3D printed and spiral lithographically patterned Erbium-doped polymer micro-waveguide amplifiers

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Abstract: We present spiral erbium-doped polymer micro-waveguide amplifiers fabricated using lithographic patterning and the first demonstration of 3D printed polymer waveguide amplifiers. A maximum gain of 8 dB and gain bandwidth of 60 nm is achieved.

1. Introduction

In fiber optic communication systems, efficient optical amplifiers and sources are indispensable components. Due to the significantly longer excited state lifetime and weaker refractive index change ($\Delta n \sim 10^{-6}$) induced by the excitation of rare-earth (RE) ions [1], RE doped materials are of high interest in integrated optics. These can provide spatially and temporally stable optical gain, allowing for high-speed amplification [2] and narrow-linewidth lasers [3,4]. Extensive research into doping Er-ions into various host materials, such as Al_2O_3 [5] and lithium niobate [6] has been performed over the years. Polymer materials are ideal host materials, owing to their favorable mechanical, thermal and optical properties.

In this manuscript, an 8 cm long, spiral, lithographically defined, on-chip, erbium-doped polymer waveguide amplifier, with footprint of 16 mm^2 is demonstrated. A total gain of 8 dB and a length normalized gain of 1 dB/cm is obtained. We further demonstrate the first 3D printed polymer waveguide amplifier, with a length of 2.7 cm and gain of 0.47 dB/cm. The results showcase the flexibility of 3D printing in creating rapidly prototyped integrated active photonic components.

Experiment

The polymer waveguide amplifiers studied in this report are shown in Fig. 1. Figure 1 (a) is the spiral waveguide, consisting of an SiO_2 trench with width of 5 µm, depth of 3 µm. The trench is fabricated by lithography and wet etching. Subsequently, the NaYF4:Yb,Er,Ce@NaYF4 core-shell RE nanoparticles (RENPs) doped SU8 is spin coated over the entire sample to fill the trenches and also to provide a cladding, 2 µm in height. The RENPs loading in SU8 is about 6 vol%. Figure 1 (b) shows the 3D printed waveguide amplifier with a width of 2 µm and a height of 2 µm, on an SiO_2 substrate. The structure is air cladded. The multi-photon lithography system (Nanoscribe GmbH Photonic Professional GT) is used to 3D print the polymer waveguide amplifier [7,8]. In this structure, IP-Dip is used as the host and the RENPs loading is around 0.6 vol%.

The gain characteristics of the two different waveguide amplifiers are studied. The schematic experimental setup is shown in Fig. 1 (c), involving a 980 nm laser diode pump and an amplified spontaneous emission (ASE) source

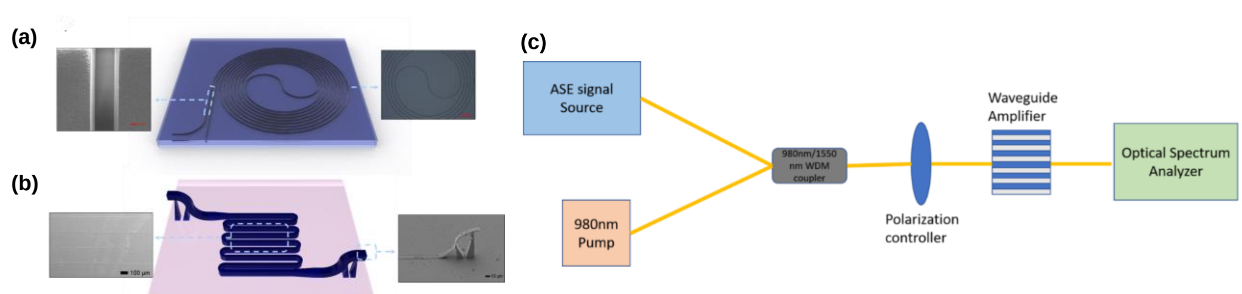

Figure 1. Device schematic of the polymer waveguide amplifier fabricated using (a) photolithography and (b) direct 3D printing. Inset of (a) shows a scanning electron micrograph (SEM) of the trenches and an optical micrograph of the fabricated trenches. Inset of (b) shows SEMs of the 3D printed waveguide and the 3D printed suspended couplers used for fiber-waveguide coupling. (c) Waveguide device characterization setup used to measure the gain performance from our Er-doped waveguide amplifier.

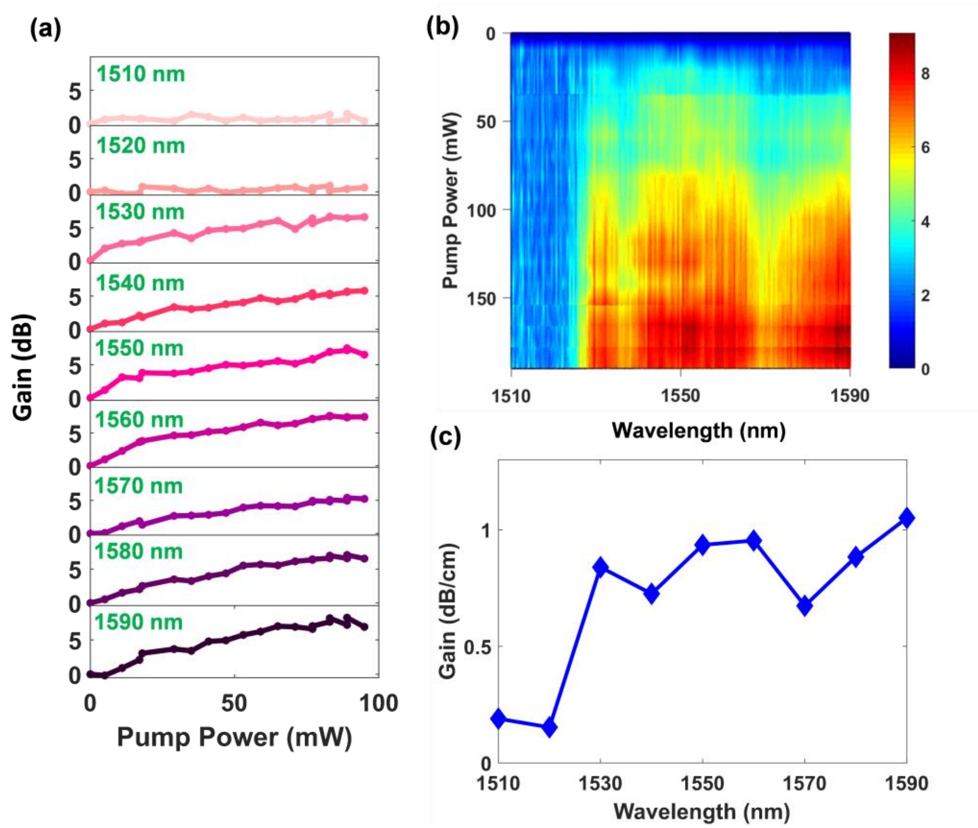

Figure 2. Gain properties for photolithography fabricated polymer waveguide amplifiers with a length of 8 cm (a) Experimentally measured gain as a function of pump power for wavelengths from 1510 nm to 1590 nm. (b) Gain spectrum as a function of pump power and wavelength from 1510 nm to 1590 nm. (c) Length normalized gain as a function of wavelength. The maximum gain achieved is 8.4 dB at a wavelength of 1590nm.

covering 1530 nm – 1600 nm as the signal. Both light sources are combined using a wavelength division multiplexer and adjusted for transverse-electric polarization before being coupled into the polymer waveguide amplifiers. The gain experienced by the signal is varied by controlling the amount of power emitted by the 980 nm laser diode pump. In this report, the input signal power was set to 0.5 mW, and the pump power was varied from 0 to 190 mW. The coupling loss at each fiber-waveguide interface is ~3 dB. Consequently the range of powers coupled the waveguide was 0 to 95 mW.

The optical characterization of the spiral polymer waveguide amplifier is shown in Fig. 2. It is observed from fig. 2 (a) and (b) that the gain increases as the pump power increases for all wavelengths from 1530 nm to 1590 nm. The maximum gain of 8 dB is achieved at 1550 nm over an 8 cm device length, which indicates a length normalized gain of 1 dB/cm. The gain at 1580 nm and 1590 nm is 7.1 dB and 8.4 dB respectively, which is comparable to that observed at 1550 nm, as shown in Fig. 2(c). This result indicates that good gain is achieved at longer wavelengths up to 1590 nm, showing that the down conversion process is efficient over a wide bandwidth, providing efficient amplification span of 60 nm. This result represents the first demonstration of an Er-doped spiral polymeric waveguide amplifier.

Next, experimental characterization is performed on the 3D printed waveguide amplifiers. The concentration of the Er-doped nanoparticles used is 10% of which used in Er-doped SU8. This lower particle concentration is selected to facilitate high quality patterning using 3D printing – Higher particle loading may introduce more scattering sites during the two-photon polymerization process. The gain performance of the 2.7 cm long 3D printed waveguide amplifier is shown in Fig. 3. The maximum length normalized gain is 0.47 dB/cm at a 1550 nm. Lower concentrations of optically active particles and the higher propagation loss of the waveguide fabricated by direct laser writing caused the lower length normalized gain compared to the spiral waveguide. Despite the particle concentration being 10-fold lower than that used in the lithographically defined amplifiers, good amplification of 1.3 dB is achieved in the 3D printed polymer micro-waveguide amplifier. This result represents the first demonstration of a 3D printed, directly written erbium-doped waveguide amplifier.

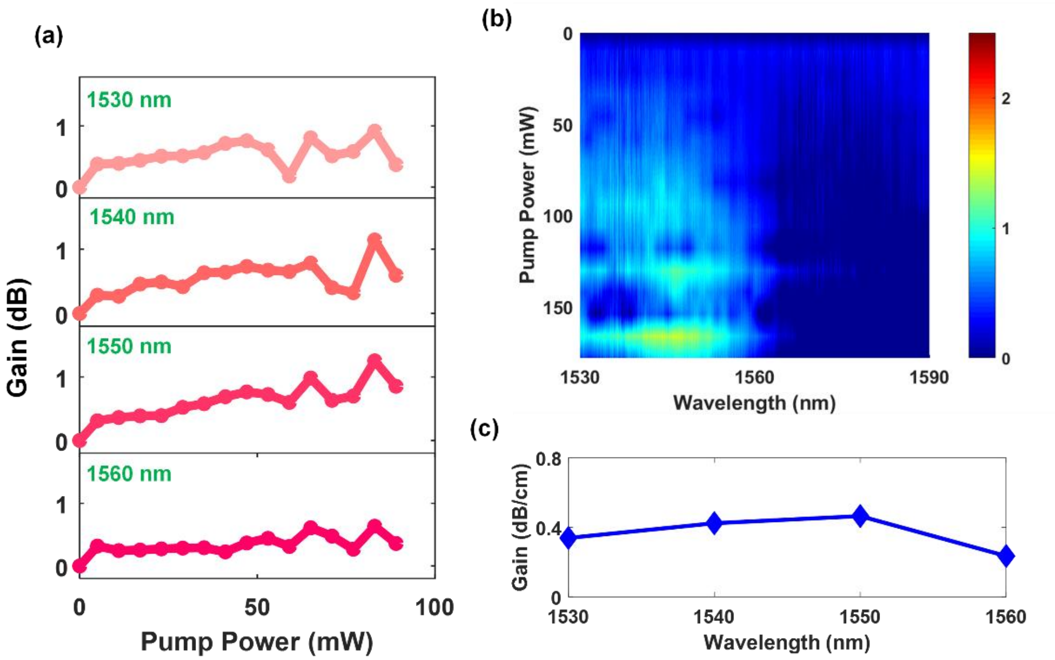

Figure 3. Gain properties for 3D printed amplifiers with a length of 2.7 cm. (a) Gain as a function of pump power for individual wavelengths. (b) Gain spectrum as a function of pump power and wavelength. (c) Length normalized gain as a function of wavelength. A maximum gain of 1.3 dB is achieved at a wavelength of 1550 nm.

Conclusion

We have demonstrated an 8 cm long spiral Er-doped polymer waveguide amplifier and a 2.7 cm long 3D-printed Er-doped waveguide amplifier. The maximum gain is 8.4 dB and 1.3 dB respectively. In addition we achieve a wide gain bandwidth of 60 nm (1530 nm – 1590 nm) in the spiral waveguide amplifier. The two approaches to fabricating Er-doped polymer micro-waveguide amplifiers showcase promising approaches for realizing high gain on-chip waveguide amplifiers with flexible designs, extending typical planar structures to the third dimension.

Acknowledgments

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