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Injection lasers with a discretely scanned radiation pattern

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***Abstract*. A theoretical model is developed that describes self-locking of transverse modes in the cavity of an injection laser in the presence of a parabolic inhomogeneity of the refractive index along the $p-n$ junction in the active region. A periodic discrete spatial displacement of the radiation pattern is obtained. The frequency and angle of scanning are estimated. All the results are in good agreement with experimental data obtained earlier.**

Keywords: *injection lasers, transverse mode locking, numerical simulation.*

1. Introduction

In first injection lasers with a broad contact in separate emitting regions of width ~ 50 μm, a nearly harmonic scan of a light spot over the output mirror could be observed with the help of an electrooptical converter [1]. This effect was reasonably attributed to self-locking of transverse modes [2], which are formed due to the inhomogeneity of the permittivity of the cavity [3]. Similar effects were observed in gas lasers with spherical mirrors, for which it was shown [2] that an in-phase addition of Hermitian – Gaussian polynomials with a Poisson distribution of amplitudes results in the sinusoidal scanning of the laser beam.

It is known that the emission spectrum of an injection laser with a Fabry – Perot resonator is formed in the general case by a family of longitudinal and adjacent transverse modes [4]. The phase locking of longitudinal modes results in the appearance of a periodic train of short pulses [5]. The pulse-repetition period is inversely proportional to the spectral mode interval, while the duration of each pulse is inversely proportional to the spectral interval of all modes involved in phase locking. The self-locking of longitudinal modes in an injection laser with a cavity of length 300 – 500 μm is hindered because of a large spectral interval (100 – 200 GHz) between adjacent longitudinal modes. The passive locking of longitudinal modes can be achieved only by using a saturable absorber with a very fast recovery of absorption (faster than for 50 ps) [6].

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In the case of transverse-mode locking, the radiation pattern is periodically scanned in space due to periodic variations in the phase front of a wave at the laser output. The self-locking conditions in such a laser are substantially simplified because of a narrow (of the order of 10 GHz) transverse-mode interval [4].

The aim of this paper is to develop a theoretical model describing the appearance of self-locking of transverse modes in a planar semiconductor laser (Fig. 1).

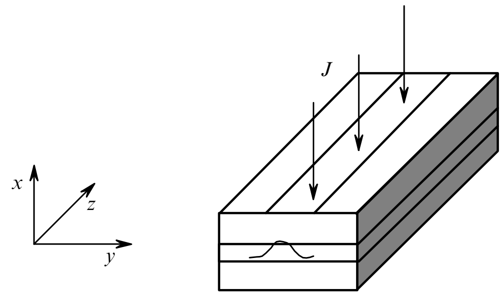

Figure 1. Scheme of the structure under study.

2. The model

Let us determine the conditions required for transverse-mode locking. Because mode locking is assumed periodic, an electric field at the laser input can be expanded into the Fourier series

$$E(r,t)=\sum_m A_m(r)\exp(-\mathrm{i}\omega_m t).$$

This series will describe a periodic process if the frequency interval between adjacent harmonics is constant.

It is well known that the components $\{\kappa_x, \kappa_y, \kappa_z\}$ $[(\kappa_x^2)_l+(\kappa_y^2)_m+(\kappa_z^2)_n=\omega_{nml}^2c^{-2}\varepsilon]$ of the wave vector in an injection laser satisfy the inequalities $\kappa_z>\kappa_x\gg\kappa_y$ (the x axis is perpendicular to the $p-n$ junction plane). For this reason, we have for the emission frequency

$$\frac{\omega_{nml}}{c}\sqrt{\varepsilon}\approx\left[(\kappa_x^2)_l+(\kappa_z^2)_n\right]^{1/2}\left\{1+\frac{(\kappa_y^2)_m}{2\left[(\kappa_x^2)_l+(\kappa_z^2)_n\right]}\right\}. \quad (1)$$

One can see from (1) that the transverse modes can be equidistant if only the square of an eigenvalue of the wave vector $(\kappa_y^2)_m$ along the y axis is linear over its subscript, which is the case, for example, when $(\kappa_y^2)_m$ is the square of the eigenvalue of the eigenfunction of the Hermitian equation. We arrive at this equation by solving the Helmholtz equation for a medium with a parabolic dependence of the permittivity on the transverse coordinate. Our choice of the inhomogeneity type is explained by this circumstance.

If the dependence of the permittivity on the coordinate y has the form

$$\varepsilon(y) = \varepsilon^{(0)}\left(1 - \frac{y^2}{s^2}\right),$$

where s is the inhomogeneity parameter and $\varepsilon^{(0)}$ is the maximum of the unperturbed permittivity, then, after separating variables, the dependence of the field on the transverse coordinate will be described by the equation

$$\frac{d^2 B_m}{dy^2} + \left[(\kappa_y^2)_m - \frac{\omega_m^2}{c^2}\varepsilon^{(0)}\frac{y^2}{s^2}\right]B_m = 0. \quad (2)$$

By changing variables according to $\xi = y\left[(\omega_m/c)(\varepsilon^{(0)}/s)\right]^{1/2}$, Eqn (2) can be written in the form

$$\frac{d^2 B_m}{d\xi^2} + \left[(\kappa_y^2)_m \frac{sc}{\omega_m \varepsilon^{(0)}} - \xi^2\right]B_m = 0. \quad (3)$$

The solutions of Eqn (3) are Hermitian–Gaussian polynomials

$$B_m(\xi) = H_m(\xi)\exp\left(-\frac{\xi^2}{2}\right) \quad (4)$$

[where $H_m(\xi)$ is the mth Hermitian polynomial] under the condition that

$$\kappa_{ym}^2 = \frac{\omega_0}{c}\frac{\varepsilon^{(0)}}{s}(2m+1). \quad (5)$$

It follows from (2) that in the case of a parabolic inhomogeneity

$$s_m \leqslant \left(\frac{w}{2}\right)^2 \frac{k_0 \varepsilon_0^{1/2}}{2m+1}$$

(where $k_0 = \omega_0/c$ and w is the width of an active strip), m modes can exist in the cavity. This relation cannot be used as even a rough threshold criterion for involving a new mode in lasing with increasing the width of the active region or with decreasing the parabolic inhomogeneity parameter because it was obtained for an inactive resonator. However, the numerical calculation shows that a superlinear, similar to quadratic, dependence of the number of locked modes on the parabolic inhomogeneity indeed takes place.

To analyse rigorously transverse-mode locking in an injection laser, we propose a model based on the solution of two equations: the diffusion equation for nonequilibrium carriers and the equation of light propagation. The equation of the optical part of the model is obtained from the wave equation by separating a slow dependence of the field on the longitudinal coordinate and integrating over the coordinate perpendicular to the $p-n$ junction plane. The unperturbed permittivity depends on the transverse coordinate as $\varepsilon(x) = \eta_a^2$ within the active region and as $\varepsilon(x) = \eta_p^2$ in emitter layers. By introducing the effective refractive index [7, 8], we arrive at the equation

$$\pm 2ik\frac{\partial\psi_\mu}{\partial z} + \frac{\partial^2\psi_\mu}{\partial y^2} + k_0^2\Gamma\Delta\varepsilon(y,z)\psi_\mu = 0. \quad (6)$$

Here, $k = k_0\bar{\eta}$; $\overline{\eta^2} = \Gamma\eta_a^2 + (1-\Gamma)\eta_p^2$; ψ_μ is the intracavity electric field; the subscript μ corresponds to two types of waves: the forward (ψ_f) and backward (ψ_b), according to which the sign at the derivative over z is chosen; and Γ is the factor of optical confinement. The function $\Delta\varepsilon(y,z)$ includes both a technologically specified variation in the permittivity profile and its variation induced by the inversion burning by the field:

$$\varepsilon^{(0)} = \eta_a^2,$$

$$\Delta\varepsilon(y,z) = -\varepsilon^{(0)}\frac{y^2}{s^2} + \varepsilon'(y,z) + i\varepsilon''(y,z),$$

$$\varepsilon'(y,z) = -a\eta_a RNk_0^{-1},$$

$$\varepsilon''(y,z) = -i\eta_a k_0^{-1}[(aN-b) - a_{fc}N] + i\eta_a k_0^{-1}(1-\Gamma)\frac{\alpha_p}{\Gamma}.$$

Here, ε' and ε'' are the real and imaginary parts of the permittivity perturbation caused by the burning of inversion by the field; a and b are parameters characterising the concentration dependence of amplification: $g(N) = aN - b$; R is the antiwaveguide parameter; a_{fc} are specific losses caused by scattering from free carriers; and α_p are losses in passive layers.

The diffusion equation for nonequilibrium carriers has the form

$$\frac{\partial N}{\partial t} = \frac{j}{ed} + D_{am}\Delta_{yz}N - \frac{N}{\tau_{nr}} - \frac{\Gamma g(N)}{d\hbar\omega}|\psi_f + \psi_b|^2, \quad (7)$$

where j is the pump current density; D_{am} is the ambipolar diffusion coefficient; e is the electron charge; d is the active-region thickness; and τ_{nr} is the time of nonradiative recombination. The field functions are normalised in such a way that the integral

$$W_\mu = \int |\psi_\mu^2| dy$$

over the active-region width gives the output power at the corresponding mirror. The time dependence of the concentration should be taken into account because the sought operating regime of the laser is nonstationary (Fig. 2).

3. Calculation method

As the initial condition for the solution of Eqn (6), we used an arbitrary (Gaussian) profile of the electric field at one of the mirrors, with the amplitude that was substantially lower than that upon lasing. The initial concentration of nonequilibrium carriers is assumed zero.

The pump current causes with time the accumulation of inversion in the active region, and, beginning from a certain moment, the imaginary part of the permittivity becomes negative. From this moment, we followed the propagation of the electric field through the active region. Due to

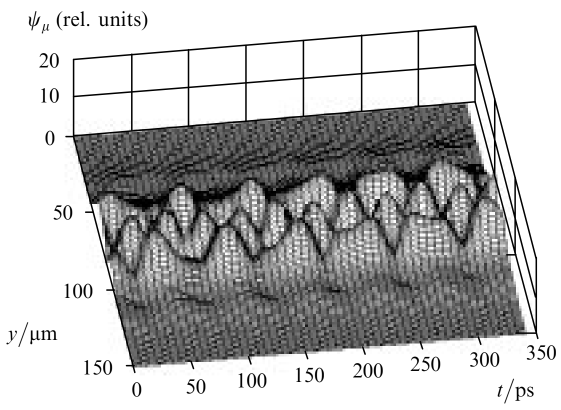

Figure 2. Time base of the spatial distribution of the electric field strength at the output mirror in a laser with three locked modes.

radiative losses and also because the active region occupies not the entire width of the laser resonator, the output power after first trips of radiation in the resonator can be lower than the initial power. However, if the pump current is sufficiently high, the decay changes to amplification after a few trips. From this moment, Eqns (6) and (7) are solved jointly. After each trip of radiation in the cavity, we calculated the burning of inversion by the field and recalculated the permittivity.

4. Results of simulation

One can see from Figs 3a, b that an emitting spot runs over discrete positions on the output mirror. The number of these positions is equal to the number of locked modes, and the emitting spots as if lie on a sinusoid. All the parameters of the problem in Figs 3a and 3b are the same except the active-region width, which is equal to 60 and 80 μm,

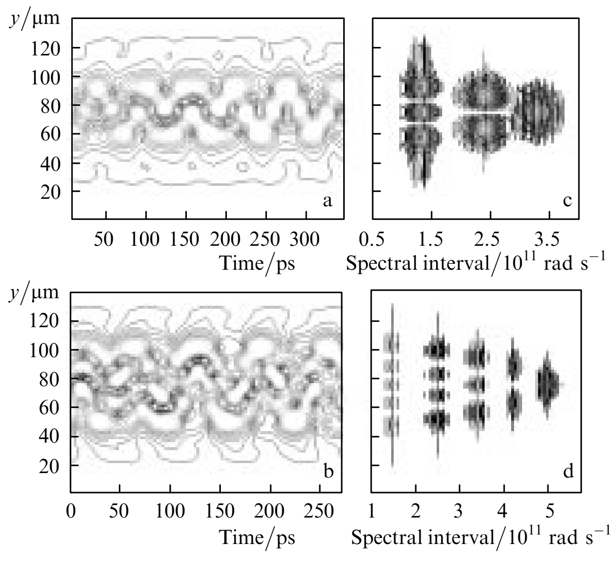

Figure 3. Time base of the spatial distribution of the electric field strength at the output mirror and the corresponding spectral distributions of radiation from a laser with the active-region width $w = 60$ μm and three locked modes (a, c) and a laser with $w = 80$ μm and five locked modes (b, d).

respectively. A narrowing of the active region results in a decrease in the number of transverse modes that can simultaneously exist in the laser.

The scan frequency of the emitting spot over the laser facet is determined by the parabolic inhomogeneity parameter of the permittivity and does not directly related to the number of locked modes [see (5)]. Thus, one can see from Figs 3c, d that the spectral interval between adjacent modes is approximately the same and is $\sim 1.1 \times 10^{11}$ rad s^{-1}. The scan frequency of radiation over the output mirror is equal to the spectral mode interval. The number of locked modes depends not only on the active-region width but also on the pump current and the parabolic inhomogeneity parameter (Fig. 4). If both the pump current and the width of the active strip are large enough, then the number of locked modes will be determined only by the parabolic inhomogeneity parameter.

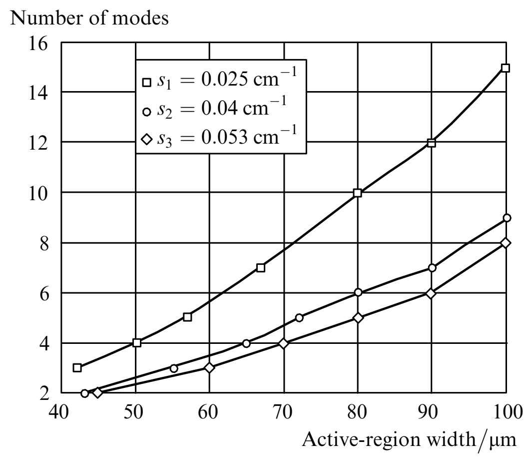

Figure 4. Dependence of the number of locked modes on the active-region width for different values of the parabolic inhomogeneity.

The far-field radiation for three locked modes is shown in Fig. 5. The radiation pattern is scanned with the frequency equal to the mode interval and has the number of fixed position equal to the number of modes involved in locking.

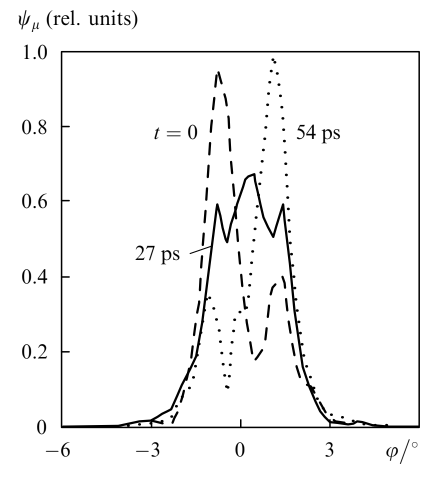

Figure 5. Far-field radiation of a laser with three locked modes for three instants of time.

5. Conclusions

We have proposed the theoretical model describing the appearance of transverse-mode locking in a semiconductor laser. The calculation of the far-field radiation allows us to find the scan angle of a lobe of the radiation pattern in space. Thus, the possibility appears for creating devices that have the radiation pattern with a multistable dynamic spatial orientation.

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