8-mW Threshold Er^{3+}-Doped Planar Waveguide Amplifier

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***Abstract*—We report on the gain characteristics of a low threshold (8 mW) Er^{3+}-doped planar optical waveguide amplifier. Net fiber to fiber gain of 4.5 dB is achieved at a signal wavelength of 1536 nm with 80 mW of 980-nm pump power. This device represents significant progress toward a planar amplifier module pumped by a single laser diode.**

I. Introduction

Er^{3+}-doped planar optical waveguide amplifiers (POWA) are of interest for 1.5 μm telecommunications applications [1], [2]. POWA's offer the possibility of integration with other planar structures [3] such as wavelength division multiplexers, splitters, and filters resulting in integrated waveguide amplifier modules that combine active and passive functions on a single substrate. Practical applications of such modules require among other things, planar amplifiers pumped by a low-power semiconductor diode laser as opposed to a high-power Ti : sapphire laser [4].[1] We demonstrate the lowest threshold to date of 8 mW in a POWA at a signal wavelength of 1536 nm, with a net gain of 4.5 dB at 80 mW of pump power.

Planar amplifiers provide gain in devices less than tens of centimeters long, as opposed to fiber amplifiers with lengths of typically tens of meters. We previously reported on a POWA with 4×10^{20} Er^{3+}/cc, which achieved 15 dB of gain in 4.5 cm with 280 mW of 980 nm pump power [1]. The high Er^{3+} concentration of these waveguides resulted in a reduction in the lifetime of the $I_{13/2}$ metastable state due to up-conversion [5]. In this letter the amplifier pump threshold has been significantly reduced due to the following two factors. First, we use a lower concentration film (0.7×10^{20} Er^{3+}/cc) to increase the lifetime to 14 msec at low power and 10 msec at high power. Secondly, the waveguide fabrication technique was improved to minimize the extra losses induced by the processing itself. Er^{3+}-doped films 1.4 μm thick were deposited by RF magnetron sputtering from a soda-lime glass target on a 15 μm oxide lower cladding grown via high-pressure thermal oxidation. The refractive index difference between the core and lower cladding is 3.0%. Ion milling through a tri-level mask was then used to define 3–9 μm wide waveguides. The etching induced side wall roughness was removed by reflowing the waveguides at a temperature above the glass transition, resulting in a smooth upper surface [6]. The end faces of the 6 cm long amplifiers were polished to optimize the waveguide to fiber coupling. An index matched oil was used as the upper cladding. The relatively low softening temperature of the Er^{3+} doped soda-lime glass precludes utilization of a standard deposited high silica cladding; alternative techniques are under investigation.

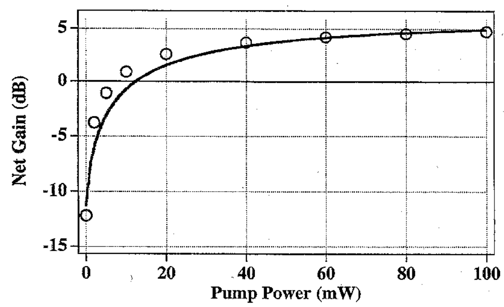

Fig. 1. Net optical gain versus pump power for amplifier no. 1. Pump wavelength is 980 nm. Input signal power is −42 dBm at 1536 nm. The open circles are experimental data points, the solid line is a fit to the model described in the text.

Optical gain measurements were performed using both a 975 nm semiconductor diode laser and a 980 nm Ti : sapphire laser as pump sources. A single-mode fiber with a high numerical aperture (NA) of 0.31 was used for input and output coupling to the waveguides. Fig. 1 shows the small signal net fiber-to-fiber gain for amplifier no. 1. The circles are the experimental data points and the solid line is a fit to the model described below. This device achieves a gain threshold at 8 mW of pump power with an input signal of −42 dBm at 1536 nm. The low threshold is enabled by two factors. First, the mode is very tightly confined within the core of the amplifier as evidenced by the fact that at the signal wavelength the waveguide absorption is 1.5 ± 0.05 dB/cm while that of the bulk target glass is 1.6 dB/cm. The waveguide absorption was determined by subtracting the insertion loss at 1.3 μm from that at 1.5 μm. The target glass absorption was measured between 7500–5000 cm^{-1} using a Perking Elmer model 1700X spectrophotometer. Using a 1 cm thick sample the peak absorption could be determined to within ±0.01 dB/cm after correcting for Fresnel reflection. Secondly, the background scattering loss of the waveguide is similar to that of the deposited film itself. The

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[1] A planar amplifier module pumped by an array of four laser diodes is reported in [4].

TABLE I
GAIN CHARACTERISTICS OF PLANAR WAVEGUIDE AMPLIFIERS. PUMP WAVELENGTH IS 980 nm

	Length	Width	Threshold	Net gain at 80 mW of pump power
Amplifier #1	5.9 cm	8 μm	8 mW	4.5 dB
Amplifier #2	6.0 cm	9 μm	9 mW	4.2 dB
Amplifier #3	6.0 cm	8 μm	10 mW	3.7 dB

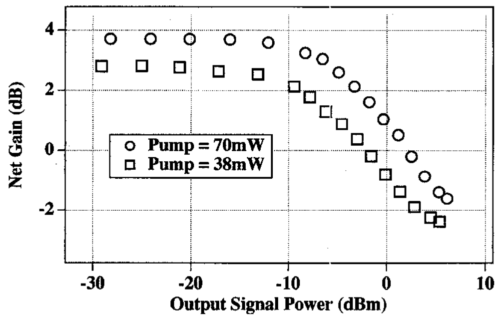

Fig. 2. Gain saturation characteristic for amplifier no. 1. Pump wavelength is 975 nm. Input signal wavelength is 1536 nm. The symbols are experimental data points.

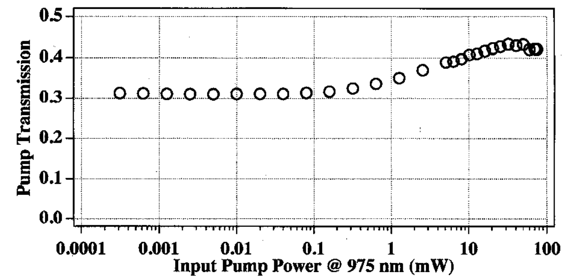

Fig. 3. Residual pump power for amplifier no. 1. Transmission, normalized with respect to input power, as a function of input pump power.

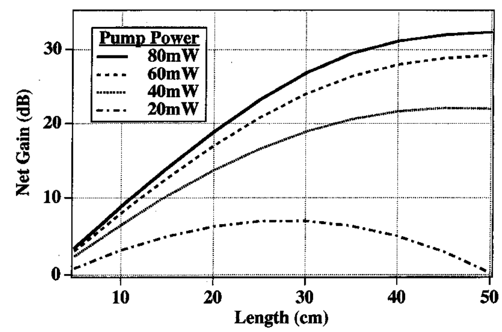

Fig. 4. Modeling results for a waveguide amplifier. Net optical gain as a function of length for 80, 60, 40, and 20 mW of 980 nm pump power.

insertion loss at 1.3 μm was measured to be 2.4 ± 0.05 dB. From previous cutback measurements, we estimate a coupling loss of about 1 dB per interface, which results in a background scattering loss of about 0.1 dB/cm.

The reproducibility of the processing was investigated by fabricating several devices on different wafers. As shown in Table I, the amplifiers have gain thresholds of 8–10 mW and a net gain of 3.7–4.5 dB at 80 mW of pump power. Commercial semiconductor laser diodes are currently available that provide 100 mW of fiber coupled power at 980 ± 5 nm. Accounting for about a 1 dB coupling loss, our POWA's have sufficient gain to be used as diode pumped 1 : 2 lossless splitters. The gain saturation characteristic of amplifier no. 1 pumped with a 975 nm laser diode at 70 and 38 mW is shown in Fig. 2. The small signal gain at 70 mW is 3.7 dB and we achieve a 3 dB gain compression at 0.6 dBm of output signal power. Note that the penalty in the small signal gain for pumping 5 nm off the pump absorption peak is about 0.5 dB. This drop in gain is consistent with the measured wavelength dependence of the absorption spectra of the bulk target glass.

Fig. 3 shows the residual pump power at the output of the amplifier. Transmission, normalized with respect to the input power, is plotted as a function of input pump power. The 0.31 NA single-mode fiber was used for input coupling. To ensure collection of all the exiting radiation, a 0.57 NA microscope objective was used to collimate the output light on to a large area detector. At low power about one third of the pump is transmitted through the waveguide; the fraction of transmitted radiation increases with power due to inversion of the Er^{3+} ion system. The figure indicates that better performance could be attained with a longer waveguide that would utilize all of the available pump power. The slight dip in transmission above 60 mW of pump is probably due to excited state absorption.

In order to investigate the optimum amplifier design we have modeled the net optical gain characteristic of amplifier no. 1 as shown in Fig. 1. A reasonable fit to the amplifier threshold and the small signal gain is obtained. Standard rate equations were used to model [7] the population in the ground and excited states, as well as the evolution of pump, signal, forward, and backward amplified spontaneous emission powers along the length of the waveguide. The model also accounts for up-conversion along with the following experimentally measured parameters: 1) the waveguide cross sectional area and mode confinement factor, 2) absorption by the Er^{3+} ions at the pump wavelength, 3) absorption and emissions by the Er^{3+} ions at the signal wavelength, 4) the low- and high-power $I_{13/2}$ state lifetime, and 5) the background and coupling losses of the waveguide. The potential performance of a longer version of amplifier no. 1 is shown in Fig. 4. The small-signal net gain as a function of waveguide length is plotted for a range of pump powers. The results indicate that a gain of 30 dB is achievable for a 36-cm-long amplifier with only 80 mW of pump power. We anticipate fabricating longer devices in a small area because the high delta of our waveguides should allow for a 1 mm bend radius.

In conclusion, we have fabricated and tested Er^{3+}-doped planar waveguide amplifiers with 8–10 mW thresholds and 3.7–4.5 dB of net gain. Modeling indicates that a longer devices would result in more efficient and higher gain amplifiers. These planar devices can be pumped with a single 980 nm diode laser, making them attractive components for an integrated amplifier module.

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