Amplification of Millimeter-Wave Radiation by Stimulated Emission of Bremsstrahlung

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Amplification of millimeter-wave electromagnetic radiation within the cathode region of a cold-cathode glow discharge is reported. A model based on stimulated emission of bremsstrahlung is suggested.

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We report the observation of amplification of millimeter-wave radiation by stimulated emission of bremsstrahlung from the electrons in the cathode region of a cold-cathode glow discharge. This phenomenon can be applied for developing a new type of a tunable maser.

The discharge was formed in a glass tube, with an inside diameter of 20 mm, and with aluminum electrodes fixed 90 mm apart. An IMPATT oscillator produced 70 mW of electromagnetic radiation, at frequency of 70 GHz (wavelength 4.3 mm). This radiation was modulated at 833 Hz, and collimated with a lens into the discharge tube, so that the propagation wave vector was perpendicular to the tube axis. This radiation was collected by a horn, placed behind the glass tube, and measured by a crystal detector. The discharge tube was movable along its axis with respect to the incident electromagnetic radiation, to enable measurements at different regions of the discharge tube.

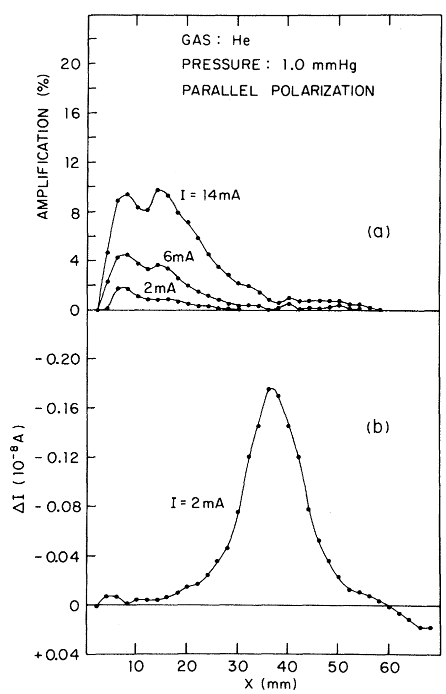

FIG. 1. (a) Amplification vs the distance X from the cathode. (b) Current change ΔI vs X.

We measured the variations in the intensity of the collected radiation as a function of the discharge current I. Also the small changes ΔI in the discharge current, caused by the incident electromagnetic radiation, were measured. These measurements were performed as a function of the distance X from the cathode to the irradiated region for two polarizations—electric field vector parallel and perpendicular to the tube axis.

Typical results for a He glow discharge, in the abnormal range, are presented in the figures. In every figure, part (a) describes the percent of amplification versus the distance X, for several values of discharge current. In part (b), the small current changes ΔI are plotted versus X, at a discharge current of $I = 2$ mA [negative changes (decrease in current) are drawn upwards]. Figure 1 contains the results at a pressure of 1.0 Torr with polarization parallel to the tube axis. Both amplification and discharge-current decrease persist up to the beginning of the positive column. The results at this pressure for perpendicular polarization are shown in Fig. 2. The results for both polarizations are similar, although the amplification for the perpendicular polarization is greater. As the pressure was increased to 6.0 Torr, the cathode regions contracted toward the cathode. For parallel polarization this contraction is seen in Fig. 3, but with no qualitative difference from the results at the lower pressure. However, for the perpendicular polarization a different behavior is found at higher pressure as described in Fig. 4; amplification becomes attenuation. At all pressures, polarizations, and distances from the cathode, the dependence of amplification on discharge current I was nearly linear, with a small increase beyond linearity at high currents. The results of measurements made for Ne were qualitatively simi-

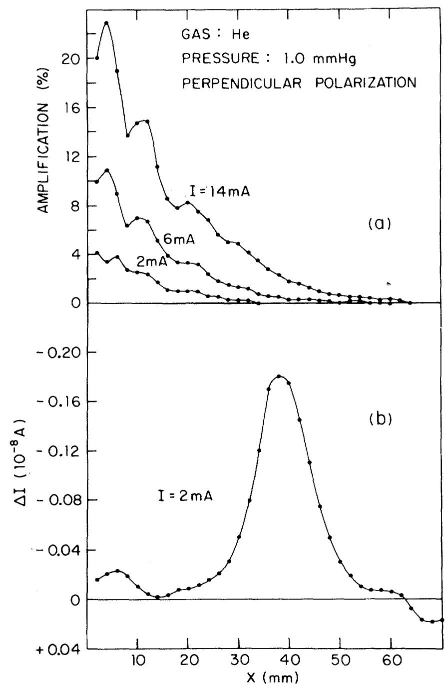

FIG. 2. (a) Amplification vs the distance X from the cathode. (b) Current change ΔI vs X.

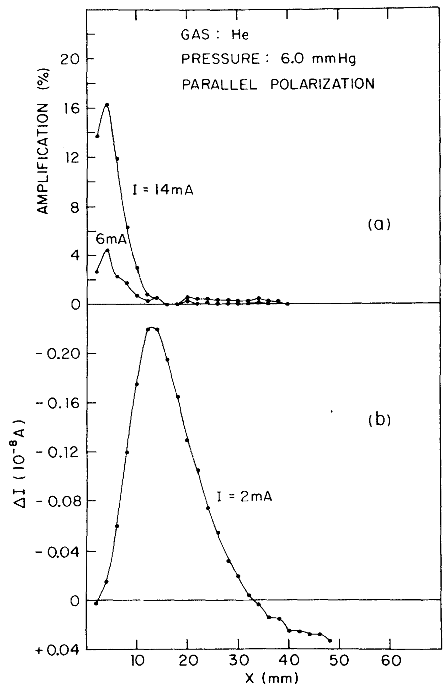

FIG. 3. (a) Amplification vs the distance X from the cathode. (b) Current change ΔI vs X.

lar to those obtained for He, but the amplification of the radiation for Ne was about twice as large.

Geller and Low[1] attributed the amplification at longer wavelengths to plasma oscillations. The experimental results reported here rule out this hypothesis. We propose a model based on stimulated emission in free-free transitions of electrons. As predicted by Kroll and Watson[2] and verified experimentally by Weingartshofer *et al.*,[3,4] a free electron scattered by an atom in the presence of a laser field may absorb or emit a number of photons. However, in their experiments a symmetry was found between emission and absorption, since they used a nearly monoenergetic electron beam. For plasmas with a Maxwellian distribution of electrons, energy is absorbed from the laser radiation.[5] But in the cathode region of a cold-cathode glow discharge, at the abnormal conditions, the electron distribution is not Maxwellian. The electrons emitted from the cathode are accelerated in the cathode fall region to energies of hundreds of electronvolts, within 1–2 mm. These electrons, making elastic and inelastic collisions, create in the negative glow and Faraday regions, a special distribution of electrons with an "inverted" population, i.e., more electrons are in the high-energy range. This distribution is anisotropic, with preference for the tube-axis direction. For such distributions of electrons, emission outweighs absorption and the electromagnetic radiation is amplified. The discharge current is also affected by the bremsstrahlung emission: When the electrons moving in the current direction lose energy to the radiation field, the discharge current decreases.

For a quantitative treatment we use the classical expression of Kroll and Watson.[2] This is justified since our experiments are made at very long wavelengths and of order one-hundred photons may be absorbed or emitted in a single electron-atom collision. Balancing emission and absorption rates, we obtain the following expression for the power absorbed in a unit volume:

$$\dot{W}=\frac{1}{m^2}n_e n_a\int d^3q_1\int d^3q_2\int_0^\pi \frac{d\alpha}{\pi}\left(\frac{e}{c}\,\vec{a}\cdot\vec{Q}\cos\alpha\right)\times\frac{d\sigma}{d\Omega}\left[f(\vec{q}_1)-f(\vec{q}_2)\right]\delta\left(q_2^{\,2}-q_1^{\,2}-2\frac{e}{c}\,\vec{a}\cdot\vec{Q}\cos\alpha\right), \qquad (1)$$

where m and e are the electron mass and charge, n_e and n_a are electron and atom number densities,

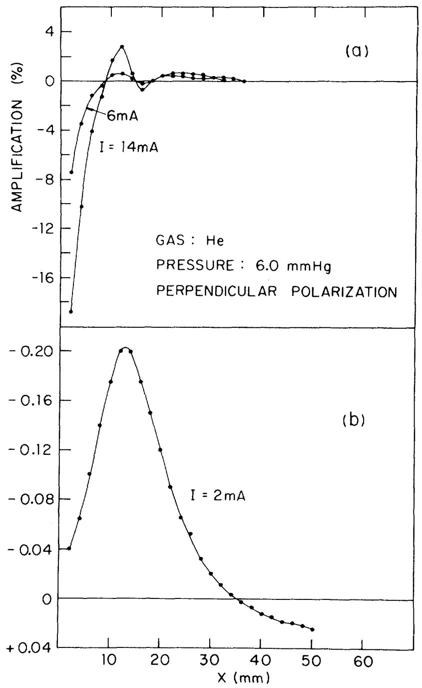

FIG. 4. (a) Amplification vs the distance X from the cathode. (b) Current change ΔI vs X.

$\vec{q}_1$ and $\vec{q}_2$ are electron momenta, $\vec{Q}=\vec{q}_1-\vec{q}_2$, $\vec{A}=\vec{a}\cos\alpha=\vec{a}\cos\omega t$ is the vector potential of the incident electromagnetic wave, $d\sigma/d\Omega$ is the collision cross section, and $f(\vec{q})$ is the electron distribution function normalized by $\int d^3q f(\vec{q})=1$.

A similar expression was used by Schlessinger and Wright[5] [Eqs. (3.1) and (3.6)] to calculate bremsstrahlung absorption in plasma with Maxwellian distribution of electrons. However, we assume $f(\vec{q})$ to be non-Maxwellian, inverted, and anisotropic. From Eq. (1) some general conclusions may be derived: (a) The linear dependence on n_e explains the linear dependence of the amplification on the discharge current. The small deviation from linearity follows from the small changes in cathode fall voltage as the current changes. (b) The dependence on $d\sigma/d\Omega$ explains why amplification for Ne is twice that for He. At electron energies above 20 eV, collision cross sections for Ne are about twice those of He.[6] (c) The dependence on polarization is expressed by the $\vec{a}\cdot\vec{Q}$ term, and the fact that $f(\vec{q})$ prefers the tube-axis direction.

Exact evaluation of Eq. (1) requires an exact knowledge of $f(\vec{q})$ and a lot of computer work. But to get a feeling of the effect we examined two kinds of simplified distributions, one isotropic and one anisotropic distribution. For the isotropic distribution we define the following variables: Θ_1 is the angle between $\vec{q}_1$ and $\vec{a}$; Θ is the angle between $\vec{q}_2$ and $\vec{q}_1$; $E_1=q_1^2/2m$ and $E_2=q_2^2/2m$ are electron energies. The electron distribution is expressed as a function of E:

$$f(E)=(2\pi)^{-1}(2m)^{-3/2}E^{-1/2}F(E), \tag{2}$$

where $F(E)$ is normalized by $\int_0^\infty F(E)dE=1$.

Since $|E_2-E_1|\ll E_1$, we expand $E_1^{-1/2}F(E_1)$ and $E_2^{-1/2}F(E_2)$ around $E=\frac{1}{2}(E_1+E_2)$ and obtain, after some calculations, the following expression:

$$\dot{W}=n_e n_a \frac{\pi}{3}8^{1/2}\left(\frac{e}{c}a\right)^2 m^{-3/2}\int_0^\pi d\Theta \sin\Theta(1-\cos\Theta)\int_0^\infty dE\,\frac{d\sigma}{d\Omega}(E,\Theta)E^2\frac{\partial}{\partial E}[E^{-1/2}F(E)], \tag{3}$$

Note that $\dot{W}$ is negative if $\partial/\partial E[E^{-1/2}F(E)]>0$ in the low-energy range, and $d\sigma/d\Omega$ decreases faster than $E^{-3/2}$ in the high-energy range, at least for large scattering angles. In He, $d\sigma/d\Omega$ decreases fast enough[7] and amplification can be achieved even for an isotropic distribution.

As an example for anisotropic distribution we examined

$$f(\vec{q})=\frac{\pi}{b}\exp[-b(q_y^2+q_z^2)]f(q_x), \tag{4}$$

where x is the tube axis direction and b is a parameter describing the width of the distribution in the perpendicular direction. $f(q_x)$ is supposed to be inverted for the lower range of q_x and vanishes below a certain value $q_{x,\min}$. In the approximation of forward scattering, we obtain, after some calculations, for parallel polarization

$$\dot{W}=-n_e n_a\frac{1}{m^2}\frac{\pi}{8}\int_{q_{x,\min}}^\infty dq_x\int_0^\infty dQQ^3\frac{1}{bq_x^4}\frac{df(q_x)}{dq_x}\left(\frac{e}{c}a\right)^2\frac{d\sigma}{d\Omega}, \tag{5}$$

and for perpendicular polarization (y direction)

$$\dot{W}=-n_e n_a\frac{1}{m^2}\frac{3\pi}{16}\int_{q_{x,\min}}^\infty dq_x\int_0^\infty dQQ^3\frac{1}{q_x^2}\frac{df(q_x)}{dq_x}\left(\frac{e}{c}a\right)^2\frac{d\sigma}{d\Omega}. \tag{6}$$

These equations show the reason for the differences between the two polarizations: The perpendicular polarization is much more sensitive to the shape of the distribution function than the parallel one. The parameter b in Eq. (5) becomes smaller for high pressures and compensates the decrease of population inversion.

In deriving Eqs. (5) and (6), large-angle electron scattering was neglected although these collisions contribute to amplification more than the small-angle scattering. However, these large-angle collisions are less important in evaluating the small current changes. This is one of the reasons why maximum amplification is closer to the cathode than the maximum of current decrease. Another reason is the recombination effect which is important in the negative glow region. The incident electromagnetic wave reduces the recombination rate between slow electrons and ions (Chen, Leiby, and Goldstein[8]), and this causes a current increase.

Application of the stimulated bremsstrahlung emission for developing a new type of a tunable maser seems quite promising, since it depends neither on relativistic electron beams nor on complicated magnetic fields as is the case in standard free-electron lasers.[9]

It is interesting to note that there was considerable disagreement concerning amplification in a plasma about twenty years ago, especially between Browne[10,11] and Twiss[12,13] over the possibility of maser action in space.

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Nonrandom Suprathermal Electron Emission in Resonance Absorption

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Evidence is reported for a nonrandom process by which laser-produced plasmas emit suprathermal electrons. Emission is dominated by a 1 to 2 psec monoenergetic burst, during which the electron energy decreases rapidly. The suprathermal tail on the energy distribution is due to the integrated temporal variation of the electron energy, not to statistical processes. The hot-electron temperature thus produced is practically independent of laser pulse energy.

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Hot-electron production in laser-produced plasmas is a crucial issue in laser fusion research. Electrons heated by "wave breaking" and resonance absorption (RA) have been predicted in computer simulations,[1] inferred from hard x-ray spectra,[2] and directly observed in gaseous targets.[3] They form a suprathermal tail, of temperature T_h, on the plasma electron energy distribution. In simulations,[1] kT_h is found to coincide with the wave-breaking energy, given by the well-known formula[4]

$$\mathcal{E}_{\mathrm{br}} = eE_d L_{\mathrm{br}}, \tag{1}$$

where E_d is the driving electric field, and L_{br} is the density-gradient scale length in the critical layer. But the mechanism by which long-mean-free-path electrons come to be emitted with a broad energy spectrum is still unclear. A recent suggestion[5] is that electrons are emitted in a monoenergetic burst every optical cycle, but that, because of the fluctuating phase of the driving field, $\mathcal{E}_{\mathrm{br}}$ fluctuates from cycle to cycle. Thus, after some time (many picoseconds, for $\lambda = 10.6$ μm), a broad spectrum is created. In this model, the plasma density structure is determined by the ponderomotive force of the laser light.

