Optical Gain around 1.5 μm in Erbium-Doped Waveguide Amplifiers

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ABSTRACT

The development in the field of erbium-doped integrated waveguide amplifiers for the generation of broadband and high-speed optical amplification around 1.5 – 1.6 μm is discussed and current and future potential applications are explored. In erbium-doped amorphous aluminium oxide on a silicon wafer, an internal net gain per unit length of 2.0 dB/cm at the wavelength of 1533 nm and internal net gain over a bandwidth of 80 nm has been demonstrated. Spiral-waveguide amplifiers of different lengths and erbium concentrations have been studied and an internal net gain of 20 dB in the small-signal-gain regime has been achieved. Currently, a highly promising crystalline host material, potassium double tungstate, which provides high emission cross sections to rare-earth ions and has generated an internal net gain per unit length of > 1000 dB/cm when exploiting the ytterbium transition at 1 μm, is doped with erbium ions and tested for amplification around 1.5 – 1.6 μm.

Keywords: erbium-doped materials, waveguide amplifier, integrated optics.

1. INTRODUCTION

Rare-earth-doped materials are of great interest as light sources in integrated optics. In particular, erbium-doped lasers and amplifiers [1] have shown a great potential for direct applications in communications [2], spectroscopy [3], imaging [4], and sensing [5, 6]. Erbium-doped amplifiers have unique properties, such as long excited lifetimes (up to several ms) allowing high-bit-rate amplification [7], weak temperature dependence of their gain performance [2], and small refractive-index change induced by rare-earth-ion excitation [8, 9], among others. Erbium-doped amorphous aluminium oxide (Al_2O_3) as a platform has shown a great performance in optical amplification in the telecom C-band, offering an amplification bandwidth of 80 nm, with up to 2 dB/cm small-signal gain per unit length [10]. Although in Al_2O_3 amplification by erbium ions has its limitations due to significant quenching of the amplifier level [11], it has proved to be a great host for rare-earth ions [2, 10, 12]. The potential of potassium yttrium double tungstate (KYW), a crystalline host material, will be discussed in this work. It has been exploited to generate highly efficient channel-waveguide lasing in Yb^{3+} [13, 14] and Tm^{3+} [15, 16]. Moreover, KYW:Yb^{3+} has shown an outstanding gain performance in optical amplification, exceeding 1000 dB/cm at 980 nm [17, 18]. KYW:Er^{3+} has approximately four-times higher peak transition cross-sections [19] compared to Al_2O_3:Er^{3+} [10], which implies a potential higher gain per unit length. In addition, large inter-ionic distances provided in the KYW matrix reduce the ion-ion interaction, thereby decreasing energy-transfer processes [20] which are detrimental to maintaining population inversion.

2. AMPLIFIER DESIGN AND FABRICATION

Agazzi *et al.* reported [11] that a limitation on gain per unit length was imposed by increasing the Er^{3+} doping concentration in Al_2O_3 (see Fig. 1). This was caused by migration-accelerated energy-transfer up-conversion (ETU) and, more important, a fast energy-quenching process, which reduces the $^4I_{13/2}$ luminescence lifetime from 7.5 ms to ≤ 1 μs in a fraction of Er^{3+} ions [11]. Consequently, rather low Er^{3+} doping concentrations in the range of $1 – 2\times10^{20}$ cm^{-3} were found to be optimum for maximum signal gain [2, 10, 11]. In order to compensate for the lower concentration and, consequently, low pump-power absorption, long channel waveguides were required. Spiral-shaped waveguides were designed to minimize the amplifier foot print. In the design, a minimum bending radius of 2 mm was selected in order to minimize the radiation losses due to the bends [2]. 1-μm-thick erbium-doped Al_2O_3 layers were deposited onto oxidized silicon wafers via reactive co-sputtering [21] and patterned using UV lithography. Rib channel waveguides were etched into the films using reactive ion-etching [22]. The rib height and the channel width were 0.35 μm and 1.5 μm, respectively. A plasma-enhanced chemical-vapour-deposition (PECVD) SiO_2 layer was deposited on top of the waveguide layer as a protective cladding. An image of a spiral waveguide is presented in Fig. 2.

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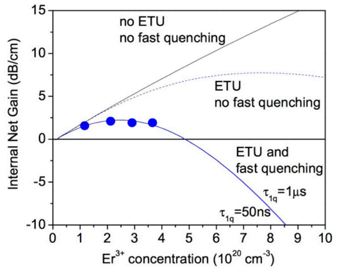

Figure 1. Internal net gain per unit length at 1533 nm versus Er^{3+} concentration, for a launched pump power of 100 mW at 976 nm and a signal power of 1 µW at 1533 nm: measured data (dots) and calculations (lines) without quenching, only ETU quenching, as well as ETU and fast quenching. Two different values τ_{1q} = 50 ns and 1 µs of the fast quenching process were tested; the two resulting curves are almost identical. Figure taken from [11].

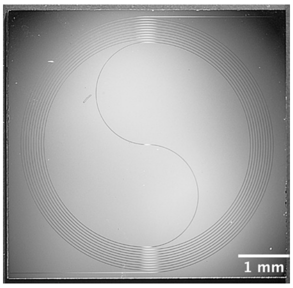

Figure 2. Image of an erbium-doped Al_2O_3 spiral waveguide.

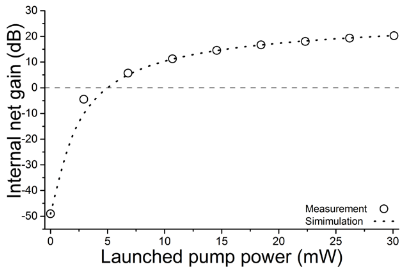

Figure 3. Simulation and measurement of the internal net gain at different pump powers for a 24.45-cm-long Al_2O_3:Er^{3+} waveguide channel.

3. CHARACTERIZATION

Gain measurements were carried out by the pump-probe method described elsewhere [2]. For a 24.45-cm-long spiral-shaped waveguide with a doping concentration of 0.95×10^{20} cm^{-3} a maximum internal net gain of 20 dB was achieved at λ_s = 1533 nm by making use of ~30 mW of pump power (λ_p = 976 nm). The amplifier model described in [11] was applied [2] to simulate the gain, which is presented in combination with the measurement results shown in Fig. 3. A gain/pump figure of 20 dB / 30 mW resulting in 0.67 dB/mW was measured, while gain can be achieved for launched pump powers of > 5 mW.

4. DISCUSSION

Several singly Er^{3+}-doped materials have been studied for the utilization as waveguide amplifiers around 1.55 µm [10, 23–27] and only a few dB/cm of peak gain have been achieved in singly-doped Er^{3+} waveguides, as presented in Table 1. In order to obtain high total gain, interaction distances on the order of tens of cm are required, since the limiting factor for higher gain per unit length is the doping concentration, which triggers detrimental effects such as ETU and fast energy quenching when the doping concentration is increased [11].

Table 1. Maximum gain and peak absorption cross-section in singly Er^{3+}-doped materials.

Erbium host	Gain per unit length	$^4I_{15/2}$ – $^4I_{13/2}$ peak σ_{abs}	Reference
Phosphate glass	~4.1 dB/cm	5.4×10^{-21} cm^{-2}	[23]
Bi_2O_3	~2.3 dB/cm	–	[24]
$(Gd,Lu)_2O_3$	~5.9 dB/cm	~18.5×10^{-21} cm^{-2}	[25]
Al_2O_3	~2.0 dB/cm	5.6×10^{-21} cm^{-2}	[10]
Ta_2O_5	~2.25 dB/cm	4.8×10^{-21} cm^{-2}	[26]
TeO_2	~2.8 dB/cm	–	[27]
KYW	–	~25×10^{-21} cm^{-2}	[19]

As can be seen from Table 1, in comparison with other Er^{3+}-doped materials, KYW offers higher absorption cross sections [19], in addition to large inter-ionic distances (> 0.4 nm) [28]. While the former indicate higher pump absorption, thus shorter propagation lengths required, and, consequently, higher gain per unit length, the latter may diminish the influence of energy-transfer processes, which reduce the population inversion and, thus, the gain. Preliminary simulations in the small-signal-gain regime at the peak emission wavelength of λ_s = 1535 nm suggest that a gain per unit length above 10 dB/cm can be achieved for an 8-mm-long rib-channel waveguide with an Er^{3+} concentration of 10 at.% [see Fig. 4(a)]. The waveguide channel dimensions chosen in the simulations are presented in Fig. 4(c). Two pump wavelengths were selected for the simulations for comparison. Although the absorption cross-section at 1490 nm is 7 times higher than at 1480 nm, as seen from Fig. 4(b), the later was selected according to the equipment available for measurements. One could benefit as well by pumping at $\lambda_p \sim 979$ nm where the absorption cross-section is ~2.5 times higher than at 1480 nm [29, 19]. Nevertheless, this option needs further investigation due to undesirable excited-state absorption (ESA) usually observed in Er^{3+}-doped materials arising from the absorption of a pump photon on the transition $^4I_{11/2} \rightarrow {}^4F_{4/2}$ [30] and subsequent characteristic Er^{3+} green emission.

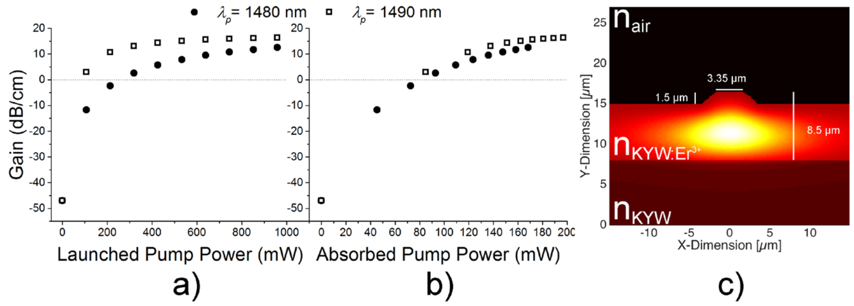

Figure 4. Simulation gain for an 8-mm-long KYW:Er^{3+} waveguide channel for two different pump wavelengths: (a) at different launched pump powers and (b) as a function of absorbed pump power. (c) Channel waveguide geometrical cross-section with an overlay of the signal mode profile.

5. CONCLUSIONS

We have demonstrated a successful design and fabrication of spiral-shaped waveguides in Al_2O_3:Er^{3+}. Furthermore, we have simulated straight channel waveguides in potassium double tungstates. A total gain of 20 dB at 1533 nm was achieved for a 24.45-cm-long waveguide with an Er^{3+} doping concentration of 0.95×10^{20} cm^{-3}. The amplifier model successfully describes the experimental results [2]. From our simulations a better potential for amplification around the telecom C-band is predicted for KYW:Er^{3+} waveguides.

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