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Characteristics of time-gated Raman amplification in GaP–AlGaP semiconductor waveguides

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Time-gated Raman amplification in the GaP–AlGaP waveguide is investigated using mode-locked Ti–sapphire pump source with 80 ps pulse width. Logarithmic Raman gain linearly increases with increasing the pump power density as long as the gain is less than about 10 dB. However, with further increasing the pump power it becomes nearly proportional to the square root of the pump power density. This is due to the fact that the equivalent linewidth of the pump pulse is comparable to the spectral full width half maximum of the Raman gain coefficient (24 GHz). Another point is that the amplified pulse broadens as the waveguide length exceeds the optical length corresponding to the pump pulse width because Raman amplification occurs mainly due to backward scattering.
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I. INTRODUCTION

Since the proposal to utilize the terahertz lattice vibrations in compound semiconductors as well as molecular vibrations to optical communication and spectroscopy,[1] Raman scattering in GaP,[2–4] Raman laser oscillation,[5,6] and Raman amplification in GaP[7] have been extensively studied. A proposal of utilizing terahertz lattice vibration was also made by Loudon, although he claimed that a uniaxial crystal was required.[8]

Stimulated Raman scattering in semiconductor waveguides has been of interest because frequency selective light amplification can be achieved with a pump power level much less than those for stimulated Raman scattering in bulk materials.[7,9]

We have measured the full width half maximum (FWHM) of the Raman gain coefficient in GaP-AlGaP waveguide to be 24 GHz, which corresponds to the longitudinal optical (LO) phonon dumping constant Γ of GaP.[7] This is suitable for light frequency discrimination such as in wavelength division multiplexing (WDM) optical communication and high sensitivity spectroscopy. Another feature of the Raman amplification in semiconductor waveguides is that time-gated amplification narrower than several tens of picoseconds is available, as has been demonstrated in our recent article.[10,11] In other kinds of light amplification like in laser diodes and Er-doped fiber amplifiers, usually the time constant of diode impedance or the lifetime of the excited state as well as the recovery time of population inversion prohibits high speed gating, although considerable improvement has recently been achieved by optical injection in semiconductor light amplifiers.[12] In contrast, time gate function of Raman amplification in the semiconductor is determined by the damping constant Γ so that time-gated amplification with several or several tens of picoseconds should be available.

However, little is known about the short pulse Raman interaction in semiconductor waveguides. In our previous article, preliminary experiments have shown that 80 ps pulse pumping using a mode-locked laser can give time-gated amplification with a high gain in GaP–AlGaP waveguides.[11]

This article describes a more detailed study of fundamental properties of the time-gated amplification in the semiconductor waveguide. It should be noted that the short pulse of pump light effectively has a frequency width comparable to the FWHM of the Raman gain coefficient. Then, we will show that the decibel gain no longer linearly depends on the pump power, but depends on the square root of pump power if the Raman gain becomes high.

We must also take into account the fact that only the backward scattering is effective for longitudinal optical (LO) phonon Raman scattering in a [100] directional waveguide.[9,13] We have previously shown that the forward scattering takes place for the transverse optical phonons instead of LO phonons when the waveguide has a small cross sectional area, because the transverse component of the phonon momentum increases.[13] For the backward scattering, the time gate width is elongated if the waveguide length is larger than the spatial length of the pump pulse because the inter-

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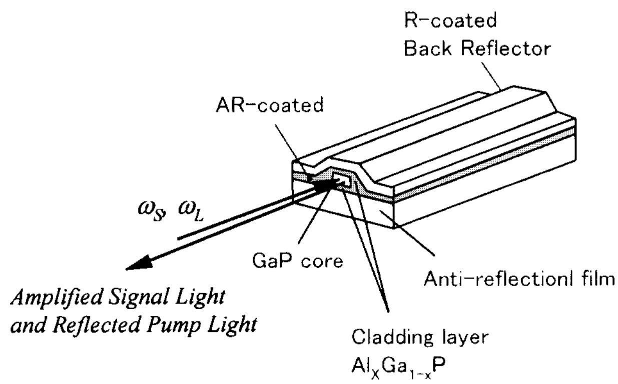

FIG. 1. Structure of GaP–AlGaP waveguide Raman amplifier.

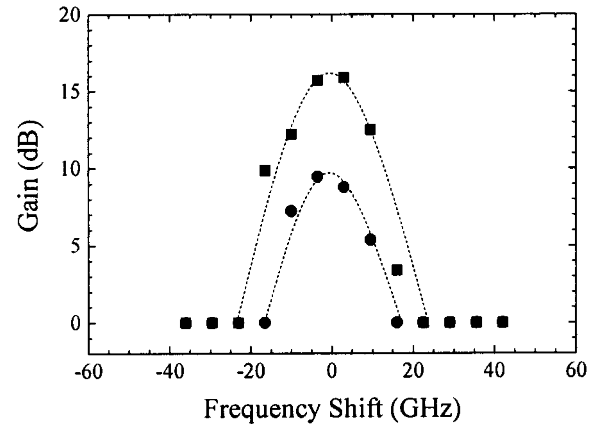

FIG. 2. Raman gain profile for a 5.2 mm long waveguide with AR-R coated facets as a function of frequency shift of the laser diode from the maximum gain frequency. Introduced pump power is 26 mW (■) and 11 mW (●). The dash lines are fitted to the experimental points.

action time for the backward scattering is increased with the increase of the waveguide length.

II. EXPERIMENT

Figure 1 shows the schematic structure of a GaP–AlGaP waveguide for Raman amplification. The waveguides with a heterostructure of a GaP core layer and AlGaP cladding layers have been formed in the ⟨001⟩ direction on a GaP(100) substrate by the liquid phase epitaxial method with the temperature difference method under controlled vapor pressure,[14,15] photolithography and reactive ion etching using Cl_2+Ar or PCl_3 gases. We have fabricated GaP–AlGaP tapered waveguides with various size waveguide structures, in order to obtain sufficiently high gain.[16] The lateral width and vertical thickness of the waveguide are designated as w and d, respectively. The lateral width is photolithographically patterned, so that the length of the laterally tapered region is 0.5 mm from the input facet. However, the vertical thickness is more gradually tapered using natural growth thickness change of the active layer. Tapered waveguide parameters ($w_{3\text{-}1}$-$d_{2.3\text{-}1}$-$l_{5.7}$) are defined as follows. The width at the input (w_{in}) is 3 μm and the width at the back facet (w_{back}) is narrowed to 1 μm ($w_{3\text{-}1}$). The thickness at the input (d_{in}) is 2.3 μm and the thickness at the back facet (d_{back}) is 1 μm ($d_{2.3\text{-}1}$). The total length of the waveguide is 5.7 mm ($l_{5.7}$), while the length of the tapered region is about 0.5 mm.

The Raman gain measurements of the waveguides are investigated by using a mode-locked Ti–sapphire laser (925 nm) as a pump light source. The pump pulse width measured by the autocorrelation method is 80 ps and the pulse repetition rate is 80 MHz (pulse repetition period of 12.5 ns). A wavelength-tunable cw laser diode (960 nm) is used as a signal light source. Detection of the amplified pulse signal has been performed using a photodiode with a detection bandwidth of 25 GHz.

III. RESULTS AND DISCUSSION

For the amplification experiment, the sample is coated on the waveguide facets; the input facet is antireflection coated and the back facet is high reflection coated (AR-R). The signal and pump beams are introduced into the waveguide through the AR-coated facet, reflected by the high reflection mirror and taken out from the input facet. The reflected pump power was measured via a Faraday rotator and we used it as the value of pump light power actually introduced into a waveguide. The coupling efficiency is about 30% when we use a focal lens with $f=6.4$ mm. The wavelength of the Ti–sapphire laser for the pump light is approximately fixed at 925 nm. The tunable laser diode wavelength can be changed around 960 nm. The difference of the pump and signal light frequencies is nearly set to the LO phonon frequency of GaP (12.12 THz).[3,4,7]

Figure 2 shows the gain spectrum around LO phonon frequency shift (12.12 THz) for a stripe with the waveguide length of 5.2 mm. The gain spectrum is obtained with changing the signal light frequency point by point. The maximum gain of this sample is 16 dB at an introduced average pump power level of 26 mW (peak pulse power of 4.0 W), and the 3 dB gain bandwidth for pulse pumping Δf_B is 17 GHz.

It is noted that the Raman gain G is given by

$$G=\exp(gI_pl), \tag{1}$$

where g is the Raman gain coefficient which has FWHM of 24 GHz.[7] I_p is the pump power density in the waveguide and l is the length of the interaction between the pump light and the backward propagating signal, which is twice the waveguide length. It was shown that the gain coefficient g is approximately given by the following Lorenz shape:[4,7]

$$g=\frac{g_0}{1+\left(\dfrac{2\Delta f}{\Delta f_0}\right)^2}, \tag{2}$$

where Δf is the deviation of the signal light frequency from the center frequency, and Δf_0 is the FWHM of the gain coefficient (24 GHz). This feature originates from the fact that FWHM of the gain coefficient is determined by the dumping constant Γ of the LO phonons. From the exponential dependence of G on I_p, and g, we can calculate the 3 dB Raman gain bandwidth for single frequency continuous wave pumping Δf_{B0}. As is given by Eq. (A2) in the Appendix, Δf_{B0} decrease with increasing I_p. Using this equation, Δf_{B0} should become 8 GHz at $x=30$ dB corresponding to the observed gain of 17 dB as is described later. However, the

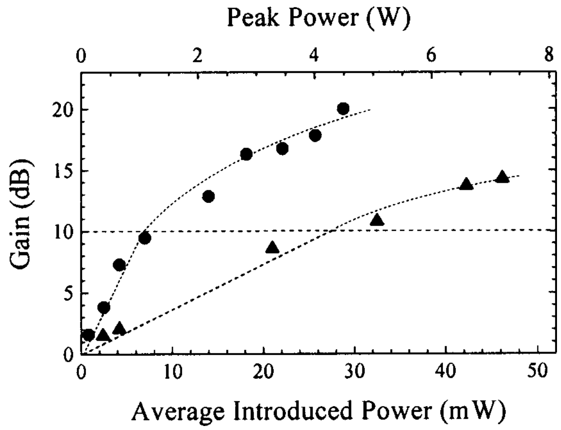

FIG. 3. The Raman gains of the tapered waveguides with $w_{3\text{-}1}$-$d_{2.3\text{-}1}$-$l_{5.7}$ (●) and $w_{5\text{-}3}$-$d_{2.3\text{-}1}$-$l_{5.7}$ (▲), for pumping with 80 ps pulse.

measured 3 dB bandwidth of the pulse gain spectrum Δf_B is about 17 GHz at an actual maximum gain of 17 dB, as is seen in Fig. 2. The reason for this discrepancy is that the mode-locked pump pulse should have a linewidth $\Delta f_p = 12.5$ GHz corresponding to the pulse width of 80 ps. The spectral bandwidth of the pump laser has been actually measured to be 12 GHz using a spectral analyzer, which is a near-transform-limited linewidth as is expected. This finite linewidth of the pump pulse should contribute to the 3 dB bandwidth of the gain spectrum at high gain.

In Fig. 2, it is seen that the light frequency width at which the gain reduces to lower than 1 dB is about 40 GHz. Therefore, the actual logarithmic gain does not show a pure Lorenzian shape below 1 dB. This should also be due to the fact that the short pump pulse has a finite linewidth. This effect also appears in the pump power dependence of the gain, as discussed later.

Figure 3 shows the results of Raman gain measurement for two typical waveguides with different parameters of the tapered regions. Raman gain in decibel unit $G(\text{dB})$ shows a linear dependence at a low introduced pump power level as is given by Eq. (1), but becomes nearly proportional to the square root of the introduced pump power at a higher gain exceeding about 10 dB, as is shown by the dashed curves in the figure.

This sublinear behavior can be interpreted in terms of the finite linewidth of the mode-locked pump light. When the pump power is increased much higher than the level at which the 3 dB bandwidth of the gain becomes comparable to the linewidth of the pump pulse $\Delta f_p = 12.5$ GHz, only a part of the pump pulse power contributes to the gain. In such a case, as shown in the Appendix, G in decibel units can be roughly described as

$$G(\text{dB}) \approx \left(\frac{\Delta f_0}{\Delta f_p}\right) \cdot (3x)^{1/2}, \quad \text{with } x = 4.34 g_0 I_p l, \tag{3}$$

where Δf_0 is the FWHM of the gain coefficient ($\Delta f_0 = 24$ GHz), and x is the maximum gain expected for single frequency pumping with pump light intensity I_p. This equation is obtained with an approximation that the pulsed gain is reduced with a ratio ($\Delta f_{B0}/\Delta f_p$), or equivalently the gain bandwidth products are equal for the cw and pulse pumping cases.

From the above equation, it is understood that $G(\text{dB})$ depends on the square root of the pump power when the gain is considerably larger than 3 dB. By increasing the pump power, Δf_{B0} becomes smaller and it becomes 14 GHz at 10 dB, which is comparable to Δf_p. Therefore, it is seen that G tends to be sublinearly dependent on the pump power when G exceeds roughly about 10 dB. Another possible origin of the sublinear behavior of Raman gain versus pump power is the nonlinear absorption of pump light due to the two photon absorption, as was reported for InP waveguides.[17] However, we have shown that the threshold wavelength of nonlinear absorption in GaP is 900 nm, and the absorption gradually increases with decreasing the pump wavelength.[7] Therefore, we can assume that the effect of nonlinear absorption can be neglected in the present experiment.

It should be noted that, in the case of the narrower stripe (waveguide 1), a 20 dB gain is obtained at the introduced average pump power of 30 mW (peak power of 4.7 W). Moreover, in the linear dependence region, 10 dB amplification can be obtained with the introduced average pump power as low as 8 mW (peak power of 1.25 W).

The symbols ● and ▲ in Fig. 3 represent the Raman gain of the tapered waveguide 1 with $w_{3\text{-}1}$-$d_{2.3\text{-}1}$-$l_{5.7}$ and the tapered waveguide 2 with $w_{5\text{-}3}$-$d_{2.3\text{-}1}$-$l_{5.7}$, respectively. The gain at low power of waveguide 1 is about three times larger than that of waveguide 2. In the case of waveguide 1 the internal pump power intensity increases about three times in the lateral direction and 2.3 times in the vertical direction, while for waveguide 2, there is little increase in the pump light intensity in the lateral direction because the pump beam diameter is about 3 μm. It is therefore expected that the internal intensity of waveguide 1 is about three times larger than that of waveguide 2. Thus, it is shown that the Raman gain increases for the same introduced pump power by reducing the size of the tapered waveguide.

In comparison with the continuous wave pumping, pulse pumping has a merit of time gate function. For example, only a selected pulse channel can be amplified for each of the wavelength channels in WDM optical communication. Also it will give high gain light amplification for spectroscopic detection of high speed optical phenomena.

From the viewpoint of time gate amplification, there is an optimum length of the Raman waveguide for a given pulse width. Figure 4 shows that the amplified signal pulse widths linearly increase with increasing waveguide length when the waveguide length is longer than 4 mm. In this experiment, the input signal is a continuous wave. For the 80 ps pump pulse the interaction length is about 8 mm, so that a 4 mm long waveguide with AR-R structure is the most suitable, taking into account that the backward Raman interaction is dominant.[9,13] This is another limitation for the time gate amplification other than the finite linewidth of the pump pulse. If the waveguide length is longer than 4 mm, the observed signal pulse width will inevitably increase, because only the backward Raman scattering is effective. For example, it takes about 120 ps for a round trip of a light wave

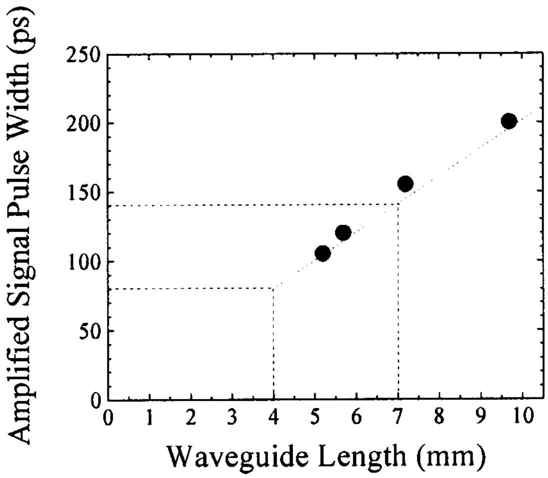

FIG. 4. Amplified signal pulse widths for various waveguide lengths.

in the 5.7 mm long waveguide, so that the observed signal pulse width in Fig. 4 is seen to increase as much.

It should be noted that the pulse pumping has another advantage. Amplifier instability at high gain due to the optical feedback can be avoided because the amplification occurs only for a round trip time of signal light propagation in the waveguide. Also, the center frequency of the amplifier is not affected by the instantaneous temperature rise due to the pulse pumping, as well as by the change in the ambient temperature.

IV. CONCLUSION

We have investigated the short pulse-gated Raman amplification characteristics of the GaP–AlGaP waveguides. As long as the Raman gain is less than about 10 dB, the logarithmic gain linearly increases with increasing pump power density. However, when the pump power increases further, the logarithmic gain tends to increase as the square root of the pump power density. This is because the short pump pulse has a finite linewidth comparable to the FWHM of the Raman gain coefficient. Nevertheless, we have attained the pulse-gated Raman gain as high as 20 dB.

APPENDIX

The 3 dB gain bandwidth Δf_{B0} for single frequency pumping (continuous wave pumping) decreases with increasing pump intensity I_p as follows. From Eqs. (1) and (2), we obtain

$$10 \log G_{\text{signal}} = 4.34 \ln G_{\text{signal}} = \frac{g_0}{1+\left(\frac{2\Delta f}{\Delta f_0}\right)^2} \times 4.34 I_P l, \tag{A1}$$

where Δf is the frequency shift from the center frequency. Here, $10 \log G_{\text{single}}$ should become x-3 at $\Delta f = \Delta f_{0B}/2$, where $x = 4.34 g_0 I_p l$ is the maximum decibel gain at $\Delta f = 0$ for single frequency pumping. Inserting these parameters into Eq. (A1), Δf_{B0} is given by

$$\Delta f_{B0} = \left(\frac{3}{x-3}\right)^{1/2} \cdot \Delta f_0, \quad \text{with } x = 4.34 g_0 I_P l. \tag{A2}$$

Then, we consider the pulse pumping. The linewidth of the pump pulse Δf_p is smaller than FWHM of the gain coefficient Δf_0. However, as the pump pulse intensity I_p is increased, the 3 dB gain bandwidth Δf_{B0} becomes smaller than Δf_p (i.e., $\Delta f_{B0} < \Delta f_p < \Delta f_0$). Then, as a rough estimation, we assume that the maximum pulsed gain is reduced with a ratio $(\Delta f_{B0}/\Delta f_p)$, as follows:

$$\ln G \approx g_0 \left(\frac{\Delta f_{B0}}{\Delta f_p}\right) I_P l \tag{A3}$$

instead of $\ln G = g_0 I_p l$. This approximation is equivalent to assume that the gain bandwidth product does not change, i.e., $(g_0 I_p l)\ \Delta f_{B0} = (\ln G)\ \Delta f_p$.

Then, from Eqs. (A2) and (A3), the signal gain for short pulse pumping is obtained as

$$G(\text{dB}) \approx \left(\frac{\Delta f_0}{\Delta f_p}\right) \cdot \left(\frac{3}{x-3}\right)^{1/2} \cdot x. \tag{A4}$$

When x, the linear maximum gain expected for single frequency pumping, is considerably higher than 3 dB, $G(\text{dB})$ is approximated as

$$G(\text{dB}) \approx \left(\frac{\Delta f_0}{\Delta f_p}\right) \cdot (3x)^{1/2}. \tag{A5}$$

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