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Evaluation of optical absorption and light propagation loss in $Er_xY_{2-x}SiO_5$ crystal waveguides

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Abstract An Er_2SiO_5 Crystal is expected to be a light source material for compact amplifiers in Si-Photonics. However Er_2SiO_5 crystal has a problem so-called "Cooperative Upconversion" (CUC). We demonstrate introduction of $Er_xY_{2-x}SiO_5$ compound system to the waveguide, resulting in suppression of CUC in this system. And optical absorption cross section of Er ions and light propagation loss in the $Er_xY_{2-x}SiO_5$ crystal waveguide are evaluated.

Introduction

In recent years, it is expected that the cupper wiring in LSIs should be replaced by Si-photonics which is optical intra- or inter-connection system. In order to realize this system, compact optical devices have been developed. However compact optical amplifiers have not yet been developed. We have suggested that Er_2SiO_5 crystal can be a light source material for compact waveguide amplifiers at around 1.5μm. This crystal can contain $2\times10^{22}cm^{-3}$ Er atoms as a constitution element of crystalline matrix [1], resulting in expectation of optical amplifiers with a length less than 1mm. The crystalline nature can suppress the formation of defects and Er segregation which cause the concentration quenching. However cooperative upconversion (CUC) occurs strongly in Er_2SiO_5 crystal because the distance between neighboring Er atoms is very short (average ~0.4nm). CUC increases non-radiative transitions for 1.5μm emission. Consequently, the crystalline system with too much Er ion leads to a reduction of the emission efficiency at around 1.5μm.

We have attempted to introduce $Er_xY_{2-x}SiO_5$ crystal to resolve CUC problem. The Y atom has almost the same radius of the Er atom. Furthermore, the energy transition from Er to Y does not occur because Y has no 4f-intra shell electrons. Therefore, Y atom can extend the distance between each Er atom without changing the crystalline field. Recently, we have confirmed an increase of the emission efficiency by decreasing Er concentration of $Er_xY_{2-x}SiO_5$ crystal under a weak excitation.

In this work, we demonstrate the CUC suppression in $Er_xY_{2-x}SiO_5$ crystal waveguide. In addition, optical absorption cross section of Er ions and light propagation loss in the $Er_xY_{2-x}SiO_5$ crystal waveguide are evaluated.

Experiment

SiO_2 of about 1.8μm thickness was formed on p-Si (100) substrate by thermal oxidation. Si stripes of 4μm width and about 30nm thickness were formed on the SiO_2/Si substrate by Si evaporation using lift-off method. Then, $Er_xY_{2-x}SiO_5$ (x=0.25, 0.5, 1.0, 2.0) crystal thin films were formed on the prepared substrates by sol-gel method. Thickness of $Er_xY_{2-x}SiO_5$ film was about 250nm and the corresponding optical confinement factor was estimated to be 0.54. Optical pumping was performed by using a 1.48μm light source with output power of 20mW through the lensed fiber.

Results and discussion

Top views of the $Er_xY_{2-x}SiO_5$ (x=0.25) and Er_2SiO_5 waveguides taken by CCD were shown in Fig. 1. The green emission due to CUC was observed as only 140μm long tail from the input facet edge in the pure Er_2SiO_5 crystalline waveguide, whereas it extended to about 230μm in the $Er_xY_{2-x}SiO_5$ waveguide which was 1.8 times as long as that of the pure Er_2SiO_5. In addition, the intensity of CUC emission at the facet edge of Er_2SiO_5 crystalline waveguide was stronger than that of $Er_xY_{2-x}SiO_5$. These results indicate that CUC is suppressed in $Er_xY_{2-x}SiO_5$ system.

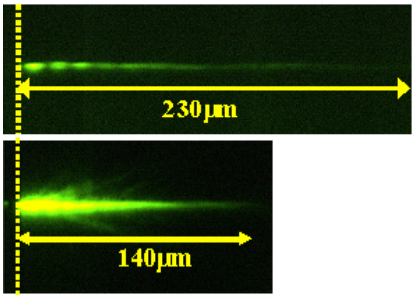

Fig.1 Upper surface images of upconversion emission from $Er_xY_{2-x}SiO_5$ (x=0.25), and Er_2SiO_5 waveguide pumping at 1.48μm

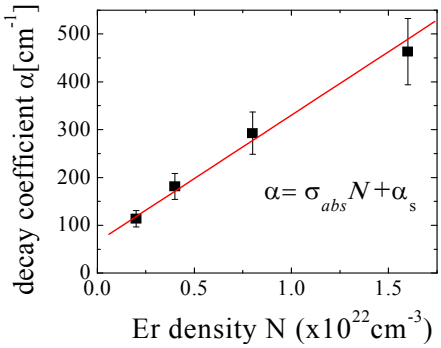

Fig2. Decay coefficient α in dependence on Er

CUC green emission tail behaves exponential decay. We tried to estimate propagation loss of pumping light from the decay profile of green emission in $Er_xY_{2-x}SiO_5$ waveguides. Pumping light decay ϕ in the propagation is given by

$$\phi = \phi_0 \exp(-\alpha\Gamma x) \ldots (1),$$

then α and Γ are the decay coefficient of Er ions for 1480nm light and the optical confinement factor, respectively. The green emission corresponds to 4f intra-shell transition from the excited states of $^4S_{3/2}$ and $^2H_{11/2}$ to the ground state $^4I_{15/2}$ in Er^{3+} and to the energy as 3 times as the pumping light photon energy. It means that CUC is three step upconversion from the first excited state $^4I_{13/2}$ due to ϕ. Therefore the relation between the CUC emission profile and the pumping light decay is given by

$$I_{PL}^{green} \propto \phi^3 = \phi_0^{\ 3} \exp(-3\alpha\Gamma x) \ldots (2).$$

The estimated decay coefficient α is plotted as a function of Er density in Fig.2. In Er_2SiO_5 crystal, the decay coefficient of pumping light α is estimated to be 463.4[cm^{-1}] which includes absorption and scattering loss. The plots are approximately on the straight line. Absorption coefficient is product of absorption cross section σ_{abs} and Er concentration N_{Er}. From this plot, σ_{abs} was estimated to be 2.6×10^{-20} cm^2, which is comparable to the reported value. In addition, intercept of this plot indicates optical scattering loss α_s. Then the scattering loss α_s is 65.4[cm^{-1}] which equals to 284[dB/cm]. $Er_xY_{2-x}SiO_5$ crystal prepared by sol-gel method is poly crystalline. Therefore this remarkable loss may be due to the scattering at $Er_xY_{2-x}SiO_5$ crystalline boundaries.

Conclusions

Suppression of CUC by introducing $Er_xY_{2-x}SiO_5$ crystalline system has been demonstrated. CUC is depressed enough when Er concentration is $2.5\times10^{21}cm^{-3}$. Even so $Er_xY_{2-x}SiO_5$ crystal has Er atoms one order higher than doping materials, therefore the crystal is expected to realize compact amplifiers on Si chip. Additionally, the absorption cross section of Er_2SiO_5 is estimated to be $2.6\times10^{-20}cm^2$. It is same order as that of previous reports [2], [3]. PL measurement from the edge through $Er_xY_{2-x}SiO_5$ crystalline waveguides now goes on. On the other hand, the scattering losses of the waveguides are supposed to be α_s=65.4[cm^{-1}] =284[dB/cm]. This loss may be due to the grain boundary of $Er_xY_{2-x}SiO_5$ crystallite. We also have attempted to reduce the scattering loss.

Reference

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