Laser Original**Amplification of Semiconductor Laser to Kilowatt Pulses
by Using YAG Laser Pumped Dye Cell**

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We have succeeded in the amplification of semiconductor laser to kilowatt pulses by using a two-stage dye laser amplifier system pumped by a Q-switched Nd:YAG laser. The signal-to-noise ratio of the overall system was about 90 and the overall amplification was of the order of 10^5 . We also investigated the lower limit of input power that can be successfully amplified by a dye cell amplifier. We show that this is a few milliwatts or less, and confirm the feasibility of semiconductor laser amplification by dye cell.

Key Words: Semiconductor laser, Laser pulse amplification, Amplified spontaneous emission, Dye cell amplifier.

1. Introduction

Semiconductor lasers are known for their compactness, stability, durability and ease of operation. They are being rapidly improved to provide higher powers and shorter wavelengths. They have been mode-locked to provide picosecond pulses¹⁻⁵⁾. But in many applications where high peak powers are essential (like nonlinear spectroscopy), their peak powers are still insufficient even in pulsed operation. If we can amplify the low-level light of semiconductor lasers to high peak powers, it will be very useful in many applications.

We attempted the amplification of a low-power semiconductor laser by using a dye cell pumped by a Q-switched YAG laser. Here the predominant problem was the masking of the

low-level signal by the strong amplified spontaneous emission (ASE) emitted by the dye medium. In order to reduce the ASE as much as possible, and to improve the ratio of signal and ASE noise, a system of two apertures was used. We present here a simplified theory of noise in a laser amplifier proposed by Yariv & Kogelnik⁶⁾. Actual measurements of noise emitted by laser amplifiers were discussed by Paananen et al.⁷⁾ and Kluver⁸⁾. In the present paper, we compare our experimental data with the theory. We found that amplification at an input power level of a few milliwatts is possible, then proceeded to perform the amplification experiment of semiconductor lasers.

2. Theoretical considerations

We use a simplified model of a laser amplifier

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Fig.1 Amplifier model with an aperture of radius a_1 in the output plane.

first considered by Yariv & Kogelnik⁽⁶⁾ with a gain medium (which can be a dye maintained in an excited state by pumping) and try to find the gain and amount of noise generated by such a system. We assume the simple model shown in Fig.1. The laser medium with an inversion density $n_2 - n_1$ is distributed uniformly between the planes $z=0$ and $z=l$, which are the two faces of the amplifier. Light of frequency ν passing through the medium at an angle θ with the optic axis is amplified by a factor $\exp(\gamma l / \cos \theta)$ until it reaches the output end. Here the power gain constant $\gamma(\nu)$ is given by

$$\gamma(\nu) = \frac{[n_2 - n_1 (g_2/g_1)] c^2 g(\nu)}{8\pi \nu^2 t_{SP}}, \quad (1)$$

where g_1 and g_2 are the degeneracies of the two laser levels, c is the light velocity, $g(\nu)$ is the atomic lineshape function and t_{SP} is the spontaneous lifetime of the dye molecules.

As shown in Fig.1, the amplifier model consists of an absorbing screen in the output plane with a round hole of radius a_1 and area $A_1 = \pi a_1^2$ to allow for the passage of the signal. The amount of noise due to amplified spontaneous emission (ASE) in the laser medium in the frequency interval $d\nu$ emitted into solid angle $d\Omega$ and passing through the hole is given by

$$N(\theta) = 2h\nu d\nu \frac{n_2}{n_2 - n_1 (g_2/g_1)} \times (G-1) \frac{A_1 \cos \theta d\Omega}{\lambda^2}, \quad (2)$$

where λ is the wavelength and G is the amplifier gain, defined by

$$G(\theta) = \exp[\gamma l / \cos \theta]. \quad (3)$$

The quantity $N_0 = (G-1) h\nu d\nu \cdot n_2 / [n_2 - n_1 (g_2/g_1)]$ is called the "noise per mode" and it can be shown that it is the amount of noise radiated into a solid angle that can be associated with a single blackbody mode⁽⁶⁾. Equation (2) then becomes

$$N(\theta) = N_0 A_1 \cos \theta d\Omega / \lambda^2, \quad (4)$$

where we have assumed that a linear polarizer is used to reduce noise by a factor 2.

We imagine a detector being placed on the optic axis very far away from the amplifier. If the detector is allowed to accept radiation emitted into the solid angle $\Omega = \lambda^2 / A_1$, then the amount of noise received (in one polarization), according to eq.(4), is simply N_0 .

We assume that the signal arrive at the output plane of the amplifier with power S_0 , then the signal-to-noise ratio (S/N) at the detector is S_0/N_0 , if the signal is of the correct polarization to pass through the polarizer without attenuation. Since the gain of the signal in passing through the amplifier is G , then the input signal must be $S_{in} = S_0 / G$. The ratio S_0 / N_0 now becomes

$$S_0 / N_0 = S_{in} G / N_0. \quad (5)$$

If we assume that the dye amplifier is emitting ASE in a bandwidth $\Delta \nu$ about a center frequency ν_0 , the total ASE noise per mode reaching the detector is

$$\overline{N}_0 = \frac{n_2}{n_2 - n_1 (g_2/g_1)} (G-1) \int_{\nu_0 - \Delta\nu/2}^{\nu_0 + \Delta\nu/2} h\nu d\nu. \quad (6)$$

In case of a dye amplifier, pumped by nanosecond pulses, the lower level is almost empty compared to the upper one, $n_2 \gg n_1 (g_2/g_1)$, and the gain is much higher than unity, $G \gg 1$. Therefore, the net noise detected is

$$\overline{N}_0 = G \int_{\nu_0 - \Delta\nu/2}^{\nu_0 + \Delta\nu/2} h\nu d\nu = Gh\nu_0 \Delta\nu. \quad (7)$$

In that case, the S/N ratio for the dye amplifier at the detector is

$$S_0/\overline{N}_0 = S_{in}/h\nu_0 \Delta\nu, \quad (8)$$

and is independent of the gain G .

The following more exact analysis shows that this value of $S_0/\overline{N}_0$ is an ideal one which is always greater than the actual S/N ratio which can be obtained with a practical noise-reducing structure.

Let us consider a system of two aperture stops separated by a distance d (Fig.2). The areas of the openings are A_1 and A_2 respectively. If the dimensions of the apertures are small compared to their separation, it can be shown that the ASE noise power radiated from the active

Fig.2 Noise reducing aperture system. N is the noise power passing through this system (see text).

medium and transmitted through this system is⁶⁾

$$N = \overline{N}_0 \frac{A_1 A_2}{d^2 \lambda^2}. \quad (9)$$

We define a parameter α , called the acceptance factor of the aperture system as

$$\alpha = \frac{A_1 A_2}{d^2 \lambda^2}, \quad (10)$$

which plays an important role in the problem. Using this, eq.(9) becomes

$$N = \overline{N}_0 \alpha. \quad (11)$$

Next we consider the transmission of the signal through this system. We wish to inject the signal so as to transmit a maximum amount of signal through it. This amount is determined by the field distribution of the laser beam and diffraction effects. As the transmitted noise is constant for a given acceptance factor, we can maximize the S/N ratio by maximizing the signal transmission.

The light beam propagates in the forward direction and passes through the first aperture without attenuation with a power S_0 . A part of this beam is intercepted by the second aperture while the rest

$$S = \tau S_0 \quad (12)$$

is transmitted through the hole in it. The transmission factor τ depends on the field distribution of the signal beam. In the absence of such information, it can be determined experimentally by measuring the ratio of detected signals when the aperture A_2 was in place and when it was removed.

Combining the above results, we can calculate the S/N ratio that can be expected with the noise reducing structure described above. Let the signal be injected into the amplifier with a given power S_{in} and reach the output plane of

the amplifier with a power $S_0 = GS_{in}$ where G is the gain. The noise reducing structure following the amplifier is characterized by an acceptance factor α . Using eqs.(11) and (12), we obtain the S/N ratio at the detector

$$S/N = \frac{\tau}{\alpha} \frac{S_0}{N_0} = \eta \frac{S_0}{N_0}. \quad (13)$$

The factor η is always smaller than unity and measures how closely the ideal value S_0/N_0 is approached. Injection for maximum possible signal transmission results in maximum values of η_{max} and therefore the best possible signal-to-noise ratio for a given acceptance factor.

3. Experimental Comparison with Theory

The setup to compare the results of the theory with experiment is shown in Fig.3. Third harmonic light pulses (6 nsec duration, 1.7 mJ energy and 355 nm wavelength) from a Q-switched Nd:YAG laser were used to excite both the oscillator and the amplifier dye cells. About 20% of the incident light was used to excite the oscillator. The rest went to excite the amplifier.

The dye used in both the oscillator and the amplifier was Coumarin 500 in methanol. Both the oscillator and the amplifier were side pumped by the YAG laser. Upon excitation, the amplifier emitted ASE in the range of about

Fig.3 Schematic diagram for measuring amplifier noise and S/N ratio. Apertures A_1 , A_2 constitute a noise-reducing structure, P is a polarizer, and PMT is a photomultiplier tube.

510 nm to 530 nm. The collimated oscillator beam was focused by a lens onto the dye amplifier. The unattenuated oscillator peak power was about 570 W.

The amplifier was excited by 1.2 mJ pulses of about 6 nsec duration. The resulting gain medium amplified the oscillator pulses. In order to prevent oscillation of the amplifier cell, it was tilted at an angle with the optic axis. To reduce the ASE noise as much as possible and to improve the S/N ratio, a noise reducing structure consisting of two apertures (diameters 0.6 mm and 4.5 mm) separated by about 140 cm is placed between the amplifier and the detector. All neutral density filters and lenses too were inserted at an angle with the beam to prevent spurious oscillations.

To find the output power of the amplifier as a function of its input power, neutral density filters were inserted into the oscillator beam, and for each input power, output power and ASE noise were measured. The result is shown in Fig.4. The detected noise power was about 7.1 W (peak). The solid curve shows the total output and the broken curve shows the output minus the noise. We see that saturation of the

Fig.4 Input-output characteristics of the amplifier.

The solid curve is the total output ($\tau S_0 + N$) and the broken curve is the output minus the ASE noise (τS_0).

Fig.5 Gain of the amplifier (S_0/S_{in}) as a function of input power.

Fig.6 Signal-to-noise ratio of the amplifier as a function of input power. The broken line is calculated from theoretical considerations.

amplifier occurs at input power levels of more than 1 W. Below this, the curves are almost straight, especially the broken one. This means that the gain is constant up to about 1 W. At 5 mW input, the output power is seen to be about 70 W.

The measured gain of the amplifier as a function of input power is shown in Fig.5. Here too, the effects of saturation becomes noticeable above power levels of about 1 W. The small signal gain is of the order of 10^5 .

The measured values of S/N ratio as a function of input power are shown in Fig.6. We see that as the input power is decreased, the S/N

ratio also decreases. The curve for S/N also exhibits the same saturation behaviour as in Fig.4 at high power levels. We see that even at a power level of 5 mW, the S/N ratio is of the order of 5. We now calculate the S/N ratio as a function of input power from theoretical considerations. The experimental parameters are as follows:

Center frequency of laser

$$\nu_0 = 5.8 \times 10^{14} \text{ Hz } (\lambda = 520 \text{ nm})$$

ASE bandwidth

$$\Delta \nu = 1.7 \times 10^{13} \text{ Hz}$$

Signal transmission factor

$$\tau = 9.1\% = 0.091$$

Radius of aperture 1

$$a_1 = 0.3 \text{ mm}$$

Radius of aperture 2

$$a_2 = 2.3 \text{ mm}$$

Separation of the apertures

$$d = 143 \text{ cm}$$

Acceptance factor of the noise-reducing structure is

$$\alpha = \frac{A_1 A_2}{d^2 \lambda^2} = \frac{\pi^2 a_1^2 a_2^2}{d^2 \lambda^2} \simeq 8.$$

From eq.(8)

$$S_0/\overline{N_0} = \frac{S_{in}}{h \nu_0 \Delta \nu} = \frac{S_{in} (W)}{6.7 \times 10^{-6}}.$$

Therefore, the S/N ratio is given by eq.(13)

$$S/N = \frac{\tau}{\alpha} \frac{S_0}{\overline{N_0}} = 1700 S_{in} (W).$$

The S/N ratio is thus seen to be proportional to the input power (as long as there is no saturation). This is shown in Fig.6 as a broken line. We see that the agreement between theory and experiment is quite satisfactory.

From the previous results, it is clear that amplification of the order of 10^5 is possible at input power level of 5 mW with a S/N ratio of about 5 or more. Therefore, we conclude that it is possible to amplify small low power semiconductor laser (having power ratings of the order of 5 mW) by means of a YAG laser-pumped dye

cell.

4. Semiconductor Laser Amplification

Using the above experiment as a guide, we designed a setup for amplification of semiconductor laser. The semiconductor laser used was a single-mode semiconductor laser (Sharp LT024MD0) having a rated output power of 20 mW and lasing at 780 nm. A very serious obstacle was the damage of the active region of the semiconductor laser by intense backward-propagating ASE from the amplifier dye cell. To protect the semiconductor laser, we used an optical isolator (Hoya M-500) which attenuated the backward-going ASE by about 36 dB while transmitting the forward-going signal with little loss.

The schematic diagram of the experiment is shown in Fig.7. A two-stage dye amplifier was used. The dye solution was LDS 765 in acetone. Both amplifiers were side-pumped by the 6 nsec, second harmonic light (532 nm) pulses from the Q-switched YAG laser. About 20% of the incoming energy was used to excite the first amplifier. The pumping pulse energies incident on the first and the second amplifiers were 10 mJ and 33 mJ, respectively. The input intensity of semiconductor laser at the first amplifier was 6 mW.

As already mentioned, a system of two apertures was placed after the first amplifier to improve its S/N ratio. The diameters of the

Fig.7 Schematic diagram of the amplification experiment of a semiconductor laser. LD is the laser diode, A's are the apertures, P is the polarizer and PMT is the photomultiplier tube.

apertures were 0.5 mm and 2 mm, respectively, and their separation was 158 cm. To further improve the S/N ratio, a diffraction grating having a grating constant of 1200 lines/mm was placed at a small distance after the aperture A_1 . The purpose of the grating was to disperse the wide-band ASE as much as possible, but which would have little effect on the narrow-band semiconductor laser beam, so that the noise can be reduced further by the aperture A_2 . The lens between the apertures focuses the semiconductor laser beam onto the second amplifier. A system of two more apertures was used after the second dye cell. The amplified kilowatt pulses from the second amplifier, even of several nanoseconds duration, can be seen by naked eye.

The performance of the two individual ampli-

Table I Characteristics of the amplifier system.

	1st Amp.	2nd Amp.	Overall System
Pumping Pulse Energy (6nsec, 523nm)	10 mJ	33 mJ	43 mJ
Net gain	220	1800	3.9×10^5
Output Power (peak)	1.3 W	2.3 kW	2.3 kW
S/N ratio	600	200	90

The net gain is defined as the ratio of the output through the second aperture to the input of the dye cell.

fiers and of the whole system is shown in Table I.

There are two reasons for the higher obtained value of S/N ratio for the first amplifier compared to the previous experiment performed with the dye oscillator: (1) The better spatial coherence of the semiconductor laser beam permit a higher value of η (in eq.13), and (2) the diffraction grating used between apertures A_1 and A_2 results in better discrimination of signal and ASE noise.

5. Conclusion

In conclusion, we can say that it is possible to obtain kilowatt giant pulses from a semiconductor laser with an acceptable S/N ratio by amplifying it with Q-switched YAG laser-pumped dye cells. To the best of our knowledge, this is the first instance where a semiconductor laser is amplified to kilowatt pulses by dye cell amplifiers.

It is possible to obtain laser light of high spectral purity (bandwidth < 100 MHz) by simply controlling the current of a laser diode. Therefore, we can easily obtain transform-limited giant pulses from a semiconductor laser by amplifying with dye cells.

We are planing to amplify mode-locked

picosecond pulses (having a peak power of a few tens of milliwatts) from a semiconductor laser by means of a YAG laser-pumped dye cell so that we can obtain picosecond giant pulses from a simple laser system. We believe that these pulses may enable us to perform a variety of experiments in the spectroscopy of ultrafast phenomena.

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