAG laser externally frequency-doubled using a KTP crystal. Due to the high mode-locking repetition rate (100 MHz) and the long metastable lifetime of the fiber gain medium (15 ms), the mode-locked laser could essentially be considered as a CW pump source.

The pump power was coupled into the erbium-doped fiber with a dichroic coupler which was fabricated to give a high coupling coefficient at 532 nm and low coupling at 1536 nm. The silica fiber was doped with 0.1 wt% Er^{3+} and 15 wt% GeO_2. The fiber had a second mode cutoff of 1070 nm and a NA of 0.15 which was compatible with convention telecoms fiber. The signal from a DFB semiconductor laser at 1536 nm was launched into the doped fiber using the other port of the coupler. In order to prevent Fresnel feedback into the amplifier, both the fiber ends were terminated to eliminate reflections and an optical isolator was placed between the input fiber end and the DFB laser.

Amplifier Results

The amplifier was characterized by measuring a) amplified signal output, b) amplified spontaneous emission (ASE) in the absence of signal, and c) pump throughput as a function of fiber length. The results in Fig. 3 show a peak signal output of 0.4 mW (a gain of 34 dB for a fiber length of 5 m and an input power of 150 nW. At higher signal output powers (> 1 mW), reduced gain (22 dB) is observed due to gain saturation of the amplifier (see curve for input signal power of 10 μW). The dotted curve shows the axial variation of ASE with fiber length. At the

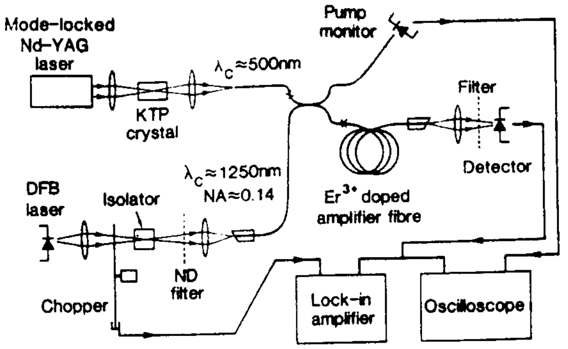

Fig. 2. Experimental arrangement for 532 nm pumping of an erbium-doped fiber amplifier.

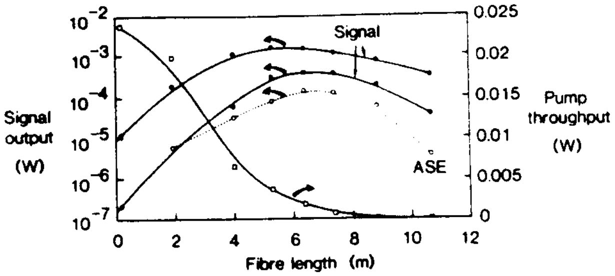

Fig. 3. Growth of signal and amplified spontaneous emission and decrease in pump throughput along the fiber amplifier. Upper and lower signal curves are for signal inputs of 8.5 μW and 150 nW, respectively.

fiber length of maximum small-signal gain (5 m) the equivalent ASE input power is ~ 60 nW, measured in an optical bandwidth of 2–3 nm. For clarity Fig. 4 shows the amplifiers optical gain as a function of fiber length. The maximum gain is limited by the launched pump power of 25 mW.

Maintaining other fiber parameters constant, increasing the fiber NA to 0.3 would be expected to give similar small-signal gain for pump power in the region of 5 mW.

A pump wavelength of 532 nm produces gain of 34 dB with a pump of 25 mW (1.45 dB/mW) in this fiber. Comparing this result with published data; an 807-nm source produces a gain of 8 dB with 20-mW 0.4 dB/mW [6] and is principally limited by excited state absorption. An alternative diode source at 1.49 μm produces a gain of 12.5 dB gain for 40-mW pump power (0.31 dB/mW) [7]. This source with minimal stokes shift is very attractive but the gain is limited by the poor absorption cross section. The only reported data with a gain per milliwatt higher than that achieved here is that with 980-nm pumping using 11 mW to achieve a gain of 24 dB (2.2 dB/mW) [8]. There is no excited state absorption at this wavelength but to date the only suitable source has been dye laser.

Pump Noise

The performance of the optical amplifier will deteriorate considerably if noise on the pump laser is transferred onto the signal. In this amplifier the pump source was a mode-locked laser producing 200-ps pulses at a repetition rate of 100 MHz. Signal modulation in the amplifier at

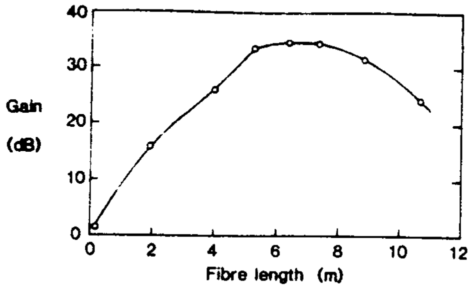

Fig. 4. Small signal gain against fiber length for a pump power of 25 mW and a signal input power of 150 nW.

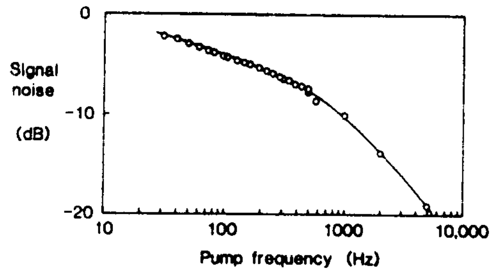

Fig. 5. Frequency response of noise on the signal due to pump modulation.

this frequency would fall into the telecommunication receiver bandwidth and cause data errors. The spontaneous decay time by radiative and nonradiative processes was measured as 1.6 μs from the pump band (3 in Fig. 1) and 15 ms from the meta-stable level (2 in Fig. 1). Modulation of the amplifier gain by pump noise at a frequency greater than 66 Hz will be smoothed by the long lifetimes of these energy levels.

The effect of pump noise was measured by modulating the pump with an external chopper at frequencies below 1 kHz and by Q-switching the Nd-YAG laser at frequencies up to 20 kHz while monitoring the modulation of the ASE at the pump modulation frequency. The amplifier noise referenced to 100-percent induced signal noise is shown in Fig. 5. The -3-dB noise point occurs at approximately 80 Hz and the coupled pump noise is -10 dB at 1 kHz. The increased rolloff above 1 kHz is due to detector response and the lifetime of the pump band.

It is therefore possible to operate the pump laser Q-switched at a frequency greater than 1 kHz and introduce less than -10-dB additional noise. No modulation of the amplifier gain was observed at the mode-locking frequency of 100 MHz. These measurements assume that the amplifier is operating in the small signal regime where stimulated emission will not decrease the lifetime of the energy levels.

Laser Operation

A frequency doubled Nd-YAG laser is an efficient pump source for erbium-doped fibers as described above. It may also be used to pump an erbium-doped fiber laser. During lasing the medium is dominated by stimulated emission and will therefore show a strong coupling between the laser output and the pump noise. Gain modulation by pulse pumping was used to produce short, 280-ns-duration laser pulses at 1.538 μm.

Theory of Gain Modulation

In most laser systems the pump energy is continuous or from a pulsed source of which the pulse length is long compared with the lifetime of the absorbing level. In this case the pump pulses at a wavelength 532 nm have a pulsewidth of 100 ns and a repetition rate of 2 kHz. A simplified energy level diagram of Fig. 1 is referred to in this theoretical model. The pump band is the $^2H_{11/2}$ $\{3\}$ and it has a lifetime of 1.6 μs. Most of the ions in the pump band will decay by multiphonon action to the metastable $^4I_{13/2}$ level $\{2\}$. The fluorescence life time of level $\{2\}$ is 15 ms. Erbium is effectively a 3 level laser emitting at 1.538 μm by stimulated emission from level 2 to the ground state level 1.

To analyze the problem the basic rate equations, below, for a three level laser have been solved numerically.

Fluorescence Pumping Laser emission

$$\frac{dN_1}{dt} = \frac{N_2}{T_2} - (N_1 - N_3)W_P + (N_2 - N_1)W_L \quad (1)$$

$$\frac{dN_2}{dt} = -\frac{N_2}{T_2} + \frac{N_3}{T_3} - (N_2 - N_1)W_L \quad (2)$$

$$\frac{dN_3}{dt} = -\frac{N_3}{T_3} + (N_1 - N_3)W_P \quad (3)$$

$$\frac{dW_L}{dt} = (N_2 - N_1)W_L. \quad (4)$$

In this analysis N_1, N_2, and N_3 are the populations of ions in each of the energy levels and dN_1, dN_2, and dN_3 are the changes in these populations per time interval. W_P and W_L are the pump and stimulated emission rates, respectively. Initially the metastable level $\{2\}$ is unpopulated. After the first short pump pulse level $\{3\}$ has a population N_3 equal to the reduction in population of the ground level dN_1. Pump pulses are assumed to be short compared with the lifetime of the pump band. The population of this level decays mainly nonradiatively to the metastable level $\{2\}$. We can ignore the weak direct transition to ground from level $\{3\}$. The population of level $\{2\}$ will approach dN_1 in a few microseconds. After the first pump pulse, N_2 is less than N_1.

There is small decay, due to fluorescence, of the population of level 2 between pump pulses. As the fiber is pumped by subsequent pulses the population of level $\{2\}$ increases by dN_1 after each pulse. In this analysis we are able to ignore the effects of nonuniform pumping to a first approximation.

After a number of pulses, level $\{2\}$ will be inverted with respect to level $\{1\}$ and the medium will have sufficient gain to overcome the resonator losses and produce a pulse of laser emission. Fig. 6 shows the population of all the levels before and after pumping. The population of

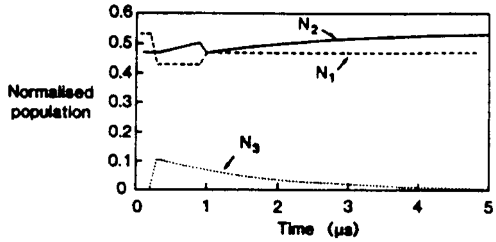

Fig. 6. Population of energy levels in Er^{3+} doped fiber during pulse pumping and laser emission.

level {2} drops rapidly during laser action at a rate given by (the stimulated emission rate—the decay from level {3}). There is a time delay between the pump pulse and the laser emission which shortens as the pump power or the pump repetition rate increases due to the finite decay time of level {3}. Fig. 7 shows the calculated laser pulse for various pump powers. After laser emission occurs the population of level {2} is clamped so that $N_2 = N_1$ which is below the laser threshold. However if the pump power is large enough then there will be sufficient number of ions in level {3} to reinvert level {2} above threshold and produce further laser pulses as shown in Fig. 3. As the pump pulse power is increased the laser threshold will be attained due to depopulation of the ground level {1} by the pump pulse and not by an increase in N_2 via level {3}. The delay between the pump pulse and the laser emission will only be due to the pump pulse duration and the laser cavity build up time which in this case is less than 100 ns.

Experiment

The experimental laser is shown in Fig. 8. The pump is an intracavity frequency doubled Q-switched Nd-YAG laser. The pump pulse energy absorbed in the fiber is up to 5 μJ. This is sufficient to cause damage to a dielectric mirror when focused. For this reason the input end of the fiber also serves as the output coupler with 4-percent Fresnel reflection providing optical feedback. A dichroic beam splitter is used to separate the pump and output beams. Three meters of fiber doped with 150 molar ppm Er^{3+} was used as the gain medium. The far end of the fiber was butted up to a silvered mirror with a reflectivity of over 99 percent. The pump pulse and output laser pulses are shown in Fig. 9 for various pump powers. For an absorbed pump energy of approximately 3 μJ a single laser pulse of 0.9 W peak power was emitted. The delay between the pump and laser emission is 4 μs during which 91 percent of the excited ions have decayed from level {3} to level {2}. The pulsewidth was 280 ns and the wavelength was 1.538 μm. An increase in the pump energy produces 3 laser pulses, the first one was 1.2 μs after the pump pulse.

Conclusions

In conclusion, we have demonstrated small signal gain of 34 dB in an erbium-doped telecommunications-compatible silica fiber amplifier optically pumped with 25 mW

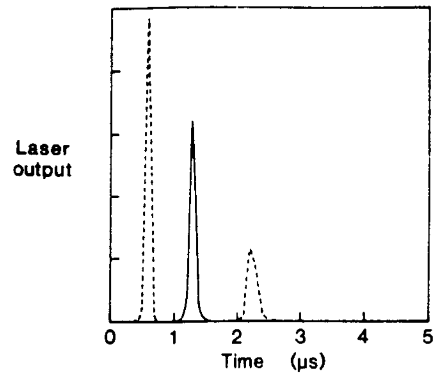

Fig. 7. Calculated laser pulses produced during pulsed pumping.

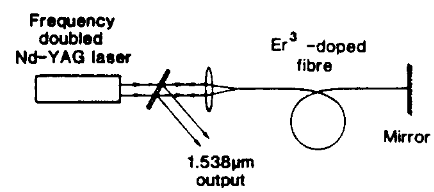

Fig. 8. Experimental arrangement for pulse pumping an erbium-fiber laser.

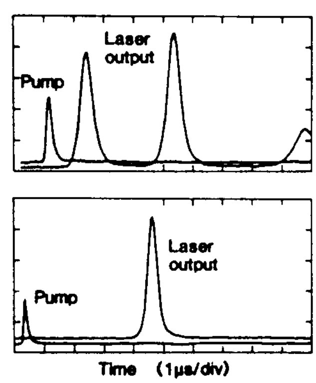

Fig. 9. Output of erbium fiber laser at different pump powers.

of 532-nm light. This pump wavelength is seen to be efficient owing to significant ground-state absorption and negligible ESA which enables high gain to be obtained at only 25 mW of pump power. Since compact frequency-doubled diode-pumped mini-YAG lasers are readily available with this power output, a practical in-line high-gain fiber amplifier can now be realized.

We have also shown that a similar pump source can be used to pump a fiber laser emitting at 1.538 μm. Short intense pulses are obtained from a fiber laser by pulse pumping a 3 level laser which is partially inverted. Nd-YAG lasers operating at 1.064 μm or 1.319 μm are frequently used in optical fiber analysis. However a suitable intense pulsed source at 1.55 μm was previously only obtained by Raman shifting the Nd-YAG output or from a color center laser. The laser described here provides a convenient method for obtaining short intense pulses at 1.538 μm.

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