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The Properties of a GaAs-GaAlAs Traveling-Wave Laser Amplifier

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Abstract *The reflectivity of the cavity mirrors of a GaAs-GaAlAs DH semiconductor laser are reduced to* $1*10^{-4}$ *by sputtering a film* Si_3N_4*. The gain of traveling-wave laser amplifiers is measured. The highest gain is about 25 dB. The dependence of gain on the injection current is measured. The measured frequency bandwidth shows the great advantage over other types of semiconductor laser amplifiers.*

Introduction

Semiconductor laser amplifiers can be used as repeaters in fiber optic communication systems, as preamplifiers of detectors, or as optical power amplifiers to compensate for losses in optical systems. There are three types of semiconductor laser amplifiers: the traveling-wave type, the Fabry-Perot type, and the locking-in type. The traveling-wave laser amplifier has high gain, wide spectral bandwidth, and low sensitivity to changes in temperature and injection current. These attributes give the traveling-wave amplifier an advantage over the others. The main source of noise from a traveling-wave laser amplifier is spontaneous emission. Because of the suppression of spontaneous noise in coherent optical transmission systems, the traveling-wave laser amplifier is the most useful amplifier for the future.

In this article the fabrication of a traveling-wave laser amplifier is reported. The sputtering technique using antireflecting film and the results of gain measurements of the amplifier are also discussed.

The Theory of the Traveling-Wave Laser Amplifier

We now discuss the steady-state process of a traveling-wave laser amplifier. If the duration of amplification is larger than the lifetime of nonequilibrium carriers (usually a few nanoseconds), the process may be treated as steady state. Under this condition the gain

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coefficient g, the spectral and spatial density of spontaneous radiation S_ω, and the injection current J may be assumed to be independent of time. Then in the one-dimensional approximation (with the z axis along the amplifier axis), the operation of the optical signal in the amplifier can be described by the following equations[1]:

$$\begin{aligned}
\frac{\delta I^+(x,\, z)}{\delta z} &= [g(x) - \alpha]I^+ + \frac{\epsilon}{c} S_\omega(x) \\
\frac{\delta I^-(x,\, z)}{\delta z} &= -[g(x) - \alpha]I^- - \frac{\epsilon}{c} S_\omega(x) \\
\frac{\eta_e j(z)}{ed} &= S + \frac{cE_0}{\hbar} \int_x [I^+(x,\, z) + I^-(x,\, z)]g(x)\, dx \\
J &= D \int_0^L j(z)\, dz
\end{aligned} \tag{1}$$

where I^+ and I^- are the spectral and spatial distributions of the densities of the photon fluxes traveling along the amplifier in the positive and negative directions, respectively; ϵ is the relative angle of emission of spontaneous radiation governed by the waveguide properties of the active region; α is the loss factor; e is the electron charge; j is the injection current density; η_e is the injection efficiency; $x = \hbar\,\omega/E_0$; E_0 is a doping parameter; D, d, L are the width, thickness, and length, respectively, of the active region, S is the total rate of spontaneous recombination and c is the velocity of light.

In the adopted model both $g(x)$ and S_ω are independent of the coordinate z, so that the first two equations of system (1) are linear and differential. Integration of these equations gives the following distributions of photon densities along the amplifier:

$$\begin{aligned}
I^+(x,\, z) &= I^+(x,\, 0) \exp\,[g(x) - \alpha]z + \frac{\epsilon S_\omega(x)}{c[g(x) - \alpha]}\{\exp\,[g(x) - \alpha]z - 1\} \\
I^-(x,\, z) &= \frac{\epsilon S_\omega(x)}{c[g(x) - \alpha]}\{\exp\,[g(x) - \alpha](L - z) - 1\}
\end{aligned} \tag{2}$$

The first term of $I^+(x, z)$ is the amplified optical signal, $I^+(x, 0)$. The second term is the amplified spontaneous radiation. $I^-(x, z)$ is merely the amplified spontaneous radiation.

If the application at the amplifier input ($z = 0$) of a signal with a π-shaped spectral distribution is

$$P(x,\, 0) = \begin{cases} P_0 & |x - x_0| \leq \Delta x/2 \\ 0 & |x - x_0| > \Delta x/2 \end{cases} \tag{3}$$

[where $P(\chi, z)$ is the optical power, $P(\chi, 0)$ the optical power at $z = 0$, and P_0 the optical power while $\chi = \chi_0$, $z = 0$] and is of sufficiently narrow spectral width to justify the hypothesis that $S_\omega(x)$ and $g(x)$ are constant within Δx, then at $z = L$ a useful output power (P_{out}) is

$$P_{out} = P_0 \Delta x \exp\,\{[g(x_0) - \alpha]L\} = P_{in} G(x_0) \tag{4}$$

$$G(x_0) = \exp\,[g(x_0) - \alpha]L \tag{5}$$

where P_{in} is the input power and G is the gain. The output power of amplified spontaneous radiation (P_{sp}) is

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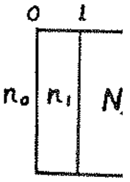

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Figure 2. Th fier No. 19 v No. 19 laser Proton Bomba

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$$P_{sp}(x, L) = DdxE_0I^+(x, L)$$
$$= DdE_0\epsilon\frac{xS_\omega(x)}{[g(x) - \alpha]}\{\exp\,[g(x) - \alpha]L - 1\} \tag{6}$$

$P(x, L)$ is merely the background power at the amplifier exit.

The Preparation of Antireflecting Film and the Measurement of Reflectivity of Cavity Mirrors

The distribution of refractivity of cavity mirrors after the antireflecting film is sputtered on the laser amplifier is shown in Figure 1. If the input optical signal is incident perpendicularly, the reflectivity R of the antireflecting film is[2]:

$$R = \frac{(n_0 - n_s)^2\cos^2\delta/2 + [(n_0n_s/n_1) - n_1]^2\sin^2\delta/2}{(n_0 + n_s)^2\cos^2\delta/2 + [(n_0n_s/n_1) + n_1]^2\sin^2\delta/2} \tag{7}$$

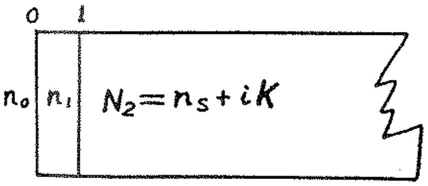
$$\delta = (4\pi/\lambda)n_1d_1\cos i_1 \tag{8}$$

where δ is the phase difference between adjacent lights, d_1 is the thickness of the antireflecting film, and i_1 is the angle of refraction in the film. Suppose $n_1d_1 = \frac{1}{4}\lambda m$, where $m = 1, 3, 5, \ldots$. Then $\delta = m\pi$ and $n_1 = (n_0n_s)^{1/2}$, hence $R = 0$. Therefore the film is antireflecting perfectly.

As before, α is set at 0 because this loss is not important. For example, if the material of the active region is GaAs, $n_s = 3.59$. Taking account of α and λ, then $n_1 = 0.97$, $n_s = 1.83$, and $d = 0.26\lambda/n_1 = 123$ nm.

The antireflecting films are made of silicon nitride, which is sputtered on the cavity mirrors of the laser amplifier by sputtering equipment. The refractivity of the antireflecting film and the growth rate of this film can be controlled by the ratio of nitrogen and argon gases in the chamber of the sputtering equipment, the electric voltage of the anode, and the vapor pressure in the chamber. The thickness of the film is controlled according to its growth rate.

The reflectivity of the cavity mirrors is measured from the spectrum of the laser amplifier. The spectrum of the laser amplifier before sputtering is shown in Figure 2. Here m is the ratio of the peaks (P_{max}) and valleys (P_{min}) of the longitudinal modes:



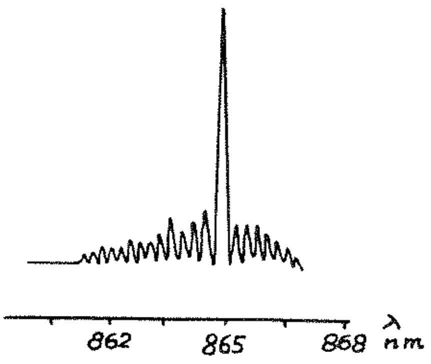


Figure 1. The distribution of refractivity of cavity mirrors with an antireflecting film. Symbols: n_0, refractivity of air; n_1, refractivity of the antireflecting film; n_s, refractivity of the action region; N_2, complex refractivity; K, specific absorption.

Figure 2. The spectrum of the laser amplifier No. 19 without the antireflecting film. No. 19 laser amplifier, GaAs/GaAlAs DH Proton Bombardment stripe structure.

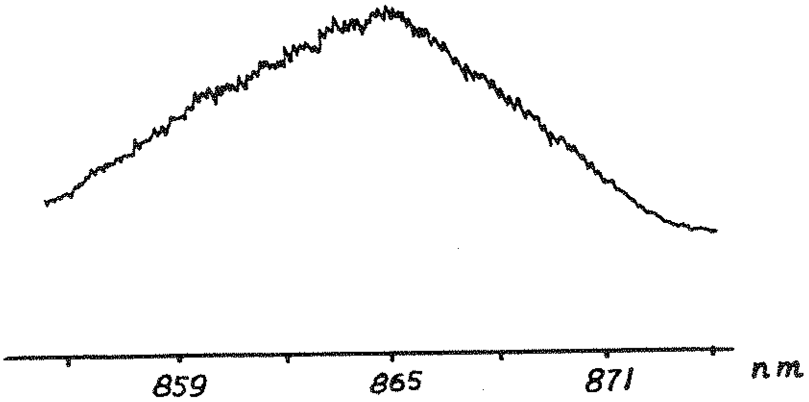


Figure 3. The spectrum of the laser amplifier with antireflecting film on one of the cavity mirrors.

$$m = \frac{P_{\max} - P_{\min}}{P_{\max} + P_{\min}} \tag{9}$$

$$m = 2|a|/(1 + |a|^2) \tag{10}$$

$$R_1R_2 = a\,R_1R_2 \tag{11}$$

a is a ratio number. R_1 and R_2 are the reflectivities of the two cavity mirrors respectively.

If an antireflecting film is sputtered on one of the cavity mirrors with strictly controlled refractivity and thickness, then the spectrum changes to that shown in Figure 3.

Suppose the reflectivity of this mirror is changed from R_2 to R_2'. Now the ratio m becomes m', and a' can be calculated. Hence $R_1R_2' = (a'R_1R_2)$.

A number 19 laser amplifier is used as an example. From Figure 3 $m' = 0.04$. Substituting this value into Eqs. (10) and (11) yields $R_2' = 1.1 \times 10^{-4}$ where $R_1 = 0.3$.

Antireflecting film was sputtered on the second cavity mirror of the laser amplifier. The spectrum of the laser amplifier is shown in Figure 4. The fluctuation in the spectrum is noise, and no longitudinal mode can be seen. Therefore, this laser amplifier is acting as a traveling-wave laser amplifier.

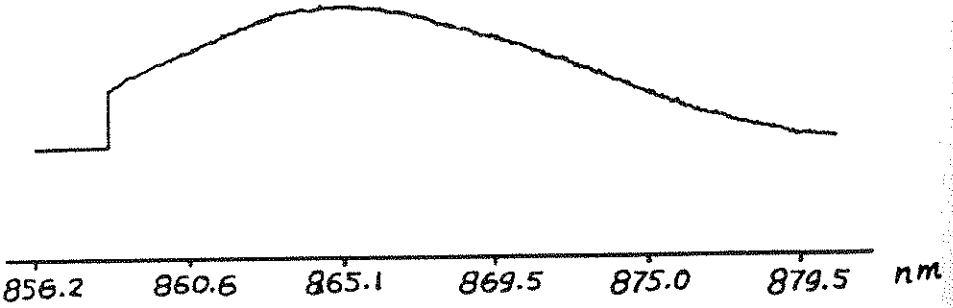
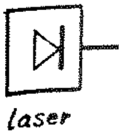


Figure 4. The spectrum of the laser amplifier after antireflecting film has been sputtered on two cavity mirrors.



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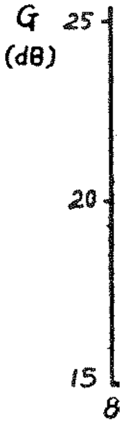

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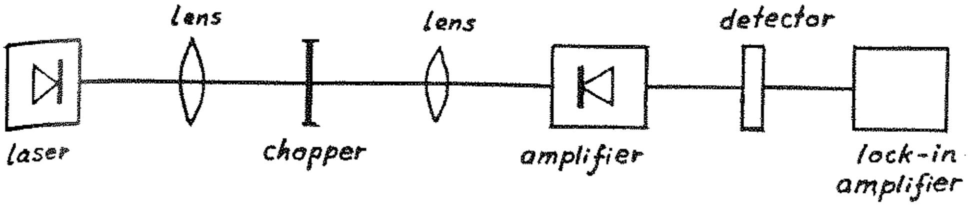

Figure 5. The experimental equipment.

The Measurement of Gain Characteristics of the Traveling-Wave Laser Amplifier

The experimental equipment is shown in Figure 5. The laser and laser amplifier are mounted in thermostats. The temperature of these thermostats can be adjusted as required. The laser beam is focused by microlenses 1 and 2 and is coupled into the active region of the laser amplifier. Let the coupling efficiency be η. If the input power is P_{in}, then the amplified optical power is ηP_{in}. The output power P_{out} and the input power P_{in} are measured by a silicon detector and a lock-in amplifier. The frequency of the chopper is about 700 Hz. The coupling efficiency η is measured by the method of short optical current.[4] The value of η is between 0.1% and 1% in our experiment. Hence $G = P_{out}/\eta P_{in}$.

The gain is measured under different injection currents. The gain is plotted against direct injection currents in Figure 6 and, with a number 21 laser amplifier, against pulse injection currents in Figure 7. Gain increases linearly with injection current from 10 dB to 25 dB. When $I \geqslant 160$ mA, gain goes to saturation.

The wavelength of the laser changes as the temperature of the thermostat is varied. The gain of the number 21 laser amplifier is measured against the variation of laser wavelength under direct injection current in Figure 8. The gain changes by about 3 dB while the laser wavelength changes by about 2.5 nm. This implies that the traveling-wave laser amplifier has a wide frequency bandwidth.

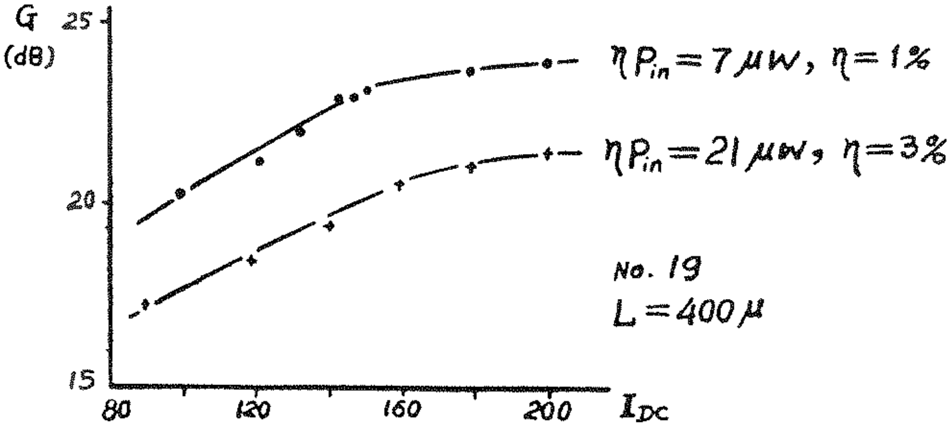

Figure 6. Gain plotted against *direct* injection current (I_{DC}, in milliamperes).

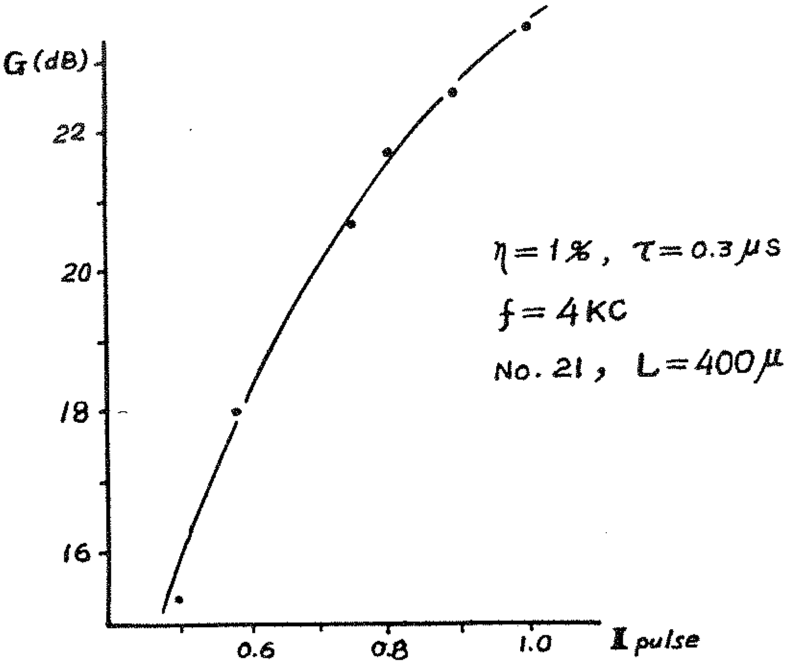

Figure 7. Gain plotted against pulse injection current (I_{pulse}, in amperes). τ = the pulse duration; f = the pulse rate.

Conclusion

From the above results, the traveling-wave laser amplifier may be recognized as a promising device for its high gain, wide frequency bandwidth, and reduced sensitivity to

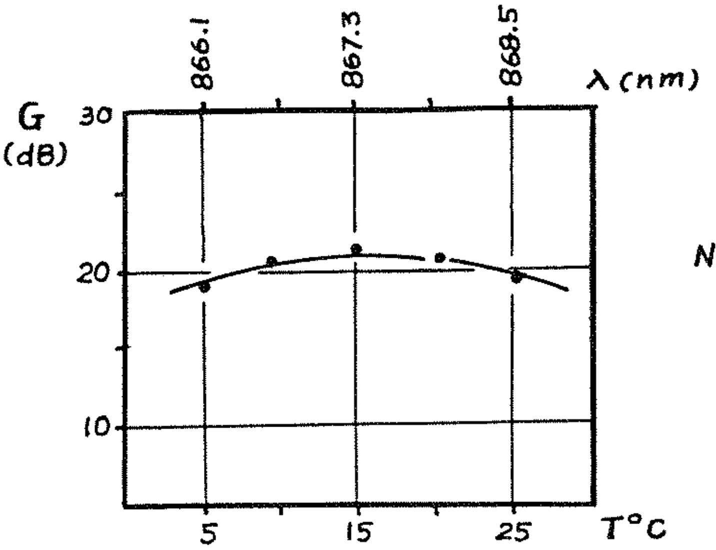

Figure 8. Gain plotted against laser wavelength. I_{DC} = 160 mA.

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changes in temperature and injection current. Direct optional amplification would allow the system to be built with more compact repeaters of a simple design. Semiconductor laser amplifiers are useful devices for potential coherent optical transmission and long-haul operation for future systems.

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