Low Threshold and Extreme High Optical Gain in $Er_xYb_yY_{2-x-y}SiO_5$ Compound Crystalline Thin Films

Ayuko Minowa, Hideo Isshiki, Fumiya Kondow, Kodai Miyagi and Ghent Nakamura

Univ. of Electro-Communications (UEC)
1-5-5, Chofugaoka, Chofu-shi
Tokyo 182-8585, Japan
Phone: +81-42-443-5152 E-mail: hideo.isshiki@uec.ac.jp

Abstract

Low threshold and high optical gain in $Er_xYb_yY_{2-x-y}SiO_5$ crystalline compound thin film are demonstrated. Optimum Yb/Er ratio in the extreme high Er density medium was estimated to be one from PL measurements. $Er_xYb_yY_{2-x-y}SiO_5$ (x=y) crystalline waveguide with Er density of 2 x 10^{21} cm^{-3} was fabricated. The waveguide shows a high optical gain of 52dB/cm with a low threshold photon flux of 93μW/cm^3 from variable stripe length (VSL) measurements. Owing to the energy transfer from Yb to Er, the excitation cross section is ten times larger than that of $Er_xY_{2-x}SiO_5$. These results suggest the effective sensitization effect of Yb.

1. Introduction

Electronics and photonics convergence by "Silicon photonics" is attracting much attention as novel approaches to information and communication technologies in near future. Many researches have investigated various Si-based optical devices. Since Si wire waveguide devices are passive components and the integration induces a great propagation loss, it is necessary to develop compact optical amplifiers in order to realize large scale integration in Si photonics.

Erbium doped fiber amplifiers (EDFA) has much contributions to develop optical communication systems. The optical gain is proportional to the product of Er^{3+} density and waveguide length. Generally EDFA contains about $10^{18}cm^3$ of Er^{3+}, and the fiber length is required about 10m or more in order to obtain a gain of 10dB. Considering the optical integration, waveguide length needs to be shorter than 1cm and consequently the high density Er^{3+} material is required. For this reason, we have proposed $Er_xY_{2-x}SiO_5$ crystal as a new light source material for the compact waveguide amplifiers [1]. This crystalline system can contain up to $1.6\times10^{22}cm^{-3}$ Er atoms as constitution elements. The crystalline nature can contribute to suppress the concentration quenching owing to Er segregation. So far we have reported 30dB/cm optical gain of the C-band in $Er_{0.4}Y_{1.6}SiO_5$ crystal waveguide on a Si chip, and then the excitation cross section is 1.74×10^{-20} cm^2 [2].

Under 980nm excitation band, the sensitization effects for Er excitation by Yb co-doping have been frequently observed. Since absorption cross-section of Yb^{3+} is about one order larger than that of Er^{3+} in the excitation band, energy transfer from Yb^{3+} ($^2F_{5/2}$) to Er^{3+} ($^4I_{11/2}$) occurs preferentially. Accordingly, the 1.53μm luminescence intensity is enhanced by increasing the excitation efficiency of Er^{3+} due to this energy transfer. Further effective sensitization by Yb co-doping is expected in $Er_xYb_yY_{2-x-y}SiO_5$ because of the high densities resulting in strong coupling between Er^{3+} and Yb^{3+}. Three times enhancement of the PL intensity was obtained between $Er_{0.33}Y_{1.66}SiO_5$ and $Er_{0.33}Yb_{0.33}Y_{1.33}SiO_5$ crystals in our previous report [2].

In order to improve the sensitization effect, optical evaluation of $Er_xYb_yY_{2-x-y}SiO_5$ crystals with different Yb/Er ratio were performed. In this paper, we demonstrate low threshold and high optical gain in $Er_xYb_yY_{2-x-y}SiO_5$ crystalline compound thin film originated from the effective sensitization effect of Yb.

2. Photoluminescence characteristics

$Er_xYb_yY_{2-x-y}SiO_5$ compounds were prepared by pulsed laser deposition (PLD) using layer-by-layer deposition technique. Fourth harmonic generation of a Q-switched YAG laser (λ: 266nm, repetition frequency: 10Hz, power: 30mJ/shot) was used for the ablation. PLD was performed at room temperature in oxygen atmosphere of 10^{-2} Pa. The back pressure was less than 10^{-5} Pa. Metal pieces of Si, Er, Y and Yb were arranged on a rotatable target holder. Composition of the sample was controlled by laser irradiation area arrangement of the metal targets (Er, Y, Yb and Si). The target holder was rotated at such a speed that one cycle deposited a group of Er–O, Y-O, Yb-O and Si–O layers having 0.86nm thickness with the (Er+Yb+Y): Si ratio of 2:1. The contents of Si and Er (x=0.29) were constant in order to confirm the effect of Yb density changes. And then those of Yb and Y was changed with changing Yb/Er ratio (R=0, 0.25, 0.5, 1.0, 1.5, 2.0). This approach leads to good quality crystal so enhances the effect of self-assembly. PLD was carried out for 200 cycles to form about 170nm thick preform on a Si (100) substrate. The samples were then annealed in Ar at 1200 ºC by rapid thermal anneal (RTA) for 30min. The crystal structure was confirmed by X-ray diffraction (XRD). PL measurements were performed using LD as an excitation light source of 975nm.

Fig.1 shows PL spectra under 975nm excitation at room temperature as a function of Yb/Er ratio R. PL peak intensity (1528nm) increases to 5.3 times with increasing the ratio of Yb/Er from 0 to 1.0. However, the intensity decreases with more increasing of Yb co-doping. Due to the Yb introduction, decay time of the 1528nm emission becomes short about half. This change indicates that the non-radiative transition is increased. This result suggests that the sensitization effect is expected to be about 10 times and the optimized Yb/Er ratio is one.

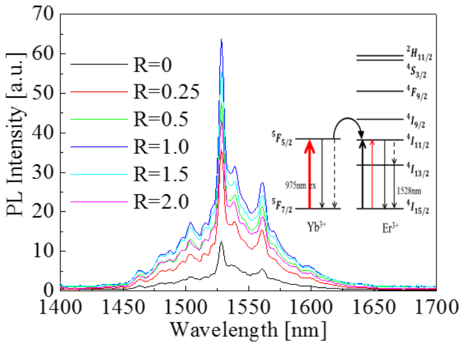

Fig.1 Room temperature PL under 975nm excitation as a function of Yb/Er ratio R in $Er_xYb_yY_{2-x-y}SiO_5$ compounds

3. Optical Gain Characteristics by VSL

The Yb/Er ratio R has been optimized to be one from PLD samples. Then we used a sol-gel solution with the content of $Er_{0.25}Yb_{0.25}Y_{1.5}SiO_5$ prepared by Kojundo Kagaku in order to fabricate waveguides. The sol-gel process for $Er_{0.25}Yb_{0.25}Y_{1.5}SiO_5$ thin film with 400nm thick was performed on a SiO_2 trench structure with 3μm width and 200nm depth. The sol-gel process in detail has been shown in our previous report [2]. The sharp PL emission at 1.5μm was confirmed from the edge of $Er_{0.25}Yb_{0.25}Y_{1.5}SiO_5$ waveguide. Furthermore, variable stripe length (VSL) measurement was performed to estimate the optical gain of the waveguide. A 975nm LD with an emitter size of 1x100μm was used as a pumping light source. Then we expanded the beam size to 10 times by microscope. The pumping light with a line-shaped pattern was irradiated along the waveguide, and the irradiation length was varied by moving a shade. The PL emission from the edge of the waveguide was collected with a lensed fiber, and monitored with a cooled InGaAs PD array.

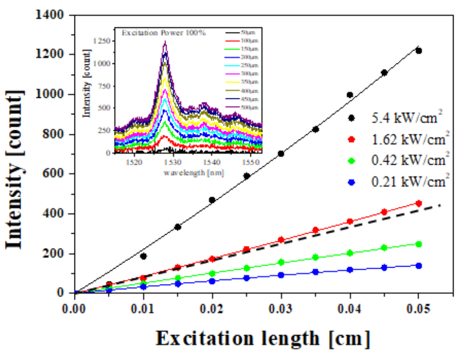

Fig. 2 PL spectra and the edge emission intensity as a function of excitation length along $Er_{0.25}Yb_{0.25}Y_{1.5}SiO_5$ waveguide.

The PL spectra as a function of the excitation length are shown in inset of Fig. 2. The PL fine structure particular to the Er silicates is observed, and is almost independent of the pumping power. Excitation length dependence of the integrated PL intensity $I(L)$ as a function of pumping power is shown in Fig.2. A relation between $I(L)$ and the gain coefficient β is given by

$$I(L) = \int_0^L i_0 \exp(\beta x) dx = \frac{i_0}{\beta}(\exp(\beta L) - 1)$$

Then gain coefficient β includes the optical confinement factor and the scattering loss of the waveguide. A dash line in Fig.2 shows a linear relation which corresponds to β=0. Superliner behavior above the excitation power of about 90mW indicates the achievement of optical gain. Optical gain estimation by the VSL plot is summarized in Fig. 3 as a function of the pumping power. The gain plot of $Er_{0.4}Y_{1.6}SiO_5$ waveguide in our previous report is also shown for comparison [2]. The optical gain increases with increasing the pumping power and reaches to 52dB/cm. Then the Er population inversion is estimated to be $8.9x10^{20}cm^{-3}$.

The relaxation time at the second excited state $^4I_{11/2}$ is 40-μs estimated from the PL decay measurement. It is sufficiently fast in comparison with the decay time at the first excited state $^4I_{13/2}$. Therefore the two level approximation can be used to derive a fitting curve, which is draw in Fig. 3.

At the zero pump power, the total propagation loss of 1.5μm light is estimated to be $15cm^{-1}$, which corresponds to the absorption cross section of Er ion $1.4x10^{-20}cm^2$. This value is almost same as that of $Er_{0.4}Y_{1.6}SiO_5$ waveguide ($1.7x10^{-20}cm^2$). The excitation cross section also can be estimated from the threshold photon flux. The threshold pump power of $Er_{0.25}Yb_{0.25}Y_{1.5}SiO_5$ waveguide is estimated to be $9.3μW/μm^2$ from the fitting curve, which corresponds to the excitation cross section of $3.7x10^{-19}cm^2$. This value is about one order larger than that of $Er_{0.4}Y_{1.6}SiO_5$ waveguide ($3.3x10^{-20}cm^2$). This result indicates that the energy transfer from Yb^{3+} ($^2F_{5/2}$) to Er^{3+} ($^4I_{11/2}$) occurs very effectively.

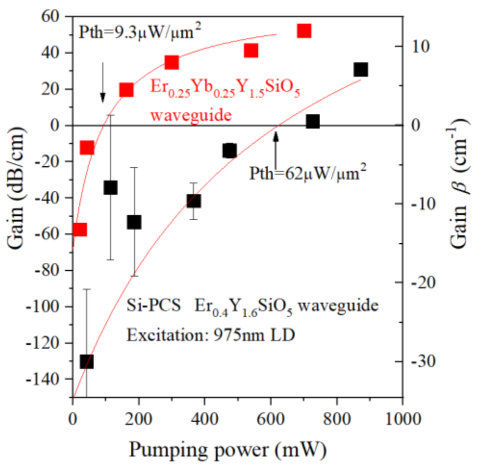

Fig.3 Optical gain as a function of pumping power

4. Conclusions

Low threshold and high optical gain in $Er_xYb_yY_{2-x-y}SiO_5$ crystalline compound thin film were demonstrated. The optical gain reaches to 52 dB/cm, and the excitation cross section is $3.7x10^{-19}cm^2$ which is one order larger than that of $Er_xY_{2-x}SiO_5$. These results suggest the effective sensitization effect of Yb and the ability for compact and high optical gain amplifier.

References

[1] H. Isshiki and T. Kimura, IEICE, E91, 138-144, (2008)

[2] H. Isshiki, et al., Photon. Res. 2 (2014) A45