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Invited

Lasers without Inversion in Microcavities

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The lasing characteristics of a microcavity laser with a high coupling efficiency of spontaneous emission into a lasing mode are studied. An output power, population inversion, spectral linewidth and intensity noise are calculated as a function of a pump rate. When a spontaneous emission coupling efficiency into a lasing mode is close to one, the lasing threshold characterized by the sharp increase in an output power, the clamping of population inversion, the decrease in a spectral linewidth and the peak of an intensity noise, is observed at a pump rate before a population inversion is created. Physical interpretation for lasing without inversion in a microcavity is given based on a photon recycling picture consisting of dissipation free stimulated emission and absorption.

In a conventional laser oscillator, most of spontaneous emission is coupled to nonlasing modes and does not contribute to laser oscillation. For instance, even a semiconductor laser with a relatively small cavity volume has the coupling efficiency of spontaneous emission into a single lasing mode of the order of 10^{-5}. That is, only one photon out of 10^5 spontaneously emitted photons is coupled into a lasing mode and serves as a *seed* for stimulated emission. For such a macrocavity laser, a threshold is usually defined by the condition that a stimulated emission gain being equal to a cavity loss. A population inversion is indispensible for oscillation. Generally speaking, any negative conductance oscillator must overcome a cavity loss by an effective gain enhanced by a positive feedback. On the other hand, coherent stimulated emission dominates over incoherent spontaneous emission if the photon number of a mode exceeds one due to Einstein's relation for the A and B coefficients. From this viewpoint, a laser threshold must be defined by the condition that the photon number in a lasing mode being equal to one. The above two definitions of a laser threshold coincide in a macroscopic laser with a negligible spontaneous emission coupling efficiency[1].

In a microcavity laser with an increased coupling efficiency of spontaneous emission and an inverted medium, the threshold can be decreased with increasing the coupling efficiency[2][3]. The two different threshold definitions give still identical results for this case[1]. On the other hand, in a microcavity laser with a noninverted medium, the photon number of a lasing mode exceeds one even though a population inversion is not created[1]. In this case, the two definitions for a laser threshold become different. In this letter, we demonstrate that the lasing characteristics are associated with one photon in a lasing mode rather than gain being equal to loss. In a sense, this is an example of *laser without inversion.* However, it is different from *laser without inversion* using the quantum mechanical interference between the two upper or lower levels [4][5], in which a medium has a net stimulated emission gain due to destructive interference for absorption. On the other hand, in the present case, a medium does not have a net stimulated emission gain.

The rate equations for the carrier density N and photon number p for a semiconductor laser can be written as

$$\frac{d}{dt}N = \frac{I}{qV} - \left(\frac{1-\beta}{\tau} + \frac{\beta}{\tau}\right) N - \frac{g}{V}p + \Gamma \quad , \qquad (1)$$

$$\frac{d}{dt}p = -(\gamma - g)p + \frac{\beta V N}{\tau} + F \quad . \qquad (2)$$

Here I is the injection current, q is the electron charge, V is the active volume, τ is the spontaneous emission lifetime. The net stimulated emission gain is assumed to be of the form

$$g = g'(N - N_0) \quad . \qquad (3)$$

N_0 is the carrier density at a transparency point where the stimulated emission and absorption rates are equal. From Einstein's relationship between the A and B coefficients, we get

$$g' = \frac{\beta V}{\tau} \quad . \tag{4}$$

That is, the spontaneous emission rate into the lasing mode is equal to the stimulated emission rate when the photon number of the lasing mode is one. Γ and F are the Langevin noise sources for the carrier density and photon number. The correlation functions of the noise terms are calculated by the fluctuation-dissipation theorem[6][7].

To find the steady state characteristics and noise properties of a microcavity laser, we separate the photon number and carrier density into a steady state value and a fluctuation term as: $p(t) = p + \Delta p(t)$ and $N(t) = N + \Delta N(t)$. Inserting these into the rate equations we get the steady state solution, plus a new set of linearized dynamic equations. The threshold current, defined by the condition that the net stimulated emission gain is equal to the loss, is given by

$$I_{th1} = \frac{q\gamma}{\beta}(1+\xi) \quad . \tag{5}$$

Here ξ is the photon number in the lasing mode when $N = N_0$ and given by

$$\xi = \frac{N_0 \beta V}{\gamma \tau} \quad . \tag{6}$$

On the other hand, the threshold current, defined by the condition that the mean photon number in the lasing mode is equal to one, is given by

$$I_{th2} = \frac{q\gamma}{2\beta}\left[1+\beta+\xi(1-\beta)\right] \quad . \tag{7}$$

The only case there is a substantial discrepancy between the two threshold definitions is when β is close to one and ξ is much greater than one. We are interested in this regime.

The mean photon number vs. the current is shown in Fig.1(a) as a function of β. There is a sharp increase in the photon number as soon as the photon number exceeds unity. This is one characteristic of a laser threshold. With increasing β, the point of the sharp intensity increase is decreased and once pinned at the current level where the carrier density N becomes N_0. A medium is not inverted at the current levels below this point. However, when a β value becomes close to one, the sharp increase in the photon number moves to below this point.

The mean carrier density vs. the current is shown in Fig.1(b) as a function of β. There is a sharp pinning in the carrier density at the threshold value. This is the other characteristic of a laser threshold. With increasing β, the point of the sharp carrier density pinning is decreased and once clamped at the current level where $N=N_0$. However, when a β value becomes close to one, the sharp carrier density clamping moves to below this point.

The second threshold current I_{th2} can properly describe such reduction of a laser threshold to a non-inverted region, while the first threshold current I_{th1} is pinned at the transparency point and cannot predict the results. The physics behind this novel phenomenon, lasers without inversion, is a photon recycling. When a β value is close to one and a ξ value is much greater than one, a photon emission process is dominated by the stimulated emission rather than the spontaneous emission even though a medium is not inverted. An emitted photon is absorbed rather than amplified in the medium, but such absorption is followed by the stimulated emission without loosing an energy. After the repetition of the stimulated emission and absorption, an injected electron comes out of a cavity as a coherent photon produced by the stimulated emission. Such photon recycling increases an effective carrier lifetime. This is why the carrier density is much higher for $\beta = 1$ than for $\beta \ll 1$ at a small current level.

To confirm the above conclusion, we also calculate the intensity noise and frequency noise (spectral linewidth). The low-frequency intensity noise spectral density normalized by the shot noise level vs. the current is shown in Fig.2(a) as a function of β. It is well known that the intensity noise is shot-noise-limited at the pump levels well below and well above the threshold [6][7] but that there is an excess noise peak at the threshold. The numerical results shown in Fig. 1(a) demonstrate that the excess noise peaks move to the current level where the inversion is not created. Those points for noise peaks coincide well with the second threshold current I_{th2}.

The spectral linewidth is calculated by using an equivalent circuit model [8] and the result is

$$\Delta\nu = \frac{1}{2\pi}\left(\gamma - \frac{\beta V}{\tau}(N - N_0)\right) \quad . \tag{8}$$

The spectral linewidth vs. the current is shown in Fig. 2(b) as a function of β. The decrease in the linewidth, i.e. the formation of a phase coherence is also the characteristic of a laser threshold. As shown in Fig. 2(b), the linewidth starts to decrease at the current level where the inversion is not created when $\beta \approx 1$. Those points for coherence formation also coincide well with the second threshold current I_{th2}.

In conclusion, we have demonstrated that a microcavity laser threshold can be decreased to the pump current levels where a population inversion is not created. A photon recycling consisting of the stimulated emission and absorption without energy loss eventually produces a coherent emission. In addition to a scientific interest of itself, it is expected to open a new possibility of coherent light wave generation at a wavelength region where a population inversion is hard to create.

References

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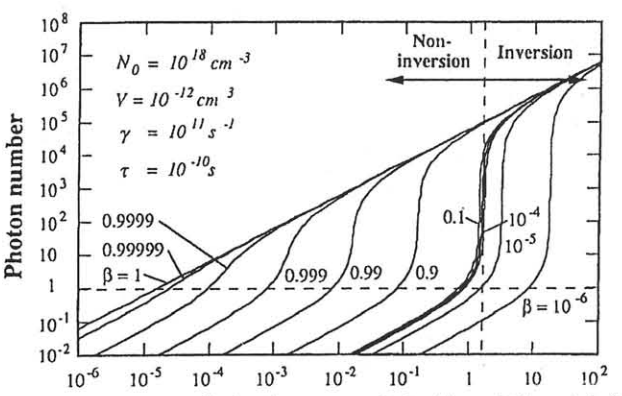

Fig. 1(a)

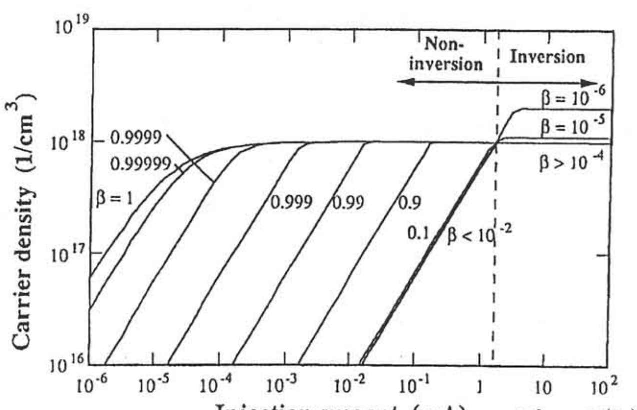

Fig. 1(b)

Fig.1 (a) The mean photon number in the lasing mode (left axis) and the corresponding output power (right axis) vs. the pump current. It is assumed $\xi = 10^3\beta$, so ξ is larger than unity for $\beta > 10^{-3}$. (b) The mean carrier density vs. the pump cuurent. It is assumed $N_0 = 10^{18}cm^{-3}$.

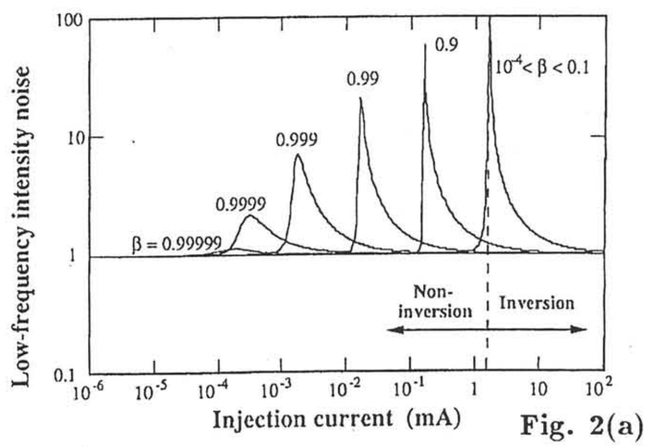

Fig. 2(a)

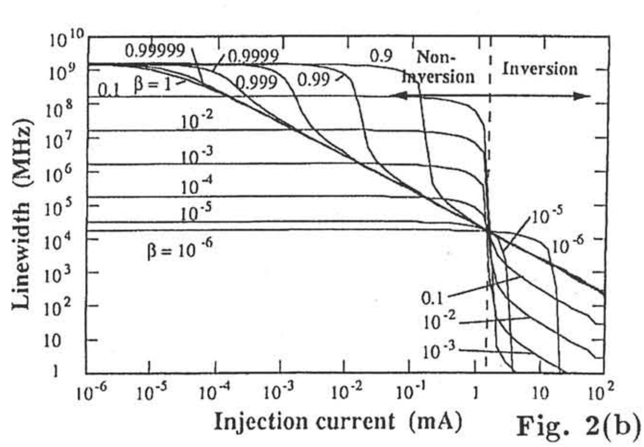

Fig. 2(b)

Fig.2 (a) The low-frequency intensity noise spectral density normalized by the shot noise level vs. the pump cuurent. (b) The spectral linewidth vs. the pump current.