SEMICONDUCTOR LASER WITH EXTERNAL RESONATOR

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The power and directivity of coherent radiation are considerably enhanced by the use of a semiconductor laser with an active material in the form of a thin layer and an external resonator. The power and generation threshold in such a laser employing gallium arsenide pumped by an electron beam are investigated as functions of the active region diameter. A power of 900 ± 90 W and an efficiency of 25 ± 5% are obtained for a diameter of 0.21 mm and electron energy of 190 keV. A complex resonator with an external mirror significantly narrowed (down to 45′) the directivity pattern of laser emission.

INTRODUCTION

SEMICONDUCTOR lasers are known to have a relatively high efficiency and yet are inferior to other laser types in a number of fundamental emission parameters (generation power, directivity pattern, and spectral width). The output parameters of semiconductor lasers can be improved however by employing a resonator with active material in the form of a thin plane-parallel plate. Such a geometry, known as the "emitting mirror"[1-3], causes the generation to proceed in a direction normal to the plate surface. The output power can be increased by expanding the surface of the active material and reducing the role of volumetric losses; a selection among the off-axis and axial modes in the complex resonator can reduce the spectra width and narrow down the directivity pattern.

Nevertheless one of the most significant drawbacks of such a system is the decrease in population inversion because of the spontaneous emission gain along the active layer and the possible parasitic generation. For these reasons the plate must be divided into individual cells by opaque partitions; the cells can be regarded as independent generators capable of being synchronized by electromagnetic energy exchange, for example, achieved through diffraction at the common external mirror[4].

The present paper deals with an experimental investigation of the threshold and power characteristics of a single cell as functions of cell dimensions; the directivity pattern has been significantly improved by selecting off-axis modes with the external mirror.

THE EXPERIMENT

Figure 1 shows the experimental setup. The electron beam is generated by a Pierce gun whose cathode receives a negative pulse from a high-voltage pulse generator. The electron energy was varied from 50 to 200 keV. A magnetic lens was placed near the gun anode to prevent beam divergence. The beam was then passed into a turn magnet capable of turning the beam through 90°. Beyond the magnet the electrons were focused by a second magnetic lens onto the crystal surface. The focusing operation shortened the current pulse from 150 to 50 nsec.

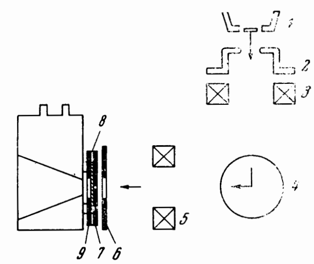


FIG. 1. The experimental setup: 1 – cathode; 2 – anode; 3 – first magnetic lens; 4 – turn magnet; 5 – second magnetic lens; 6 – current measuring diaphragm; 7 – diaphragm limiting excitation region; 8 – specimen; 9 – copper substrate.

Two diaphragms were placed in front of the crystal. The first diaphragm, about 1 mm in diameter, was used to measure the current density exciting the crystal. The diaphragm was coated on the beam side with cadmium sulfide powder which glowed in contact with the electron beam and thus provided a visual check of the beam uniformity within the limits of the diaphragm opening. The beam density distribution was checked for uniformity over the beam cross section by means of a small aperture (0.1 mm in diameter) at varying current densities and electron energies. We established that current density variation in the beam did not exceed 10% within the limits of several mm.

The second (removable) diaphragm was attached directly to the crystal. This diaphragm limited the crystal area that was excited by the electron beam. The specimen was a plane parallel plate 100 μ thick prepared by polishing an n-type gallium arsenide ingot having an electron concentration of 3×10^{18} cm^{-3} at 300°K. The plate was pressed against a copper substrate that was cooled with liquid nitrogen through sapphire fingers. A gold mirror with a reflection coefficient of 90% was sputtered on one side of the specimen while the other side was provided with a Fresnel reflector in one case and with a sputtered mirror with a reflection coefficient of 80% in another.

The generation threshold was determined by observing the near-field luminescence with an electron-optical converter. The threshold value obtained in this manner was compared with the value determined from the generation power as a function of exciting current density. These two threshold values coincided within the limits of experimental error. The generation power was determined with a specially calibrated FÉK-14 coaxial photocell. Current pulses and photocell pulses were observed with an S1-11 high-speed oscilloscope.

Figure 2 shows the threshold current density as a function of beam electron energy for various areas of the excited region. According to the figure the threshold current density increases with decreasing electron energy and with increasing diaphragm opening. When the Q of the resonator is improved by metallic coatings deposited on both sides ($r_1 = 0.9$ and $r_2 = 0.8$) the generation threshold decreases and the effect of cell dimensions (for cells below 0.5 mm) becomes less significant.

Figures 3 and 4 show the generation power amplitude as a function of pump current density (the case of electron energy of 150 keV is shown in Fig. 3 and that of 190 keV in Fig. 4). The maximum current density was 60 A/cm² in these experiments. According to computation the crystal heating does not exceed 15°K at the end of the passage of the pulse leading edge when the latter is 10 nsec long and the deviation of the mean temperature from the liquid nitrogen temperature does not exceed several degrees for a pulse repetition frequency of about 10 Hz. The maximum power was obtained with a cell 0.21 mm in diameter and amounted

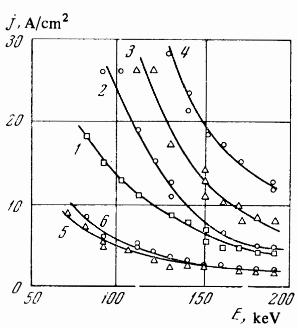


FIG. 2. Threshold current density as a function of voltage for cells of various sizes. Unilateral metal coating, aperture diameter: 1 – 0.085 mm; 2 – 0.21 mm; 3 – 0.37 mm; 4 – 0.48 mm; bilateral metal coating, aperture diameter: 5 – 0.21 mm; 6 – 0.48 mm.

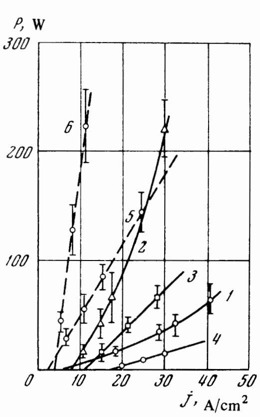


FIG. 3. Emission power as a function of current density for 150-keV electrons. Unilateral metal coating, aperture diameter: 1 – 0.085 mm; 2 – 0.21 mm; 3 – 0.37 mm; 4 – 0.48 mm; bilateral metal coating, aperture diameter: 5 – 0.21; 6 – 0.48 mm.

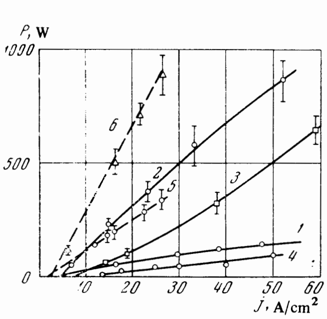


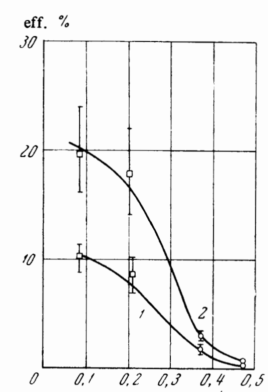
FIG. 4. Emission power as a function of current density for the case of 190-keV electrons. Unilateral metal coating, aperture diameter: 1 – 0.085 mm; 2 – 0.21 mm; 3 – 0.37 mm; 4 – 0.48 mm; bilateral metal coating, aperture diameter: 5 – 0.21 mm; 6 – 0.48 mm.

to 900 w with an accuracy of 10%. The energy flow density under these circumstances was 2.6 MW/cm².

The generation occurred at a wavelength of about 8220 Å. Near-field observation with a microscope revealed that in the case of a unilateral metallic coating and small apertures (0.085 mm and 0.21 mm) the generation region was approximately equal to the entire cell; when the cell 0.48 mm in diameter was used the generation region was about 0.16 mm in diameter. On the other hand in the case of a bilateral metallic coating the generation region in a 0.48 mm cell increased to 0.4 mm.

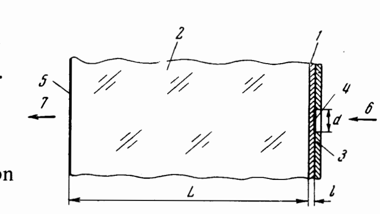
Figure 5 shows generation efficiency as a function of cell dimension when the pump power was three times the generation threshold for the case of $r_1 = 0.9$ and $r_2 = 0.3$. (We define efficiency as a ratio of power generated by the cell to the beam power expended to excite the cell). In this case the maximum value of efficiency (20 ± 4%) was observed for a maximum electron energy of 190 Kev and a minimum aperture of 0.085 mm. When the aperture is increased and electron energy decreased the efficiency drops rapidly and reaches 0.4 ± 0.1% for an electron energy of 150 keV and an aperture of 0.48 mm. In the case of a bilateral metallic coating and a 0.21 mm aperture the efficiency was somewhat lower but with the 0.48 mm aperture it increased 12.5 times in relation to the case without coating.

FIG. 5. Generation efficiency as a function of cell dimension. Unilateral metal coating, electron energy: 1 – 150 keV; 2 – 190 keV.



The semiconductor laser with a flat active layer allows for the use of an external mirror and thus makes it possible to reduce the beam divergence by the selection of off-axis modes. For this purpose the specimen was pressed against a plane parallel sapphire plate 5 mm thick (Fig. 6). The cell diameter was 0.48 mm. A metallic mirror with a reflection coefficient of about 80% was sputtered on the outside of the sapphire substrate; the mirror served as the external mirror of the complex resonator. Such a geometry provided a considerable reduction of the threshold current density. In particular when the electron energy was 180 keV

FIG. 6. Semiconductor laser with an external mirror. 1 – specimen; 2 – sapphire plate; 3 – diaphragm; 4 and 5 – metal mirrors; 6 – electron beam; 7 – optic emission (L = 5 mm, l = 0.1 mm, d = 0.48 mm).



without the sapphire plate the threshold current density was 13 A/cm^2 and it dropped to 3 A/cm^2 with the sapphire plate. At the same time the directivity diagram narrowed down considerably. If the divergence angle was 5–7° without the external mirror, when the mirror was present several concentric rings were observed in a plane perpendicular to the beam; practically the entire emitted energy was then concentrated in the center spot that was 3 mm in diameter at a distance of 220 mm from the crystal, corresponding to a divergence angle of about 45′. The distance between axial modes in the generation spectrum was the same as without the external mirror, i.e., it was determined by the distance between the surfaces of the thin part of the complex resonator.

DISCUSSION OF RESULTS

The experimental results show that an increase of cell dimensions causes a decrease in efficiency and increase of the threshold current density. In this connection we examine the amplification of spontaneous emission along the plate. The problem can be solved in principle for the two-dimensional case although there are considerable computational difficulties. We evaluate this effect using rate equations for the one dimensional case, following[5] for example.

Consider a rod of length l. Generation in the transverse direction requires a gain[2]

$$k = -\frac{\ln r_1 r_2}{2t_1} + \varkappa_1 + \frac{\varkappa_2 (t - t_1)}{t_1}, \qquad (1)$$

where r_1 and r_2 are reflection coefficients, t is the plate thickness, t_1 is the thickness of the active region, κ_1 is the volumetric loss coefficient in the active region, and κ_2 is the absorption coefficient in the passive region.

The system of velocity equations has the following form

$$\frac{dI_1}{dx} = [q(n - n_0) - \varkappa] I_1 + \gamma n \frac{1}{\tau}, \qquad (2)$$

$$-\frac{dI_2}{dx} = [q(n - n_0) - \varkappa] I_2 + \gamma n \frac{1}{\tau}$$

$$g = q(n - n_0)(I_1 + I_2) + n/\tau, \qquad (3)$$

where I_1 and I_2 are intensities of two light waves propagating right-to-left and left-to-right respectively, n is the excess electron (hole) concentration, κ is loss coefficient, τ is the spontaneous lifetime, γ is a coefficient specifying the fraction of spontaneous emission that is amplified, g is pair generation rate, and q and n_0 are the constants in the expression for gain $k = q(n - n_0)$, i.e., q is the stimulated emission cross section and n_0 is equal in order of magnitude to the degeneracy concentration.

When $n \gg n_0$, $k \gg \kappa$, and $\gamma = 1/2$ the system is readily solved analytically and we obtain an expression for the emission intensity and gain distributions where gain is expressed in terms of field intensities I_1 and I_2 (we assume that $I_1(0) = 0$, $I_2(l) = 0$, i.e., the reflection at the ends of the rod is considered absent):

$$k(x) = \frac{k_0}{\tau q [I_1(x) + I_2(x)] + 1} \qquad (3)$$

where k_0 is gain for $l \to 0$. The sum $I_1(x) + I_2(x)$ has a minimum in the center characterized by a simple relation between k and k_0:

$$k_{l/2} = k_0 / \sqrt{1 + k_0 l}. \qquad (4)$$

Figure 7 shows threshold current density as a function of electron energy determined from (4) and of the depth of electron penetration obtained from[6]. We see a good qualitative agreement between the analytical curves of Fig. 7 and the experimental curves of Fig. 2.

The quantity that characterizes the decrease of population inversion at the expense of amplification of spontaneous emission is kl, where k is the gain necessary to achieve generation in the transverse direction. Increasing electron energy (accompanied by an increasing length of the gain path) or increasing mirror reflection coefficient decreases k. In this case the generation threshold and efficiency depend significantly on cell dimensions only when the cell diameter is large.

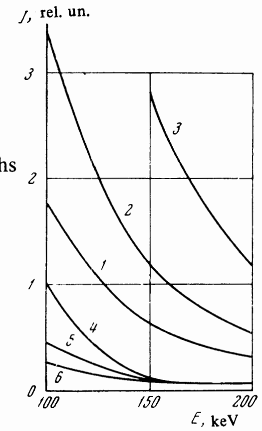


FIG. 7. Threshold current density as a function of voltage for various rod lengths (computed values). Unilateral metal coating (r_1 = 0.9, r_2 = 0.3), rod length: 1 – 0.1 mm; 2 – 0.2 mm; 3 – 0.5 mm. Bilateral metal coating (r_1 = 0.9, r_2 = 0.8), rod length: 4 – 0.5 mm; 5 – 0.2; 6 – 0.1 mm.

Figure 8 shows the computed gain distribution at the generation threshold for three cell sizes in the case of a unilateral metallic mirror. We see that when l = 0.05 mm (kl = 0.89) the gain is practically independent of the coordinate and when l = 0.5 mm (kl = 8.9) the gain drops off markedly towards the edges of the cell. These curves yield a qualitative explanation of the dependence of efficiency on cell size (Fig. 5) since in a large cell only the central region participates in generation and in a small cell almost all its surface is involved in generation.

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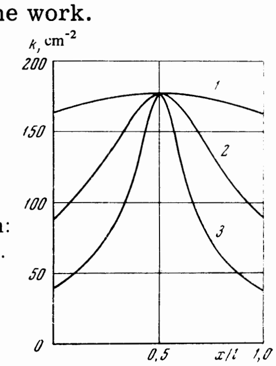

FIG. 8. Gain distribution at the generation threshold for three values of rod length (computed values). Reflection coefficients r_1 = 0.9, r_2 = 0.3, rod length: 1 – 0.05 mm; 2 – 0.2 mm; 3 – 0.5 mm.

[1] N. G. Basov and O. V. Bogdankevich, Symp. on Radiative Recombination in Semiconductors, Paris,

1964, p. 225.
[2]N. G. Basov, O. V. Bogdankevich, V. A. Goncharov, B. M. Lavrushin, and V. Yu. Sudzilovskiĭ, Dokl. Akad. Nauk SSSR **168**, 1283 (1966) [Sov. Phys.-Dokl. **11**, 522 (1966)].
[3]N. G. Basov, O. V. Bogdankevich, A. N. Pechenov, G. B. Abdullaev, G. A. Akhundov, and E. Yu. Salaev, Dokl. Akad. Nauk SSSR **161**, 1058 (1965) [Sov. Phys.-Dokl. **10**, 329 (1965)].
[4]N. G. Basov, E. M. Belenov, and V. S. Letokhov, Zh. Tekh. Fiz. **35**, 1098 (1965) [Sov. Phys.-Tech. Phys. **10**, 845 (1965)].
[5]V. N. Morozov, Opt. Spektrosk. **21**, 230 (1966).
[6]B. Ya. Yurkov, Zh. Tekh. Fiz. **28**, 1159 (1958) [Sov. Phys.-Tech. Phys. **3**, 1078 (1958).

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