Gain flattened, high index contrast planar Er^{3+}-doped waveguide amplifier with an integrated mode size converter

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Abstract: More than 10 dB gain across C-band for small signal with less than 2 dB gain variation from –30 dBm to –10 dBm input signal power is derived from a Er^{3+}-doped waveguide amplifier with 176 mW, 976 nm pump. An integrated mode size converter deposited by wide-area physical vapor deposition methods is used to improve the coupling efficiency between Hi1060 fiber and high index contrast waveguide.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators, (060.2410) Fibers, erbium

1. Introduction

Recent progress in planar erbium doped waveguide amplifier (EDWA) technology offers the potential for compact size, low cost multichannel amplifiers, as well as integration with other planar waveguide devices and silicon based micro-electronic devices[1]. Aluminosilicate has been shown to be a good host material for high Erbium concentration[2]. Er^{3+} ions in aluminosilicate with high alumina content has been shown to have low upconversion when compared to other hosts. Wide-area physical vapor deposition (PVD) combined with standard semiconductor process technology has been used to fabricate high refractive index (n=1.508) aluminosilicate waveguides. High index contrast enables the waveguide cross-section to be reduced thereby lowering the pump power required. Furthermore, high index contrast waveguides have the potential to provide compact form factor by enabling tight waveguide bending radius. However, the coupling loss between high index contrast aluminosilicate EDWA and fiber is very high. An EDWA with a monolithically integrated mode size converter, fabricated by a wide-area PVD deposition process, is shown to reduce the coupling loss between fiber and waveguide.

The peaked gain spectrum of a typical EDFA requires the use of a gain flattening filter, gain equalizer or variable optical attenuator (VOA) for WDM applications. When several EDFAs are cascaded together, the accumulated gain tilt becomes unacceptably large. The gain flattened optical amplifier with wide dynamic input power range could greatly reduce system complexity and cost. In this paper, we report gain flattened EDWA with a monolithically integrated mode size converter.

2. EDWA and MSC Fabrication

The EDWA was fabricated through PVD deposition of two aluminosilicate layers on a thermally oxidized, 150mm diameter silicon wafer. The high index active core layer is over a low index passive core layer. Waveguide structures were defined through standard photolithographic and reactive ion etch processes specifically tailored for aluminosilicate materials. A 2Å r_a atomically smooth, vertical taper of the erbium-doped aluminosilicate active core layer was produced with the PVD deposition process. The smooth adiabatic vertical taper over lengths up to 10mm is responsible for the low insertion loss mode conversion from the low index passive core at the fiber coupled facet to the high index active core. This MSC does not need sub-micron photolithography for lateral taper.

A 20cm long S-shaped buried channel waveguide, with 2 mm bending radius and 1.2µm thick by 4µm wide, was fabricated as shown in Fig.1. A companion 10cm long straight waveguide with similar geometry was also fabricated. The Er^{3+} concentration in both these waveguides was 2.9×10^{20} cm^{-3}. The waveguide geometry supported a single-mode for C-band signals and multimode for the 980nm pump. The lifetime of erbium ion $^4I_{13/2}$ state was measured to be about 5ms and an upconversion coefficient of 4.5×10^{-18} cm^3s^{-1} was measured in the waveguide. These values are comparable to those observed in erbium implanted alumina waveguides at equivalently high Er^{3+} concentration levels[3]. The FWHM of the photoluminescence spectrum of this material is 50 nm. The wide bandwidth is expected from inhomogeneous broadening of Er^{3+} emission in high-concentration alumina co-doped host materials. The low 0.05 $dBcm^{-1}$ waveguide propagation loss for a C-band signal is attributed to the dense, smooth, uniform wide-area PVD deposited films and the well-controlled etching technology for high-index aluminosilicate materials. Fabrication of this waveguide amplifier utilizes a single step 15µm PVD low temperature cladding process.

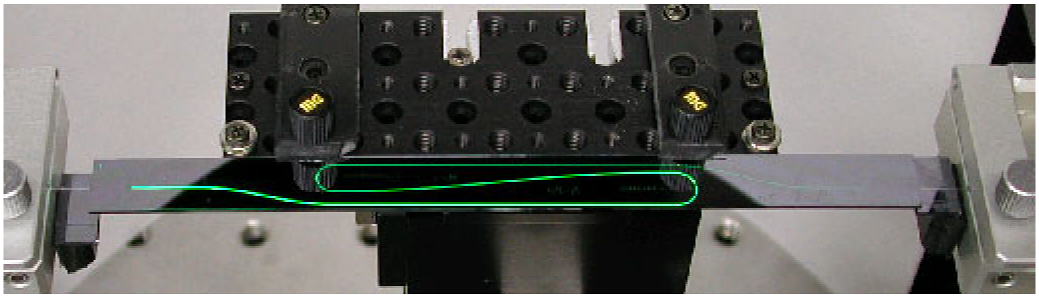

Fig. 1: 4-channel S-shape waveguide array on a 12 cm die

3. EDWA and MSC Performance

An S-shaped EDWA with mode size converters at the input and output ends is shown in Fig. 1. The low index contrast passive core is in the dark region between the input fiber and the Er-doped waveguide (emitting green light). The total fiber-to-fiber insertion loss utilizing this mode size converter (MSC) design is less than 1dB for each facet. Unlike other MSCs[4,5] which may be wavelength dependent, this MSC has the advantage to couple wide band light into a high index contrast core material. Modeling confirms that the coupling efficiency for 980 nm and for C-band signals is about the same. The measured mode images for 980 nm and SEM cross sections at facet without Erbium doped core and at the middle of the Erbium-doped waveguide were shown in Fig. 2. The mode size for 980 nm light at the passive waveguide facet and in the middle of Erbium doped waveguide are about 5.5 μm ×4.7 μm and 4.4 μm ×2.8 μm, respectively.

Fig. 2: 980nm pump mode images and SEM cross sections at facet and in the middle of Er-doped waveguide

The 20cm long EDWA gain spectra for wide input signal power range from –30dBm to –5dBm, pumped by 176mW at 976nm, are shown in Fig. 3. The gain is over 10dB for small signal input power below –20dBm in C band from 1528 nm to 1562 nm. The gain variation across the C-band is less than 2dB for input signal power between –30dBm and –10 dBm. 10cm long EDWA gain spectrum for wide input signal power range from –30dBm to –5dBm, pumped by 88mW pump power, is shown in Fig. 4. The gain variation is even smaller within 1.5dB across the entire 34nm of the C-band. The gain flatness with wide range of input power has been achieved by controlling clustered Erbium ions, the homogeneous upconversion and waveguide structure design. By increasing pump power to 319mW, the gain and noise figure spectrum for –20dBm and 0dBm signal are shown in Fig. 5. The gain is over 15.8dB across the C-band for small signal (-20 dBm) and 9.5dB for large signal (0 dBm). An output power of 9.5dBm in C-band was achieved with a 0dBm input signal. The noise figure is below 6dB with a small signal input of -20dBm. The maximum output power for this 20 cm long EDWA is over 10 dBm in C-band as shown in Fig. 6.

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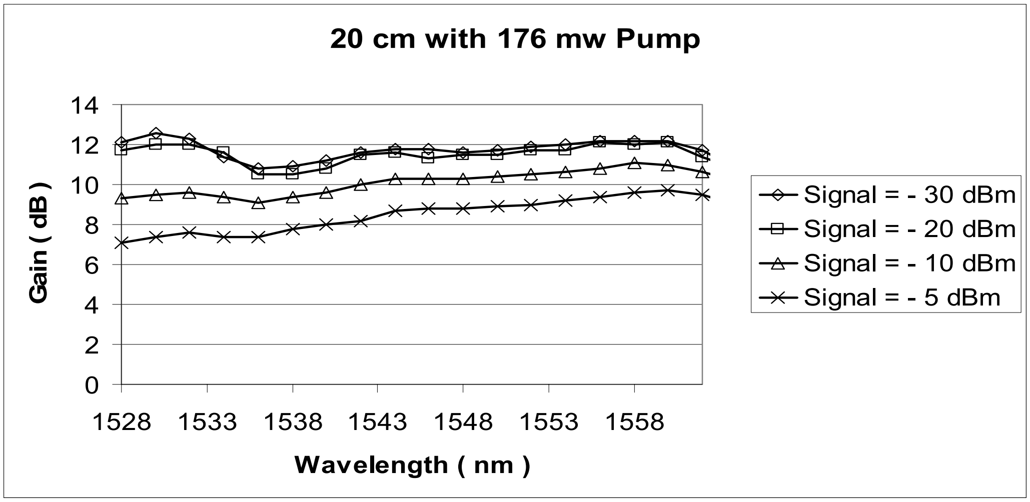

Fig. 3: Flat gain spectrum for 20 cm long waveguide

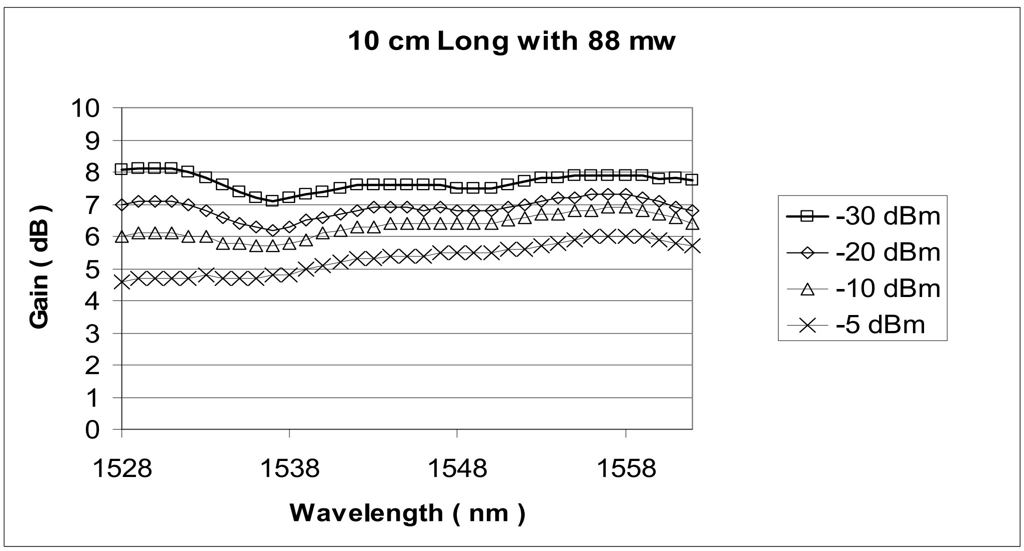

Fig 4: Gain spectrum for 10 cm long waveguide

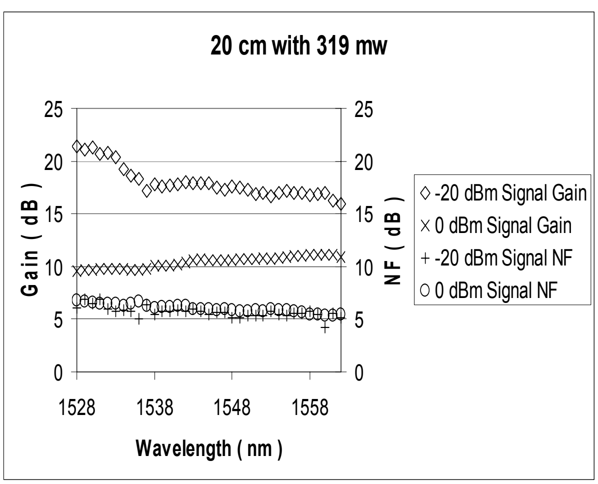

Fig. 5: Gain and noise spectrum for small and large signal

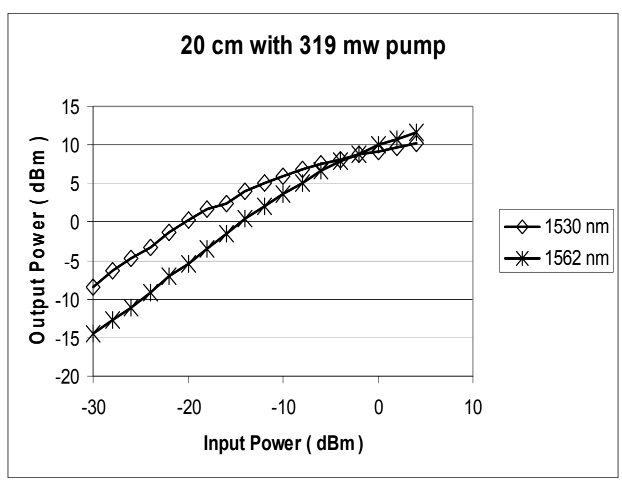

Fig. 6: Output power vs. input power