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Fabrication and evaluation of an Er_2SiO_5 waveguide with a buried Si guide layer for optical amplifier in Si photonics

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ABSTRACT

A self-organized Er_2SiO_5 crystal shows sharp and strong PL emissions at 1.5μm due to its highly-ordered crystal structure and high proportion of Er (25 at %) as a constituent element, and is highly expected as a material for realizing a compact waveguide amplifier for Si photonics. This paper demonstrates an Er_2SiO_5 waveguide with a buried Si guide layer for an optical amplifier integrated together with Si wire waveguides. This structure exhibits a higher effective refractive index and a higher confinement factor than those of strip-loaded Er_2SiO_5 waveguide in our previous report. Pumping with a 1480nm light from the one edge of the Er_2SiO_5 waveguide, green light emission originated from upconversion in Er_2SiO_5 was clearly observed. The upconversion emission profile shows a good optical confinement and propagation property of the 1480nm pumping light along the waveguide.

1. Introduction

Today, the clock speed in LSIs is approaching a limitation due to increasing RC delay in spite of Cu metallization. A Si-photonics system with optical interconnections of intra- or inter-chip is expected to be one of the solutions to overcome the limitation of copper wiring. Various optical components of the photonics system have been developed based on Si wire waveguides and photonic crystals except Si-based emitters and amplifiers. We recently have reported self-organized Er_2SiO_5 crystal as a key material for Si-based emitters and amplifiers. It shows strong and sharp Er-related PL emissions at 1.53μm in wavelength at room temperature, since it contains $2\times10^{22}cm^{-3}$ Er atoms as a constituent element of the crystalline matrix [1]. Therefore, the concentration quenching is considered to be mitigated compared with Er-doped materials, and a compact waveguide amplifier is expected using Er_2SiO_5 crystal. However, Er_2SiO_5 crystal is difficult to perform a fine etching process for the waveguide fabrication. From this reason, we have demonstrated a strip-loaded Er_2SiO_5 waveguide, in which the coupling between the Er_2SiO_5 and Si wire waveguides (SWWG) required a high accuracy of alignment. Moreover, difficulties of fine etching of the strip lead to scattering loss.

In this study, we propose an Er_2SiO_5 waveguide with a buried Si guide layer which can be formed by means of a self-align process. This waveguide shows a higher optical confinement factor than the strip-loaded waveguide, since the buried Si stripe layer functions as a guide of the propagating light. The fabrication and evaluation of this waveguide are reported.

2. Experimental

A 1.8μm thick SiO_2 layer was formed on a p-Si (100) substrate by thermal oxidation. After applying a resist, a strip groove was formed using UV lithography. Then Si was EB evaporated and the Si stripe was formed by lift-off method. The Si stripe thickness and width were 30nm and 4μm, respectively. Then, Er_2SiO_5 crystalline film was formed on the top by using sol-gel method. A sol solution with Er-O and Si-O (Er:Si = 2:1) was supplied by Kojundo Chemical Lab. Co.,Ltd. It was spin-coated at 2000rpm in 60seconds on the top of SiO_2/Si substrate. Then, the sample was dried in air at 120^oC for 30min to evaporate the solvent, and baked in Ar atmosphere at 500^oC for 30min. This process was repeated 10 times to get the film thickness of about 400nm. The thickness of the waveguide core was determined by considering the wavelength of 1.53μm signal light in the Er_2SiO_5 crystal. The sample was then annealed at 1200^oC for 30min in Ar atmosphere for crystallization by using a carbon composite heater furnace. Finally, both facets of the waveguide were formed using focused ion beam (FIB).

The cross sectional schematic diagram of the Er_2SiO_5 waveguide is shown in Fig.1. The Er_2SiO_5 crystalline layer of 320nm thickness was obtained from the SEM image. The optical confinement factor and effective refractive index of this waveguide are estimated to be 0.61 and 1.71, respectively. Photoluminescence (PL) from the Er_2SiO_5 waveguide was measured by excitation using a 980nm laser diode from the top. Pumping light power was between 2 to 250mW. PL emissions were corrected using a multi-mode fiber and detected through a 50cm spectrometer by InGaAs PD array. Further, the upconversion emission excited

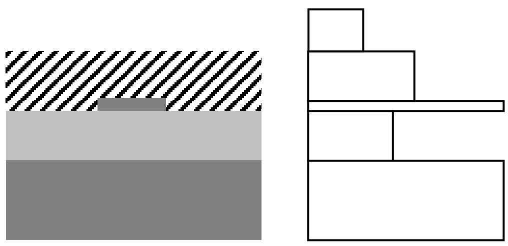

Fig.1 Cross sectional schematic diagram of the Er_2SiO_5 waveguide with buried Si guide layer

by1.48μm laser light of 20mW from the waveguide facet through a lensed fiber was observed from the top by CCD in order to investigate the light propagating behavior.

3. Results and discussion

PL peak intensities of Er_2SiO_5 crystalline waveguide are plotted as a function of the pumping power of 980nm light as shown in Fig2, and also a PL spectrum at pump power of 250mW is shown in the inset. Compared with reported spectrums of our research, it was observed broad spectrum from Er_2SiO_5 crystalline waveguide. The pumping LD have a wide active layer of 100μm width, and the lasing light was focused by a pair of objective lenses with confocal setup. Therefore we can obtain a line shape pattern of the LD light with 100μm width, and focus the beam just on the waveguide. In case of pumping power above 180mW, it seems that ASE (amplified spontaneous emission) has occurred since the slope tends to increase. From this result, it implies that Er_2SiO_5 waveguide has the sufficient potential for optical amplifier.

Fig.3 shows an upconversion emission image taken from the top of waveguide by a CCD camera. The green light emission at wavelength of 530nm is due to the cooperative upconversion of Er ions, and corresponds to the 4f intra-shell transitions from $^4S_{3/2}$ and $^2H_{11/2}$ to $^4I_{15/2}$. The green light image along to the waveguide indicates the 1480nm light traveling in the waveguide. The upconversion light was observed to about 100μm from the input facet. This reach distance is about 5 times longer than that of a strip-loaded structure waveguide [2]. This improvement is considered to be due to a decreased scattering loss at the waveguide sides and an improved confinement factor.

Then cooperative upconversion is interactions among three nearby excited Er ions, and frequently happens when the Er concentration increases or the distance among Er ions shortens. Considering dipole-dipole transition as the energy transfer mechanism, its probability is proportional to R^{-6} and this corresponds to the efficiency change proportional to N^{-2}. Since Er_2SiO_5 crystal has a high density of Er atoms ($\sim 2\times10^{22}cm^{-3}$), the distance of the nearest neighbor Er^{3+}-Er^{3+} is estimated to be less than 1nm (average distance is ~0.5nm), and the upconversion and/or energy migration which have an adverse effect on the emission and amplification should be reduced.

4. Conclusion

It has been demonstrated that an Er_2SiO_5 waveguide with a buried Si guide layer shows a high confinement factor, less scattering at the side edge and a good coupling with a fiber, compared with our previously reported a strip-loaded structure, and is expected to be effective for a waveguide optical amplifier. There remain, however, some problems in the fabrication of the Er_2SiO_5 crystalline waveguide.

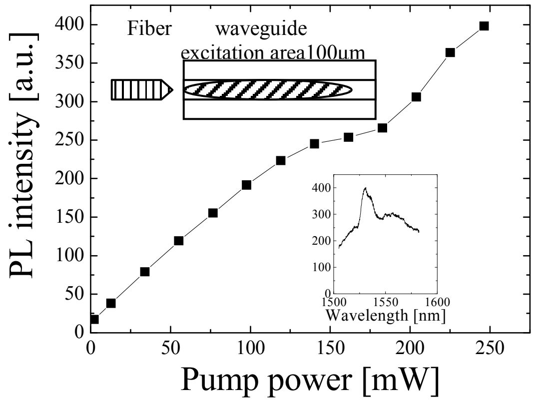

Fig.2 PL peak intensity from Si buried Er_2SiO_5 waveguide at 1.5μm pumped wavelength at 980nm

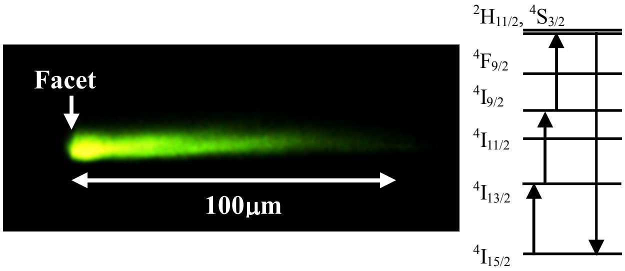

Fig.3 Top view of upconversion emission showing the pump light propagation and excitation process of cooperative upconversion to green light emission

First, Er_2SiO_5 films formed by sol-gel are poly-crystalline resulting in optical loss at grain boundary. Second, their too high Er concentration may have an adverse effect on the emission and amplification due to cooperative upconversion and/or energy migration among Er^{3+} ions. In order to solve this problem, we are now studying an $Er_xY_{2-x}SiO_5$ crystalline system to replace some of Er with Y and to reduce the Er concentration while maintaining the well-ordered crystalline structure.

5. Acknowledgements

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6. References

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