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High-gain characteristics of integrated optical amplifiers using rare-earth ion-doped garnet thin film waveguides

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Abstract

High-gain amplification of a channel waveguide optical amplifier using Nd : YGG thin film is reported, featuring a gain of 6.5 dB over a length of 4 mm, for the wavelength of 1.06 μm, the gain per unit length being 16 dB/cm. For optical wavelengths 1.5 and 1.3 μm, channel waveguide optical amplifiers are studied using Er^{3+} and Pr^{3+}-doped garnet films.

Keywords: Optical amplifiers, optical pumping, garnet crystalline thin film waveguides.

1. Introduction

Optical amplifiers are very important devices for optical fiber communication and optical signal processing. Optical fiber amplifiers and semiconductor amplifiers have been well studied. However, integrated optical amplifiers using optical pumping have not been studied in detail. Fiber amplifiers have a drawback in that they need a length of over a few meters[1,3] and semiconductor amplifiers have noise problems. On the other hand, optical amplifiers constructed using thin films with optical pumping have advantages such as combination of different optical thin film waveguide devices (modulators, switches and isolators) in monolithic optical integrated circuits. A few glass film amplifiers are studied and gain properties of <1 dB/cm are reported. We consider integration with different crystal thin-film optical waveguide devices with heavily doped ions to achieve large amplification.

Garnet or $LiNbO_3$ films are used mainly as materials for the optical thin-film waveguide devices and optical integrated circuits. Therefore, we also investigate both the materials for optical amplifiers. When Nd^{3+} ion is used as a laser-active ion in crystal garnet films, the amplifier can amplify light signals of 1.06 and 1.3 μm bands.

In this paper, we propose a garnet crystalline thin film channel waveguide-type optical amplifier and report a gain of 6.5 dB over a length of 4 mm, the gain per unit length of 16 dB/cm, and pump efficiency of 1.1 dB/mW. For convenient optical

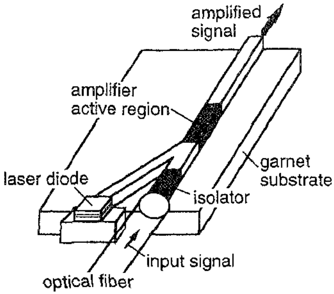


FIG. 1. Structure of optical IC.

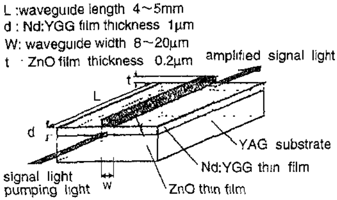


FIG. 2. Structure of channel waveguide-type optical amplifier.

wavelengths of 1.5 and 1.3 μm, channel waveguide optical amplifiers are investigated using Er^{3+} and Pr^{3+} ions in garnet crystal films.

2. Structure of waveguide optical amplifier

Figure 1 shows integrated circuits with different optical crystal film waveguide devices, and Fig. 2 the structure of the waveguide-type optical amplifier. The amplifier is essentially of channel waveguide type, formed by loading a layer of neodymium-doped yttrium gallium garnet(Nd : YGG) on yttrium aluminium garnet(YAG) with a strip of zinc oxide(ZnO). Nd: YGG film and ZnO strip are fabricated by RF sputtering. Strip-type active channel waveguide devices may be fabricated by direct etching method. Nd : YGG film is deposited at 700–800°C and crystallized by annealing at 950°C. YAG substrate is cut

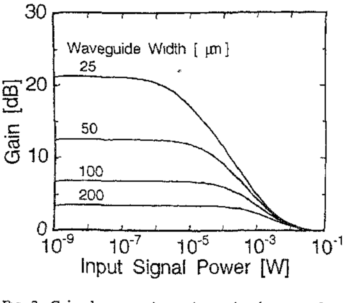


FIG. 3. Gain characteristics *vs* input signal power of channel waveguide.

on the (111) plane and polished. The refractive indices of YAG, Nd : YGG, and ZnO are, respectively, 1.82, 1.94 and 1.94 at 1.6 μm wavelength. The thicknesses of Nd : YGG film and ZnO strip are 1.0 and 0.2 μm, respectively. The concentration of neodymium active ion is 1.3 at.% in Nd : YGG film. The waveguide length is less than 1 cm. The signal light and the pumping light are confined to the Nd : YGG layer in a strip of ZnO region. The propagation losses of the waveguide are, respectively, 2.7 and 2.1 dB/ cm at 1.06 μm.

Pumping light and signal light are guided coaxially. Signal light obtains optical gain by stimulated emission when it passes through the thin film where a state of population inversion is achieved by the pumping light. Figure 3 shows the characteristics of gain *vs* input signal power of channel waveguide-type amplifier which is calculated for estimated emission cross-section $\sigma = 5 \times 10^{-19}$ cm^2, propagation loss $\alpha = 0.1$ cm^{-1}, lifetime of spontaneous emission $\tau_f = 3 \times 10^{-4}$s, concentration of Nd ion $N_T = 10^{-20}$ cm^{-3} and waveguide length $L = 5$ mm.

3. Spectroscopy

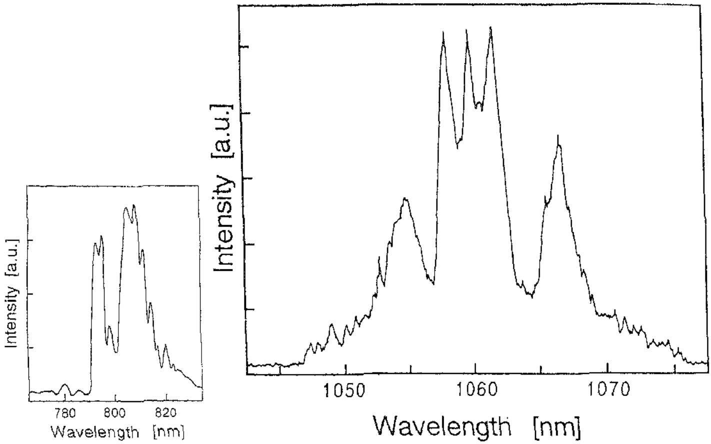
The sputtering system used to prepare the thin film waveguides is of quadruple type, which can heat the substrate. The sputtering target is made by sintering a stoichiometric mixture of Y_2O_3 and Ga_2O_3(Y/Ga = 3/5) with 1.3 mole of Nd_2O_3 relative to Y_2O_3. The sputtering gas is a mixture of 80% Ar and 20% O_2, and the pressure is maintained at 5×10^{-4} torr. The RF input power for sputtering is 100 W, and the deposition rate is 0.08 μm/h.

The crystal growth of the films depends on the substrate temperatures. To investigate the optimal conditions for the preparation of thin films, the films are prepared at various substrate temperatures. Thin films prepared at substrate temperatures below 750°C are amorphous. Crystalline films are produced by sputtering at substrate temperatures more than 750°C, or by annealing the amorphous films at more than 750°C.

The propagation loss is caused by absorption and scattering. The absorption loss due to active ions Nd^{3+} and other impurities seems to be negligible, at 633 and 1061.5 nm, as these wavelengths are away from the absorption lines of Nd^{3+} ions, and as the concentrations of other impurities in the film are <0.1 mole%. Therefore, the main cause of loss is scattering due to surface roughness of the thin film.

The active ion Nd^{3+} is a typical rare-earth ion, which is used in a laser diode-pumped solid-state laser such as Nd : YAG, Nd : GSGG and Nd : glass. It has a strong absorption band around 0.8 μm and strong fluorescence band around 1.06 μm. The absorption and fluorescence spectra depend on the host material. Therefore, detailed measurements are required for high gain.

Absorption spectrum of the Nd film waveguide was measured for the pumping excitation. LED which has luminescent centre wavelength at 800 nm was utilized for the experiment. The peak was located at 808 nm (Fig. 4 a).



a b

FIG. 4.a. Absorption spectrum of the thin film around 0.8 μm. b. Fluorescence spectra of the thin film at 1.06 μm.

The absorption peak due to Nd^{3+} ions corresponding to $^4I_{9/2} \rightarrow (^4F_{5/2} + {}^4H_{9/2})$ transition has been observed at 808 nm. This shows that the thin film is pumped efficiently at 808 nm and that GaAlAs laser diode can be utilized as a pump source.

Figure 4b shows fluorescence spectrum of the Nd : YGG waveguide at 1.06 μm region. The peaks of fluorescence spectrum for the waveguide are located at 1057.75, 1060.0 and 1061.87 nm. Therefore, high gain is obtained for the signal light at $\lambda = 1060 \pm 2.5$ nm.

The fluorescence spectrum, used in determining the signal wavelength, was measured in the range 1.0–1.4 μm. It is recorded with a 0.2 nm resolution monochromator with the thin film pumped at 808 nm using a high-power laser diode. Fluorescence peaks are observed at 1.06 and 1.3 μm corresponding to $^4F_{3/2} \rightarrow {}^4I_{11/2}$ and $^4F_{3/2} \rightarrow {}^4I_{13/2}$ transitions in Nd^{3+} ions, respectively. The $^4F_{3/2} \rightarrow {}^4I_{13/2}$ transition is effective in the 1.3 μm telecommunication window, but its fluorescence intensity was lower than that of $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition.

The fluorescence lifetime of Nd : YGG thin film is defined as the duration within which the fluorescence intensity decays by 36.7% (1/e) of its maximum value. To determine this parameter experimentally the light from a laser diode at a wavelength of 808 nm is guided into the Nd : YGG thin film sample, and the fluorescent light coupled out through a prism coupler and a monochromator is displayed using an oscilloscope. The fluorescence lifetime of the Nd : YGG thin film is thus measured to be 230 μs for

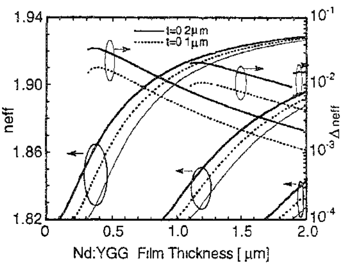


FIG. 5. Effective index, difference effective index *vs* ND:YGG thickness.

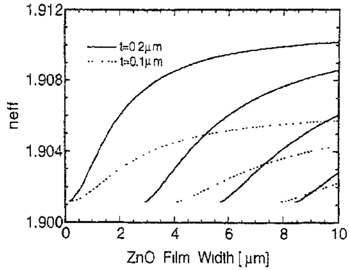


FIG. 6. Effective index *vs* Zno film width.

${}^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition. This value compares to be approximately the same with that of bulk Nd : YGG which is about 240 μs.

4. Channel waveguide using ZnO loading

The dispersion curves of three-dimensional channel waveguide in construction of ZnO-loaded Nd : YGG/YAG are calculated by the effective index method. The results are shown in Figs 5 and 6 assuming the refractive index of ZnO to be 1.94 for the wavelength 1.06 μm and TE mode. The width of the ZnO film is $w = \infty$ and the film thickness d of Nd : YGG is 1 μm. It is seen from Fig. 4, that ZnO thickness t is 0.2 μm, and the difference in the refractive index of loaded ZnO region and that of the unloaded region $\Delta n_{eff} = 0.01$. These conditions give enough field confinement and also from the dispersion curve of ZnO film width the single mode condition can be obtained when $w < 3$ μm. These results are almost equal to the case of rib-type three-dimensional channel

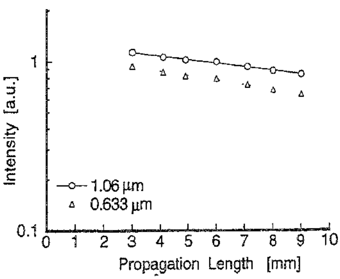


FIG. 7. Propagation loss of ZnO/Nd:YGG/YAG slab waveguide.

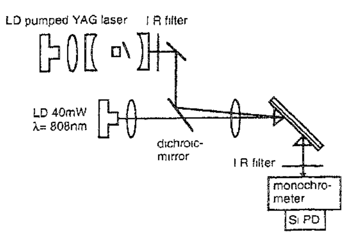


FIG 8. Experimental set-up for gain measurement

waveguides. Figure 7 shows propagation loss of slab waveguides consisting of ZnO/Nd : YGG/YAG waveguide for optical wavelength of 0.633 and 1.06 μm when the thickness of ZnO film is $t = 0.2$ μm and that of Nd : YGG film is $d = 1$ μm, respectively. We have observed field confinement in ZnO-loaded Nd : YGG film waveguides of ZnO film thickness ($t = 0.2$ μm and $w = 8$ μm).

5. Optical amplification

In the amplifier experiment, we measured the single pass gain at 1.06 μm region. The experimental set-up for the gain characteristics is shown in Fig. 8.

At the signal light source of 1.06 μm region, we prepared a tunable Nd : YAG laser using an etalon plate pumped with GaAlAs laser diode. The Nd : YAG laser could oscillate at two wavelengths, 1064.1 and 1061.5 nm, by tuning the angle of the etalon. For the tuned output at 1061.5 nm, the lasing threshold and the slope efficiency are 10 mW and 5%, respectively. We tuned at 1061.5 nm for the experiment. For the pumping light we used a high-power GaAlAs laser diode tuned to $\lambda = 808$ nm.

The signal and pumping light beams are combined coaxially with a dichroic mirror. Next, their beams are coupled into the waveguide by prism coupling method. After propagation, the beam from the output prism is separated from the pumping light with an IR filter and is detected with a Pin–Si photo diode through a monochromator. Signal light power, the waveguide length and the wavelength width are 5 μW, 4 mm and 20 μm, respectively.

Figure 9 shows the single pass gain *vs* pumping power where the signal and pump power are the launched power into the waveguide. The gain depends linearly for pumping powers less than 4 mW. A gain of 6.5 dB is obtained at a pumping power of about 10 mW for waveguide length of 4 mm. The pump efficiency is 1.1 dB/mW and the gain per unit length is 16 dB/cm. The dashed line is the theoretical result which is calculated using rate equations[5]. Hence, we consider Nd : YGG crystalline film to be not a perfect

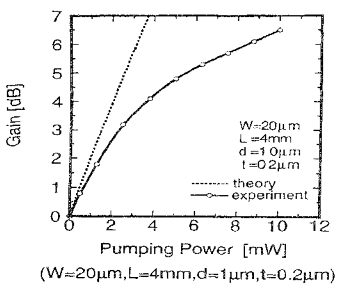


FIG. 9. Gain characteristics of optical channel waveguide amplifier.

crystal. The FWHM of Nd : YGG film is 5 nm, but that of Nd : YAG used for gain calculations using rate equation is 2 nm and that for the stimulated emission cross-section is 5×10^{-19} cm^2.

For optical amplification of wavelength required (1.55 μm) in optical communication, Er : YGG 1.3 at.% film waveguide is fabricated by RF sputtering. Optical characteristics of Er : YGG film waveguide amplification are studied.

6. Conclusion

We propose optical amplifiers constructed with ion-doped garnet crystal thin film waveguide and optical pumps, for miniaturization and combination of different optical waveguide devices into optical integrated circuits. Rare-earth-doped crystal thin films have high active ion density, high stimulated emission cross section and high density of light in active crystal film region. The channel waveguide optical amplifier using Nd-doped garnet thin film was studied for the gain characteristics at 1.06 μm region as fundamental property. The gain is dependent linearly for pumping power < 4 mW, and a gain of 6.5 dB is obtained at a pumping power of about 10 mW for waveguide length of 4 mm. The pump efficiency is 1.1 dB/mW and the gain per unit length is 16 dB/ cm. Based on these results, we plan to optimize the structure of the amplifier and investigate doping of Pr^{3+} and Er^{3+} for amplification at 1.3 and 1.55 μm regions.

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