SOVIET PHYSICS JETP VOLUME 29, NUMBER 4 OCTOBER, 1969

EFFECT OF A FREQUENCY FILTER ON THE EMISSION SPECTRUM OF SEMICONDUCTOR LASERS

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Submitted November 21, 1968

Zh. Eksp. Teor. Fiz. 56, 1412–1418 (April, 1969)

The effect of a nonsaturating frequency filter introduced into the feedback circuit of a semiconductor laser on the emission spectrum of the generator is considered for the purpose of obtaining single-mode operation. It is shown that excitation of the generator near the long-wave wing of the amplification coefficient by means of the filter can greatly increase the threshold for the excitation of a second mode relative to the excitation threshold of the first mode. Parameters are determined for a filter that can be used for increasing the single-mode radiation intensity 30–50 times by increasing the generation threshold 3 times. Various means of designing such generators on the basis of existing semiconductor lasers and optical filters are suggested.

UNTIL recently, relatively powerful emission of semiconductor lasers (SL) could be obtained only in the multimode regime. The neighboring axial modes are usually excited when the pump is increased beyond the generation threshold by several percent. Since the SL emission line is homogeneously broadened in a large energy interval, the excitation of several modes near the generation threshold is connected with different spatial inhomogeneities[1,2]. In an injection SL, for example, the inhomogeneity of the field in the plane of the p-n junction and the nonuniform gain in a direction perpendicular to the p-n junction leads to excitation of a second mode when the current is increased 5–10% beyond the threshold. The present article is devoted to a theoretical investigation of the possibility of increasing the emission intensity in a single-mode generation regime by introducing into the optical feedback circuit a frequency filter, the presence of which greatly decreases the influence of the spatial inhomogeneities on the excitation of the various modes.

As the model of the active medium of the SL, we use the ordinary band model of a strongly doped semiconductor with exponential "tail" of the state density for the electrons and with δ-like level for the holes[3]. The calculations presented pertain to a single spatial generation channel and are applicable for both injection SL and for SL with optical and electronic excitation.

Beyond the excitation threshold of the first mode, in that section of the active medium where the field of the first mode is small or equal to 0, the concentration of the electrons increases in proportion to the increase of the pump. The gain in this part of space increases, and as a result a second mode can become excited. The expression relating the current increment necessary to excite the second mode with the generator parameters is

$$\tfrac{1}{2}(\ddot{g}_i - \ddot{\alpha}_i)(\hbar\delta\omega)^2 + g_i' N\eta_E(\Delta J / J) = 0, \qquad (1)$$

where $g_i \equiv g(\omega_i)$ is the gain at the frequency ω_i, $\alpha_i \equiv \alpha(\omega_i)$ are the losses, $\dot{g} \equiv \partial g/\partial\hbar\omega$, $g' \equiv \partial g/\partial N$, $N = J\tau$ is the concentration of the electrons at the generation threshold. J is the threshold pump density. $J + \Delta J$ is the threshold of excitation of the second mode, $\delta\omega$—distance between modes, η_E—coefficient that depends on the space shift of fields of different modes, and also on the carrier diffusion coefficient. In the customarily employed linear approximation[2] ($N_\omega \sim \Delta J$, $n \sim \Delta J$, where n is the change of the electron density beyond the threshold), η_E does not depend on the pump density[1)].

The first term in (1) represents the loss that must be overcome in order to excite the second mode; the second term expresses the increase of the gain connected with the increase of the pump. In an SL the increase of the gain with increasing electron density depends strongly on the frequency (Fig. 1). A large change of the gain occurs in the short-wave region, where $g \lesssim 0$. Near the maximum, the gain increases less, but this increase suffices to excite the second mode at $\Delta J/J \approx 5\%$. Finally, in the low-frequency region the gain remains practically unchanged with increasing electron density. Consequently, if the generator is excited on the long-wave wing of the gain, it is possible to increase greatly the excitation threshold of the second mode relative to the excitation threshold of the first mode, i.e., it is possible to increase $\Delta J/J$. Indeed, although in this case the electron density increases in the same manner as in an ordinary laser, the gain responds little to the change of the electron density, and in accordance with (1) we can expect an appreciable increase of the radiation intensity in the first mode (N_ω) at the excitation threshold of the second mode ($N_\omega \sim \Delta J$).

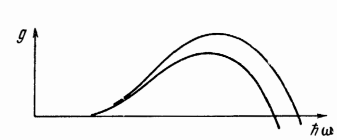

FIG. 1. Character of the increase of the gain with increasing electron density. The upper curve corresponds to a larger electron density.

[1)]For the shift of the antinodes and nodes of the neighboring axial modes [2] $\eta_E = [3 + 2(4\pi L/\lambda)^2]^{-1}$, where L is the ambipolar diffusion length and λ is the wavelength in the semiconductor.

In order to obtain generation on the long-wave wing of the gain, it is necessary to insert between the amplifying medium and the mirror a non-saturating filter. This filter should introduce large absorption in the short-wave region and should be transparent on the long-wave wing of the gain, it being desirable that the absorption coefficient increase more rapidly than the gain (Fig. 2). At other frequencies, the form of the absorption coefficient of the filter can be arbitrary. In particular, this can be both a band and a tuned filter. The filter absorption coefficient will be denoted by $\alpha(\omega)$. As seen from Fig. 2, generation on the long-wave wing of the gain is possible only as the result of the increase of the threshold pump, and the larger the threshold the weaker the dependence of the gain on the change of the electron density. An increase of the threshold leads to an increase of the working temperature of the generator. It is therefore necessary to take into account in the calculations the increase of the smearing of the electron energy distribution, and also to shift the filter to the long-wave region, since the width of the forbidden band of the semiconductor decreases with increasing temperature (Fig. 3).

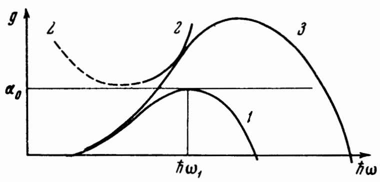

FIG. 2. Form of the gain of a generator without filter at the excitation threshold (curve 1), frequency dependence of the filter absorption coefficient (curve 2), and form of the gain of a generator with a filter at the excitation threshold (curve 3).

We shall consider below two generators. The first, a generator without a filter, has the following parameters: excitation threshold of the first mode J_1, frequency of the first mode ω_1 (Fig. 3), absorption α_0, excitation threshold of second mode $J_1 + \Delta J_1$, temperature at the excitation threshold of the second mode T_1. analogous parameters of the second generator (with the filter) will be denoted J_2^*, ω_2, $\alpha_0 + \gamma\alpha_2$ (Fig. 3); $\gamma = L_\alpha / L_g$ is the ratio of the length of the filter to the generator length), $J_2^* + \Delta J_2$, and T_2. If the filter is characterized by a transparency $S(\omega)$, it is necessary to replace $\gamma_\alpha(\omega)$ throughout by $[-\ln S(\omega)]/L_g$.

The threshold J_2 corresponds to a constant temperature T_2, which depends on the total pump $J_2^* + \Delta J_2$. Actually, the excitation threshold of the first mode of the generator with the filter J_2 is larger than J_2^*, for when the current increases the temperature increases, the width of the forbidden band decreases, and by virtue of the necessary condition that the gain and loss be equal, the Fermi quasilevel of the electrons (ζ) shifts with increasing current towards the lower energies ($\zeta_2 + \Delta\zeta_2$, ζ_2, Fig. 3). However, relation (1) contains the quantities J_2^* and ΔJ_2, for when $T = T_2$ the pump density J_2^* determines the electron density level $N_2^* = J_2^*\tau$, which ensures equality of the gain and loss at the frequency ω_2, namely $g(\omega_2, N_2^*) = \alpha_0 + \gamma\alpha(\omega_2)$. The radiation density in the first mode N_{ω_2} is proportional to ΔJ_2. Wherever the field of the first mode is small or equals zero, the concentration of the electrons also increases in proportion to ΔJ_2.

The parameters of both generations are determined by the system of equations

$$g_1 = \alpha_0, \quad \dot{g}_1 = 0, \quad g_2 = \alpha_0 + \gamma\alpha_2, \quad \dot{g}_2 = \gamma\dot{\alpha}_2. \tag{2}$$

We can use for the gain the expression obtained in[4]:

$$g = K(\omega)\,\mathrm{th}\,u(\omega, N),$$
$$K(\omega) = K_0 \exp\left(\frac{\hbar\omega - \Delta_a}{\varepsilon_0}\right), \quad u = \frac{\Delta_a - \hbar\omega}{2kT} + \xi \ln\left[\frac{N}{N(\varepsilon_0, kT)}\right], \tag{3}$$

where $N(\epsilon_0, kT) = \rho_0\epsilon_0\xi \sinh \xi^{-1}$, $\xi = \epsilon_0/2kT$, K_0 is a factor that depends little on the frequency, ϵ_0 is the parameter of the density of states of the electrons, Δ_a is the energy interval between the acceptor level and the arbitrary edge of the conduction band, from which the electron energy ϵ_e is reckoned, ρ_0 is the density of the states of the electrons at $\epsilon_e = 0$, and the probability of filling the acceptor level equals $1/2$[3].

The solution of the system of equations (2) can be written in the form

$$\frac{\hbar\Delta\omega}{\varepsilon_0} = \sigma\frac{\Delta T}{\xi_1 T_1} + \ln\left[\frac{v_1}{v_2}\left(1 + \frac{\gamma\alpha_2}{\alpha_0}\right)\right], \tag{4}$$

$$\frac{J_2^*}{J_1} = \left(1 + \frac{\gamma\alpha_2}{\alpha_0}\right)\frac{v_1}{v_2}\left(\frac{1 - v_1}{1 + v_1}\right)^{1/2\xi_1}\left(\frac{1 + v_2}{1 - v_2}\right)^{1/2\xi_1 + \Delta T/T_1}; \tag{5}$$

$$v_1 = \frac{\sqrt{1 + 4\xi_1^2} - 1}{2\xi_1}, \quad v_2 = \frac{\sqrt{1 + 4\tilde{\xi}_2^2} - 1}{2\tilde{\xi}_2},$$
$$\tilde{\xi}_2 = \xi_2 \frac{\alpha_0 + \gamma\alpha_2}{\alpha_0 - \gamma(\dot{\alpha}_2\varepsilon_0 - \alpha_2)}. \tag{6}$$

where $\Delta\omega = \omega_2 - \omega_1$, $\Delta T = T_2 - T_1$, $\sigma = \partial\Delta_a/\partial 2kT$. In order to calculate the ratio J_2^*/J_1 it is necessary to specify the quantities $\gamma\alpha_2/\alpha_0$, $\gamma\alpha_2\epsilon_0/\alpha_0$ and $\Delta T/T_1$. It is then possible to determine from (4) the frequency at which the filter absorption should be equal to α_2, i.e., to find the position of the filter on the wavelength scale. The conditions under which the chosen value of $\Delta T/T_1$ can be realized can be determined after the total value of the pump $J_2^* + \Delta J_2$ is determined.

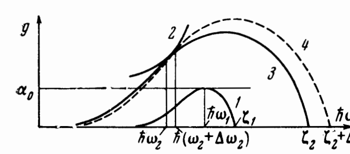

FIG. 3. Gain of a generator without filter at the excitation threshold (curve 1); total absorption coefficient $\alpha_0 + \gamma\alpha(\omega)$ (curve 2); gain of generator with filter, averaged over the spatial distribution of the field of the first mode at the excitation threshold of the second mode (curve 3); gain of generator with filter at the excitation threshold of the first mode (curve 4).

From the system (1) ($i = 1, 2$), the system (2), and expression (3) we can find the ratio $\Delta J_2/\Delta J_1$, which determines the increase of the radiation intensity in the first mode at the excitation threshold of the second mode, due to the introduction of the filter:

$$\frac{\Delta J_2}{\Delta J_1} = A\,\frac{\gamma(\ddot{\alpha}_2\varepsilon_0 - \dot{\alpha}_2)\varepsilon_0 + (1 + 2\xi_2 v_2)(\alpha_0 + \gamma\alpha_2 - \dot{\gamma}\alpha_2\varepsilon_0)}{\alpha_0\sqrt{1 + 4\xi_1^2}}$$

$$\times \frac{\alpha_0}{\alpha_0 - \gamma(\alpha_2\varepsilon_0 - \alpha_2)} \frac{J_2^*}{J_1}; \tag{7}$$

here $A = (\delta\omega_2/\delta\omega_1)^2 (\eta E_1/\eta E_2)$, the second factor is the ratio of the second derivatives with respect to the frequency: $(\gamma\ddot{\alpha}_2 - \ddot{g}_2)/\ddot{g}_1$; the saturation of the gain in the long-wave wing of the gain is represented by the third factor. By selecting the parameters $\gamma\alpha_2/\alpha_0$ and $\gamma\alpha_2\epsilon_0$ it is possible to make this saturation very large. It is necessary for this purpose to have $\gamma(\alpha_2\epsilon_0 - \alpha_2) \to \alpha_0$. However, as follows from (5) and (6), such a deep saturation of the gain is possible only when $J_2/J_1 \to \infty$, which is in full agreement with the qualitative arguments presented above. When $[\alpha_0 - \gamma(\alpha_2\epsilon_0 - \alpha_2)] \ll \alpha_0$, we have

$$\Delta J_2/\Delta J_1 \sim (J_2^*/J_1)^t, \tag{8}$$

where

$$t = 1 + 2\xi_1/[1 + 2\xi_1(\Delta T/T_1)]. \tag{9}$$

An increase of the threshold of the excitation of the second mode relative to the excitation threshold of the first mode can be obtained also by increasing the frequency-independent loss. Indeed, it follows from (6) and (7) that when α = const we get $\Delta J_2/\Delta J_1 = J_2^*/J_1$. This is reflected in the first term of (9). The second term in this formula is connected with the saturation of the long-wave edge of the gain. An increase of the temperature with increasing current leads to an undesirable decrease of the parameter t.

The excitation of the first mode in a generator with a filter occurs at a pump density $J_2 = N_2/\tau$, a temperature $T_2 - \Delta T_2$, and a frequency $\omega_2 + \Delta\omega_2$. The quantities $\delta J_2 = J_2^* + \Delta J_2) - J_2$ and $\hbar\Delta\omega_2/\epsilon_0$ can be obtained from the system of equations (2):

$$\delta J_2 = \Delta J_2 \left[1 - \frac{\sigma}{\xi_1} \frac{\gamma\dot{\alpha}_2\varepsilon_0}{\alpha_0 - \gamma(\alpha_2\varepsilon_0 - \dot{\alpha}_2)} f(T_2)\right]^{-1}, \tag{10}$$

$$\frac{\hbar\Delta\omega_2}{\varepsilon_0} = -2\sigma\frac{\dot{\alpha}_2}{\alpha_2\varepsilon_0 - \dot{\alpha}_2} f(T_2)\frac{\delta J_2}{J_2^*}, \tag{11}$$

where $f(T_2)$ is a coefficient relating the change of the temperature with the change of the current: $\Delta T_2/T_2 = f(T_2)(\delta J_2/J_2^*)$. Formulas (10) and (11) were obtained in the following approximation: $g(\omega, N_2) = g(\omega, N_2^*) + g'(\omega, N_2^*)(N_2 - N_2^*)$, $\Delta T_2 \ll T_2$, and $\hbar\Delta\omega_2 \ll \epsilon_0$. The least exact is the first of these conditions, for when $\Delta J_2 \gg \Delta J_2$ the quantities $(N_2 - N_2^*)g''$ and g' can be of the same order. Therefore formula (10) is inexact. However, this formula represents qualitatively correctly the influence of the change of the width of the forbidden band with increasing temperature on the threshold pump of a generator with a filter.

The dependence of the temperature on the current density in an injection laser operating in the cw mode can be calculated with the aid of the differential relation[5]:

$$\varkappa(T)\,dT = lU[1 - \eta(j)]\,dj, \tag{12}$$

where κ is the thermal conductivity, j the current density, U the p-n junction voltage, η the differential efficiency of the generator, and l the distance between the cold finger and the p-n junction. In particular, in formula (10) we have

$$f(T_2) = \frac{j_1 U(1-\eta)l}{T_2\varkappa(T_2)} \frac{J_2^*}{J_1}. \tag{13}$$

To calculate the temperature change connected with the large increase of the pump density, it is necessary to integrate (12) between suitable limits. It can be assumed here that up to the excitation threshold ($J < J_1$ or $J < J_2^*$) we have $\eta = \eta_1 \ll 1$, and beyond the excitation threshold ($J > J_1$ or $J > J_2^*$) we have $\eta = \eta_2$, where η_1 and η_2 do not depend on the current. The integral

$$\theta = \int_0^T \varkappa(T)\,dT$$

is tabulated in[5]. In the pulsed regime, the temperature change can be decreased by shortening the pulse or by increasing the off-duty cycle.

By way of an example we present the calculation of the parameters of a generator with a filter, having an exponential absorption edge: $\alpha(\omega) = \alpha_2 \exp[\hbar(\omega - \omega_2)/\epsilon_0']$. The larger the parameter $p = \epsilon_0/\epsilon_0'$, the more effective the filter. One cannot count, however, on being able to select a filter with $p \gtrsim 5$. Therefore settle on p = 4. We assume that the resonator length is not changed by the introduction of the filter: A = 1. The temperature T_0 of a cold finger is assumed to be 77°K. Accordingly, $\sigma = -1.1$. We assume further $\xi_1 = 1$ (ϵ_0 = 14 meV), η_1 = 7%, and η_2 = 30%. The parameter $\gamma\alpha_2/\alpha_0$ is chosen such that $J_2^*/J_1 = 3$. Using then this value of $\gamma\alpha_2/\alpha_0$ in formulas (5)–(7), (10)–(13), we calculate $\Delta J_2/\Delta J_1$, $\hbar\Delta\omega/\epsilon_0$, and other parameters of the generator with the filter. Since the temperature rise is connected principally with the threshold pump, it was assumed in the calculation of the temperature T_2, to simplify the calculation, that $\Delta J_2 = J_1$. In the case $\Delta T/T_1 = 0.1$ this corresponds to $\Delta J_1/J_1 \approx 3\%$.

The results of the calculation of these quantities for several values of $\Delta T/T_1$ are listed in the table. The increase of the intensity of the single-mode radiation that emerges to the outside (P) is

$$\frac{P_2}{P_1} = \frac{\Delta J_2}{\Delta J_1}\left(1 + \frac{\gamma\alpha_2}{\alpha_0}\right)^{-1}.$$

To obtain maximum power of single-mode radiation from one end of the generator, it is necessary to insert behind the filter a completely-reflecting mirror. The quantity $P_2/P_1 \geq \Delta J_2/\Delta J_1$ if $\gamma\alpha_2 L_g \leq -\ln\sqrt{r}$ (or $S(\omega_2) \geq \sqrt{r}$) where r is the reflection coefficient at the end face of the generator.

The numbers in the column $j_1 l$ impose requirements on the initial generator without the filter. Thus, for example, $j_1 l$ = 6 a/cm denotes that the increase of the temperature $\Delta T/T_1 = 0.1$ at $J_2^*/J_1 = 3$ takes place when l = 60 μ and $j_1 = 10^3$ a/cm². Such values of j_1 and l correspond to modern injection lasers operating in the continuous regime. To establish the lower limit of the values of the parameter p, at which introduction of the filter leads to positive results, it is necessary to investigate the proportionality coefficient in formula (8). This coefficient contains the factor $\varphi(p) = p^{1-t}(p-1)^t$. When $p \lesssim t$, the quantity $\varphi(p)$ is small, and when

$\Delta T/T_1$	$\gamma\alpha_2/\alpha_0$	$\hbar\Delta\omega/\varepsilon_0$	$\Delta J_2/\Delta J_1$	T_2, °K	$j_1 l$, A/cm
0	0.3	−0.17	48	77	—
0.1	0.28	−0.27	32	88	6
0.2	0.25	−0.36	20	98	10
0.5	0.17	−0.56	9	130	20

$p > t$ we have $\varphi(p) \sim p - t$. We thus find that at $\Delta T/T_1 = 0.1$ it is desirable to have $p > 3$.

Let us determine the contribution made to the increase of the single-mode generation power by a change in the difference of the losses at the neighboring modes and the gain saturation (the second and third factors in (7), respectively). When a filter with the parameters indicated above was introduced, when $J_2^*/J_1 = 3$ and $\Delta T/T_1 = 0.1$, the loss difference at the neighboring frequencies increases by a factor 1.7 and the change of the gain with increasing electron density decreases by 6.3 times. Thus, the main contribution to the increase of the power of the single-mode generation is made by the saturation of the gain.

The inaccuracy of the foregoing calculations is connected principally with the linearization of the gain with respect to N in formula (1). Since $g_2'' < 0$, the corresponding corrections should improve the results. To construct the generator described above, it is necessary to have a non-saturating filter, so that when a semiconductor filter is used, the generator radiation must not saturate its absorption. At the same time, the dependence of the absorption coefficient of the filter on the frequency should be sufficiently steep: $\alpha\epsilon_0 > \alpha$, $\alpha > 0$. The need for simultaneously satisfying these two conditions determines the choice of the suitable material. In the region of strong absorption ($\alpha \sim 10^2$–10^3 cm^{-1}), where the filter is not saturated by the SL radiation, many semiconductors have an exponential

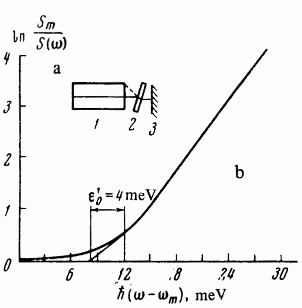

FIG. 4. a—diagram and ray paths of a generator with an interference filter: 1—SL with an end face made transparent on the filter side, 2—interference filter, 3—totally reflecting mirror. b—dependence of relative transparency of the double band interference filter on the detuning energy.

frequency dependence of absorption. For example, in the case of GaAs at $\alpha \sim 10^3$ cm^{-1} ($\hbar\omega_0 \approx 1.56$ eV), the quantity $\epsilon_0' = 4$–5 meV[6]. At the frequency corresponding to $\hbar\omega = 1.56$ eV, the initial generator can be tuned by varying the composition of the semiconductor used in its construction. When $\gamma\alpha_2/\alpha_0 = 0.3$, $\alpha_0 = 100$ cm^{-1}, and $\alpha_2 = 10^3$ cm^{-1}, we have $\gamma = 0.03$; when $\epsilon_0' = 4$ meV and $\epsilon_0 = 14$ meV, we have $p = 3.5$.

Figure 4a shows the diagram of a generator with an interference filter. Figure 4b shows a plot of the logarithm of the relative transparency of a double band filter[7] on the energy $\hbar(\omega - \omega_m)$, where ω_m is the frequency corresponding to the maximum transparency S_m. The width of the transmission band of this filter $\Delta\lambda$ amounts to 180 Å, the maximum transmission is $S_m = 30\%$[7]. Since $S_m \neq 1$, the filter introduces additional losses, $(-\ln S_m)/L_g$, which are partly compensated by the completely reflecting mirror: $\frac{1}{2}\ln r$. Thus,

$$\gamma\alpha(\omega) = \Delta\alpha_0 + \frac{\ln[S_m/S(\omega)]}{L_g},$$

where $\Delta\alpha_0 \sim \ln(\sqrt{r}/S_m)$. When $r = 0.3$ and $S_m = 0.3$, we have $\Delta\alpha_0 > 0$, leading to an additional increase of the threshold. It is advisable to use this filter in the energy region $\hbar(\omega_2 - \omega_m) \approx 12$ meV, where $\ln[S_m/S(\omega)] \approx \exp[\hbar(\omega - \omega_2)/\epsilon_0']$ with $\epsilon_0' = 4$ meV, and $\ln[S_m/S(\omega_2)] = \frac{1}{2}$. In this case $p = 3.3$–4.3 ($\Delta\lambda = 150$–200 Å, $\epsilon_0 = 14$ meV), and $\gamma\alpha_2/\alpha_0 = 0.25$ at $L = 200\ \mu$ and $\alpha_0 = 100$ cm^{-1} (the loss $\Delta\alpha_0$ is included in the loss of the generator without the filter).

Thus, on the basis of the presently existing SL and optical filters it is possible to construct a generator with a single-mode emission intensity larger by 30–50 times than that of a generator without a filter (at $J_2^*/J_1 = 3$). More effective and structurally simpler would be a generator with multilayer interference mirrors having the same frequency dependence of the reflection coefficient as $S(\omega)$ sputtered on the end surface.

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Translated by J. G. Adashko
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