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Abstract

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DIFFRACTION SYNCHRONIZATION OF OPTICAL QUANTUM GENERATORS

1. Semiconductor quantum generators with electronic [1,2] or optical [2,3] excitation use a small volume of semiconductor. Further increase of the semiconductor size in the direction of generation is disadvantageous, since it leads to a reduction in efficiency due to the growth of losses in the substance. More advantageous, in our opinion, is a quantum generator with "emitting mirrors," in which the semiconductor layer is deposited directly on the mirrors of the resonator. In this case, however, parasitic generation arises in the plane of the layer, and not on the external mirrors. To suppress this effect the semiconductor layer can be divided by absorbing partitions into separate isolated elements. Under certain conditions, owing to the diffraction coupling of neighboring elements by the electromagnetic field, a regime of synchronized generation of radiation by all elements of the semiconductor is possible. Practically the most desirable is the regime of synchronized generation of the fundamental oscillation type TEM_{00}, in which the beam divergence is minimal and is determined by the entire size of the "emitting" mirror. Below we consider the conditions for the existence of such a regime. Although the case of synchronization of two quantum generators is considered, the results obtained are of a more general character. A successive solution of the problem must include, first, calculation of the coefficient of diffraction coupling of open resonators and, second, determination of the conditions for stability of the synchronized regime.

2. Let us consider two identical adjacent resonators made of plane mirrors. Owing to diffraction at the mirrors, the resonators exchange electromagnetic energy. Such exchange may either decrease or increase the losses of the system of two resonators, depending on the phase relations between the field in each resonator and the field diffracted from the neighboring resonator.

We shall denote the types of oscillations of one resonator by the superscript (0) $\left(\mathrm{TEM}_{m0}^{(0)}\right)$, and the types of oscillations of the coupled resonator by the superscript (c) $\left(\mathrm{TEM}_{m0}^{(c)}\right)$.* In this notation, as the distance between the resonators is increased, the $\mathrm{TEM}_{00}^{(c)}$ type of oscillations passes into the $\mathrm{TEM}_{00}^{(0)}$ oscillation types that are in phase; the $\mathrm{TEM}_{10}^{(c)}$ type of oscillations passes into the $\mathrm{TEM}_{00}^{(0)}$ oscillation types that are in antiphase, etc.

Let us define the coefficient Γ_m of diffraction coupling of two open resonators for the $TEM_{m0}^{(c)}$ type of oscillations as the difference between the diffraction power losses per transit for the $TEM_{m0}^{(c)}$ type of oscillations and for the $TEM_{k0}^{(0)}$ types of oscillations into which the $TEM_{m0}^{(c)}$ type of oscillations decomposes when the resonators are infinitely separated, i.e., $\Gamma_m = \Gamma_m^{(c)} - \Gamma_k^{(0)}$ ($k = 0$ for $m = 0, 1$). The diffraction losses $\Gamma_k^{(0)}$ of one open resonator were found numerically by Fox and Li [4] for the lower types of oscillations and, in general form, by L. A. Vainshtein [5] for all types of oscillations. Therefore, to calculate the coefficient of diffraction coupling it is sufficient to find the losses of the cou-

* For simplicity the mirrors are taken in the form of infinite strips.

of a coupled resonator. In the problem of synchronized generation for practically useful types of oscillations, it is sufficient to restrict the consideration only to the even $TEM_{00}^{(c)}$ and odd $TEM_{10}^{(c)}$ types of oscillations.

For the calculation we used the numerical Fox-Li method, based on Huygens' principle.

Figure 1 gives the results of calculations of the losses of the $TEM_{00}^{(c)}$ and $TEM_{10}^{(c)}$ types of oscillations as a function of the distance between resonators*. For comparison, the value (dotted curve) of the losses $\Gamma_0^{(0)}$ of an isolated resonator is given. We restricted ourselves to the case of Fresnel number $N = 2.5$, since this case is close to "optimal" for diffraction synchronization: the effective losses are not too large, while the magnitude of the diffraction-coupling coefficient is sufficient for synchronization of real quantum generators. From Fig. 1 one can see the change in sign of the diffraction-coupling coefficients Γ_0 and Γ_1 as the resonators are moved apart. In the region of negative values of the diffraction-coupling coefficient, the losses of the coupled resonator are smaller than the losses of the isolated resonator. In this region a synchronized generation regime of either even or odd types of oscillations is energetically favorable.

We proceed to an investigation of the stability of the synchronized generation regime.

Fig. 1. Dependence of the diffraction losses of the $TEM_{00}^{(c)}$ and $TEM_{10}^{(c)}$ types of oscillations of a coupled resonator on the distance $2d$ between resonators with mirrors in the form of infinite strips of width a. The Fresnel number for one isolated resonator is $N_0 = (a/2)^2/L\lambda = 0.62$, and for the coupled resonator at $d = 0$, $N = a^2/L\lambda = 2.5$, where L is the distance between mirrors, λ is the wavelength. $\Gamma_0^{(0)}$ $-TEM_{00}^{(0)}$; $\Gamma_0^{(c)}$ $-TEM_{00}^{(c)}$; $\Gamma_1^{(c)}$ $-TEM_{10}^{(c)}$

3. The general equations describing the dipole interaction of the electromagnetic field of a resonator with an active medium were obtained in works [6,7]. For two optical quantum generators exchanging electromagnetic field because of diffraction, these equations give:

$$\ddot{E}_1 + \frac{\omega_1}{Q_0}\dot{E}_1 + \omega_0\alpha_m\dot{E}_2 + \omega_1^2 E_1 = -4\pi\ddot{P}_1,$$

$$\ddot{E}_2 + \frac{\omega_2}{Q_0}\dot{E}_2 + \omega_0\alpha_m\dot{E}_1 + \omega_2^2 E_2 = -4\pi\ddot{P}_2,$$

$$\ddot{P}_i + \frac{2}{T_2}\dot{P}_i + \omega_0^2 P_i = -2\frac{\omega_0|\mu_0|^2}{\hbar}N_{iE}i, \tag{1}$$

$$\dot{N}_i + \frac{1}{T_1}(N_i - N_{0i}) = \frac{2}{\hbar\omega_0}E_i\dot{P}_i,$$

where the indices $i = 1, 2$ refer, respectively, to the first and second generator; E_i is the electric-field intensity in the generator; Q_0 is the Q-factor of the isolated resonator ($Q_0 = Q_1 = Q_2$), depending on the reflection of the mirrors and on the magnitude of the diffraction losses $\Gamma_0^{(0)}$; ω_0 is the frequency of the working transition; ω_i is the natural frequency of the resonator, which is assumed close to ω_0; P_i is the polarization of the active substance in the resonator; T_2 is the polarization relaxation time; μ_0 is the matrix element of the dipole moment of the particle; N_i is the density of active particles in the resonator; N_{0i} is the influx of active particles, determined by the pumping, which we assume identical for the generators, $N_{0i} = N_0$; T_1 is the lifetime of the active particle

* The distance between the resonators is, of course, much greater than the wavelength.

in the excited state; the parameter a_m is related to the diffraction-coupling coefficient introduced above by the relation

$$a_m = \frac{\lambda}{2\pi L}\Gamma_m, \tag{2}$$

where L is the distance between the resonator mirrors; λ is the wavelength of the radiation. Practically always $|a_m| \ll 1$, since $|\Gamma_m| < 1$. Let us introduce the notation

$$t \to \omega_0 t; \qquad x_i = \frac{\mu_0 T_2}{\hbar}E_i; \qquad v_i = \frac{P_i}{\mu_0 N_0}; \qquad w_i = -2\frac{N_i}{N_{0i}};$$

$$\gamma = \frac{4\pi|\mu_0|^2 T_2}{\hbar}N_0; \qquad \delta = \frac{2}{T_1\omega_0}; \qquad \mu = \frac{1}{Q_0}; \qquad \varepsilon_i = \left(\frac{\omega_i}{\omega_0}\right)^2; \qquad h = \frac{2}{T_2\omega_0}, \tag{3}$$

and henceforth we shall assume that the conditions

$$\delta,\ h \gg \mu, \qquad \mu \ll 1, \tag{4}$$

are satisfied; these mean that the reciprocal relaxation time of the excited particles and the emission-line width of the active substance are much greater than the resonator linewidth, while the resonator quality factor is sufficiently high. In particular, such conditions are fulfilled in gas and semiconductor [2] quantum generators with high-Q resonators of meter dimensions.

In the notation (3), the variables x, v, w are of order unity. Therefore the solution of system (1) under conditions (4) is close to harmonic motions:

$$x_i = X_i \cos(t + \varphi_i); \qquad v_i = V_i \cos(t + \psi_i); \qquad w_i = W_i \simeq \text{const}. \tag{5}$$

To solve the problem it is convenient to use the Van der Pol method [8]. We regard X, V, W, φ, ψ as functions of time varying slowly in comparison with unity. Then their change is described by a system of shortened differential equations:

$$\begin{gathered}
\dot{X}_1 = -\frac{\mu}{2}X_1 - \frac{\alpha_m}{2}X_2\cos(\varphi_2 - \varphi_1) + \frac{\gamma}{2}V_1\sin(\psi_1 - \varphi_1), \\
\dot{X}_2 = -\frac{\mu}{2}X_2 - \frac{\alpha_m}{2}X_1\cos(\varphi_1 - \varphi_2) + \frac{\gamma}{2}V_2\sin(\psi_2 - \varphi_2), \\
\dot{\varphi}_1 = -\frac{\alpha_m}{2}\frac{X_1}{X_2}\sin(\varphi_2 - \varphi_1) - \frac{\Delta}{2}, \\
\dot{\varphi}_2 = -\frac{\alpha_m}{2}\frac{X_2}{X_1}\sin(\varphi_1 - \varphi_2) + \frac{\Delta}{2}, \\
\dot{V}_i = -\frac{h}{2}V_i - \frac{h}{4}W_{iX}i\sin(\psi_i - \varphi_i), \\
\dot{\psi}_i = -\frac{h}{4}W_i\frac{X_i}{V_i}\cos(\psi_i - \varphi_i), \\
\dot{W}_i = -\frac{\delta}{2}W_i - \delta + hX_i\sin(\psi_i - \varphi_i),
\end{gathered} \tag{6}$$

where, for simplicity of calculation, the natural frequencies of the resonators are taken to be symmetrically detuned relative to the frequency ω_0 by an amount $\omega_0\Delta$, not exceeding the resonator linewidth, i.e. $\Delta \ll \mu$.

In studying the stability of system (6) it is convenient to make use of the fact that, according to (4), phase space is divided into regions of "fast" and "slow" motions [8]. As a result of the calculations we find that the synchronized regime of two diffraction-coupled generators exists and is stable under the conditions:

$$\Gamma_m < 0, \tag{7}$$

$$\Delta < |a_m| = \frac{\lambda}{2\pi L}|\Gamma_m|, \tag{8}$$

$$\mu + \left(a_m^2 - \Delta^2\right)^{1/2} < \gamma. \tag{9}$$

The first of these conditions imposes a restriction on the sign of the diffraction-coupling coefficient. The physical meaning of this condition, according to the definition of the diffraction-coupling coefficient, is that the energetically most favorable generation regime is stable. The second condition determines the possible magnitude of the detuning for a given diffraction-coupling coefficient. The third condition is the simple self-excitation condition for the generators. The analysis carried out applies equally to the cases of even and odd types of oscillations of the coupled resonator.

4. The condition (7) that the diffraction-coupling coefficient be negative is satisfied for both the even and the odd type of oscillations (Fig. 1) over a comparatively large range of distances between the resonators. In the case of detuned resonators, the detuning of the natural frequencies must satisfy condition (8), and if the detuning is caused by a difference in resonator lengths δL^*, then condition (8) can be rewritten in the form

$$\delta L/\lambda < |\Gamma_m|/\pi. \tag{10}$$

The fundamental type of oscillations $\mathrm{TEM}_{00}^{(c)}$, according to Fig. 1, generates $(N = 2.5)$ up to a size of the absorbing partition amounting to 4% of the mirror size. In this case $0.04 < |\Gamma_0| < 0.1$, and, in accordance with (10), the maximum detuning must lie in the interval from $\lambda/80$ to $\lambda/30$, depending on the size of the absorbing partition. The diffraction losses of the fundamental type of oscillations vary from 3 to 10%.

Similar estimates are not difficult to make for larger d and for the odd type of oscillations.

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* The calculations of Sec. 2 may also be used in this case, since $|\Gamma_m| \ll 1$ and, according to (10), $\delta L \ll \lambda$.

Note: Figure translations are in progress. See original paper for figures.