Integrated optics Er-Yb amplifier with potassium ion-exchanged glass waveguides

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Abstract

Potassium Ion exchange is used to make channel waveguides in an erbium-ytterbium co-doped phosphate glass. Gain characteristics of the fabricated waveguides are studied. The effect of pump and signal wavelengths, and the waveguide length on the gain in the waveguides are investigated. At the signal wavelength of 1.530 μm, 19.5 dB internal gain is achieved in a 6 mm long waveguide; The measured noise factor is 4 dB.

1. INTRODUCTION

Erbium-doped integrated optics waveguides have attracted significant attention in the fabrication of amplifiers for 1.55 μm applications. They are interesting due to their small sizes and can be integrated with other integrated optics components in a single substrate. They are also suitable for manufacturing hybrid integrated optical circuits.

A number of different techniques have been used to make Er-doped integrated optics amplifiers. Ti-diffusion and proton exchange were employed to make Er-doped lithium niobate amplifiers.' Flame hydrolysis w.as utilized to produce Er-doped silica amplifiers[2]. Silver ion exchange was used to make Er-doped amplifiers in glass. [3,4] In our present work, we have used potassium ion exchange process to fabricate waveguides in an Er-Yb co-doped phosphate glass. In doing this, we rely on the energy transfer properties (sensitization) between Yb^{3+} and Er^{3+}. Phosphate glasses were selected because they are known to be suitable hosts for rare-earth elements in terms of spectroscopic characteristics required for photonic applications.[5] In addition, the sensitization quantum efficiency is close to unity in phosphate glasses.[6]

Potassium ion exchange results in low-loss glass waveguides.[7] This is attractive in Er-doped amplifier manufacturing. However, potassium ion exchange is carried out at elevated temperatures (~400 'C, in potassium nitrate) and the moisture usually present in the KNO_3 salt can damage the substrate. We have developed a technique to produce low-loss potassium ion-exchanged waveguides in Er-doped phosphate glasses. In section 2, we describe the waveguide fabrication process. Gain and noise measurements and waveguide length optimization results are reported in section 3. Section 4 discusses the results.

2. FABRICATION

A commercially available erbium-ytterbium co-doped phosphate glass was used to make the waveguides. The glass has the following characteristics :

Er_2O_3 concentration = 1.65 wt %
Yb_2O_3 concentration = 22 wt %
Refractive index at 1.53 5 um = *1.521*
Transformation temperature = 450°C
Deformation temperature = 485°C
Absorption at signal wavelength = 0.7 dB/mm, peak at λ = 1.530 μm
Absorption at pump wavelength = 6 dB/mm, peak at λ= 0.974 μm

Potassium ion exchange through a 5μ m opening in an aluminum mask was employed to produce channel waveguides in the glass sample. Potassium nitrate was used as the ion source and the ion exchange was carried out at 400°C for 5 hours.

Prior to ion exchange the moisture in the KNO3 Salt was removed in order to prevent damage to the surface of the sample. The salt was placed in a furnace, at 280°C under moderate vacuum for 24 hours. Then, the temperature was increased to 400°C to melt the salt. The system remained in vacuum for one hour, and afterwards a slow flow of Ar-gas was introduced in the furnace.

3. CHARACTERIZATION

3.1. Waveguide refractive index

Prism coupling method[8] was used to measure refractive index increase, Δn, due to potassium ion exchange in the Er-Yb doped phosphate glass. Δn was equal to 0.009.

3.2. Loss measurement

The method explained elsewhere[8] was employed to measure propagation and coupling losses. Loss measurements were performed at λ = 1.3 μm to avoid absorption due to erbium. The propagation losses were 0.2 dB/cm. The coupling loss between the waveguide and single mode fiber was 4.4 dB.

3.3. Signal and pump wavelength optimization

The set-up shown in Fig. 1 was used to study the gain characteristics of the fabricated waveguides. The pump laser was a tunable diode laser coupled to one of the input ports of the wavelength multiplexer. The output from a tunable Er-doped fiber laser, coupled into the other port of the multiplexer, was used as the signal light. The output power from the waveguide was coupled into an optical fiber connected to a spectrum analyzer. The input and output fibers were both single-mode at 1.55 µm wavelength.

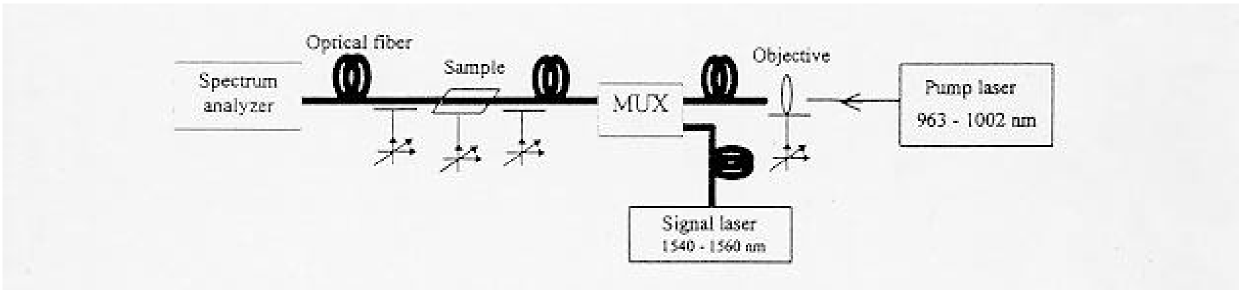


Fig. 1: Schematics of gain measurement setup.

The signal light intensities from the output of the channel waveguide without and with pump light were measured by the spectrum analyzer and the internal gain (= signal light power with pump/signal light power without pump) was calculated. The internal gain measurement was repeated for different signal and pump wavelengths. Fig. 2 shows the variations of internal gain with pump wavelength. Constant pump and signal powers were used. P_{pump} (= 25 mW) and P_{sig} (= 65 pW) in all of the measurements correspond, respectively, to the pump and signal power output from the input fiber. The maximum internal gain was obtained at pump wavelength λ_{pump}=1.000 µm. At this wavelength glass absorption is ~20% of the amount at λ= 0.974 gm.

The variation of internal gain with signal light wavelength is shown in Fig. 3. In this experiment, the pump Light wavelength wasλ_{pump}=1.000 µm and the pump power was maintained unchanged throughout the measurement.

Maximum internal gain was observed at the signal wavelength Lambda = 1.530 µm. This wavelength corresponds to the maximum in the Amplified Spontaneous Emission (ASE) of the waveguide (see Fig. 4).

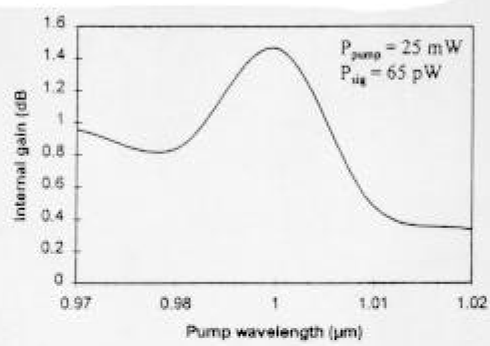
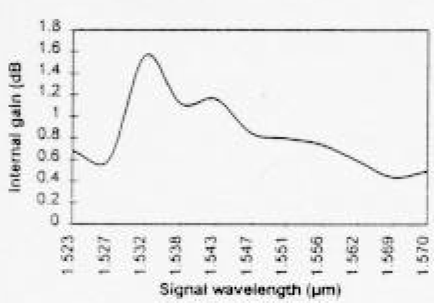


Fig. 2. Variation of internal gain with pump wavelength. Waveguide length = 10 mm.



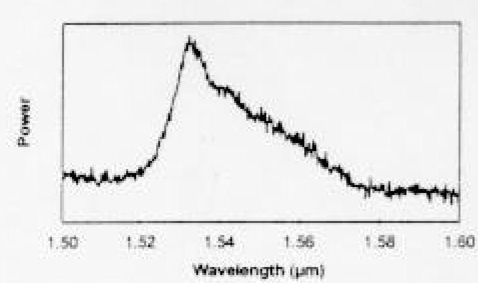


Fig. 3. Internal gain versus signal wavelength.

Fig. 4. Amplified spontaneous emission spectrum.

3.4. Gain and noise factor measurements for length optimization

Four waveguide with lengths L = 5, 6, 7, and 8 mm were used to study the effect of waveguide length on internal gain . The noise factor NF was also determined for these waveguides. NF is given by :[9]

$$NF - 2 n, = P,, / (b, -A,, G) \quad (1)$$

P_{ASE} is the amplified spontaneous emission power at signal wavelength, n_{sp} is the spontaneous emission factor, G is the internal gain, and A, is the ASE linewidth. Fig. 5 summarizes the results of internal gain and noise factor measurements for different lengths. The output signal power is the power measured by the spectrum analyzer. The pumping power P, was maintained at 50 in W. P,_, refers to the measured power at the end of the input fiber. The variation of the internal gain and noise factor with the output signal power is as expected, both becoming constant in the small signal regime. At this regime, the gain is maximum, but the noise factor is minimum as predicted by Eq. 1. The highest internal gain is obtained for the 6 mm long waveguide.

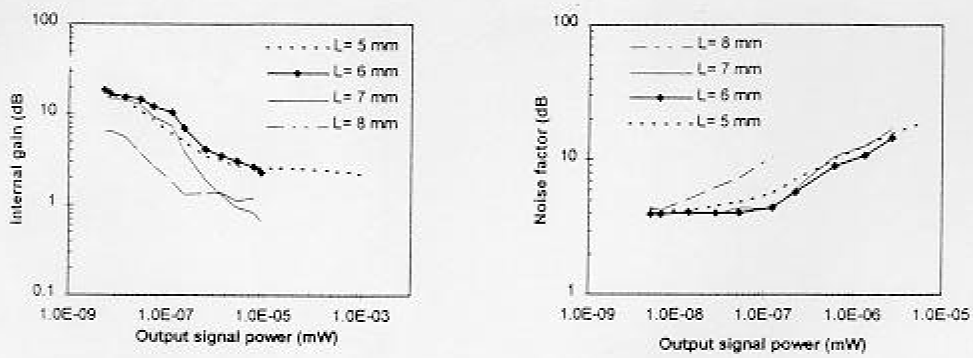


Fig. 5. Variations of internal gain (left) and noise factor (right) with output signal power. λ_{sig} = 1.530 μm ; λ_{pump} = 1.000 μm ; P_{pump} = 50 mW.

The 6 mm long waveguide was used to study the effect of pump power on internal gain and noise factor at λ_{sig}= 1.530μ and λ_{pump} = 1.000 μm and the results are illustrated in Fig. 6. Due to the limitations in our setup the maximum available pump power was 50 mW.

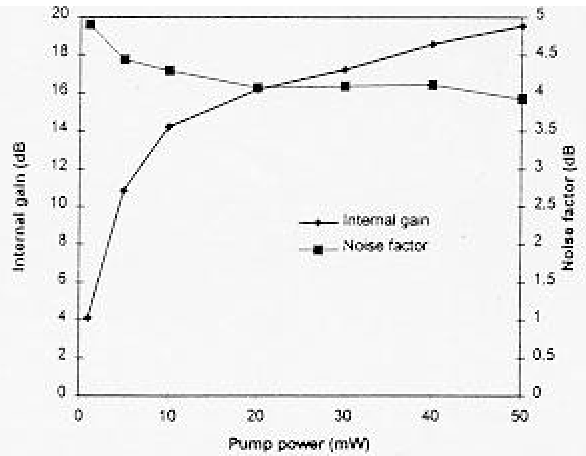


Fig. 6. Variations of internal gain and noise factor with pump power for the waveguide with optimum length (6 mm), signal (λ_{sig} = 1.530 µm) and pump wavelengths (λ_{pump} = 1.000 µm).

3.3. **Net gain measurement**

The net gain was calculated, using internal gain and loss measurement results,

Net gain = Internal gain - absorption 2 x coupling loss - propagation losses

For the 6 mm long waveguide pumped at 1.00O.um wavelength (P,_, = 50 mW) we obtain,

Net gain = 19.5 - 4.2 - 8.8 - 0.12 = 6.48 dB

The net gain was also determined directly by measuring the signal power at the end of input fiber and comparing it to the signal coupled to the output fiber. For P_{sig} = 4.8 nW and P_{pump} = 50 mW, a net gain of 7.3 dB was measured.

4. DISCUSSION

The waveguides made by potassium ion exchange in Er-Yb phosphate glass demonstrated significant gain. 19.5 dB internal gain with a low noise factor of 4 dB in a 6 mm long waveguide was achieved for signal and pump wavelengths 1.530 µm and I .000 µm, respectively. We have used pump wavelength of 1.000 µm in gain measurement in the waveguides with different lengths. The optimum pump wavelength for shorter waveguides is expected to be closer to the absorption peak wavelength of the glass. Preliminary measurements indicate that optimum pump wavelength for the 6mm waveguide is ~0.987 µm. At this wavelength, the sample absorbs ~35% of the amount at the maximum absorption wavelength. The use of optimum pump wavelength may increase the net gain. High net gain of 7.3 dB was achieved in a 6 mm waveguide using a low pump power of 50 mW. By optimizing waveguide-fiber coupling loss, it is possible to increase further the net gain.

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