го волновода составляет величину порядка 4.186 на длине волны 459.25 нм с дисперсией порядка - 0.03 $нм^{-1}$, уменьшающейся с увеличением уровня возбуждения.

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INFLUENCE OF CARRIER DIFFUSION ON COMPETITIVE MODE DYNAMICS IN VCSEL UNDER PSEUDORANDOM PULSED MODULATION

Yu. Morozov[1], I. Nefedov[1], V. Gusyatnikov[2]

[1] Institute of Radio Engineering and Electronics Russian Academy of Sciences, Saratov
[2] Saratov State University, Saratov

1. Introduction

Vertical-cavity surface-emitting semiconductor lasers (VCSELs) are presently the subject of intense research due to their potential use as a compact, efficient laser sources for the fiber communication systems as well as for the optical signal processing. Despite a remarkable progress both in numerical simulations and in experimental investigations of VCSEL's dynamics [1-3], there are many subjects of great importance which have not been studied till now. For example, it has been shown that VCSELs emit few transverse modes simultaneously for high level of pumping current [1, 2]. However, in available papers the competition dynamics of these modes has not been adequately explored, in particular, for current modulated by a pseudorandom sequence of pulses at high frequencies.

2. Model and equations

We used for calculation the model of index-guided VCSEL's structure with a cylindrical geometry. It was also assumed in our model that a ring contact supplies current to an active region whose radius corresponds to the radius of index-guided region for laser.

A system of differential rate equations defining carrier density N in the active layer and photon density S_i in the i-th laser mode looks as follows:

$$\frac{\partial N}{\partial t} = D\nabla_T^2 N + \frac{J(r,t)}{ed} - \frac{N}{\tau_n} - B_{sp}N^2 - v_g\Gamma_z g(N)\sum_{i=1}^{M}\left|\phi_i(r,\varphi)\right|^2 S_i;$$

$$\frac{dS_i}{dt} = v_g(\Gamma_z G_i - \alpha_{ti})S_i + \beta B_{sp}\overline{N^2}. \qquad i = \overline{1,M}$$

In these equations the following notations are used: D is the carrier diffusion coefficient, ∇_T^2 is the transverse Laplasian in cylindrical coordinates, $J(r,t)$ is the axial symmetric injection current density, d is the active layer thickness, e is the electron charge, τ_n is the carrier lifetime due to nonradiative recombination; B_{sp} is the spontaneous recombination coefficient, v_g is the group velocity of light, Γ_z is the longitudinal confinement coefficient, α_{ti} is the cavity loss for the i-th mode, β is the spontaneous coupling coefficient. The local gain $g(N)$ have been defined as:

$$g(N) = \frac{a_0(N - N_t)}{1 + \gamma\sum_{i=1}^{M}\left|\phi_i(r,\varphi)\right|^2 S_i},$$

where a_0 is the gain cross-section, γ is the gain compression factor, N_t is the carrier density at transparency, $\left|\phi_i(r,\varphi)\right|^2$ is the normalized Poynting vector longitudinal component for the i-th mode. The gain for each mode $G_i(t)$ is given by the spatial average of local gain weighted by the spatial distribution of that mode, $\overline{N^2}$ is the value of N^2 averaged over cross-section of laser. In a high-quality resonator, such as the VCSEL, one may assume that the approximate cavity spectrum may be obtained by modeling the VCSEL as a perfect cylindrical dielectric resonator [3]. The total number of modes taken into account under calculation was on the order of 100. The time dependence of pumping current density is expressed in the pseudorandom sequence of pulses for the non-return-to-zero (NRZ) encoding format, which are superimposed onto a constant bias current. The process of current rising during every binary "zero" to binary "one" transition is determined by the hiperbolic tangent function. For example, $J(r,t) = J_0(1 + \varepsilon_m \tanh(pt))$ for the pulse originated at t=0. The binary "one" to binary "zero" transition (i. e., current falling) is assumed to be of similar form. The parameters p and ε_m determine the rate of current rise (or decay) and modulation index, respectively. The current density distribution along the radius of active region was specified by step-like function:

$$J_0(r) = \begin{cases} J_{\min}, & 0 \le r < R_{\min} \\ J_{\max}, & R_{\min} \le r \le R_{\max} \\ 0, & R_{\max} \le r \le R \end{cases}$$

where R_{min} and R_{max} are the values of radius at which current jumps occur. By choosing the adjustable parameters J_{min} and J_{max} one can obtain the current profile close to real one. The carrier and field equations (1) are integrated numerically using a finite difference method in both the temporal and spatial domains. Relevant device parameters used for simulations are displayed in Table 1.

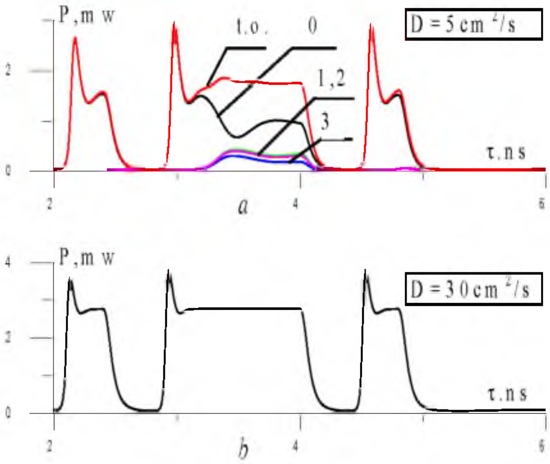
Table 1

Active region thickness d, μm	0.025
Radius of device R, μm	10
Radius of active and index-guiding region R_a, μm	3
Refractive indices n_1, n_2	3.5, 3.4
Nonradiative recombination time τ_n, ns	2
Photon lifetime τ_p, ps	5
Bimolecular recombination coefficient B_{sp}, cm^3/s	10^{-10}
Wavelength λ, μm	0.98
Gain-cross section a_0, cm^2	$2*10^{-16}$
Carrier density at transparency N_t, cm^{-3}	$2*10^{18}$
Mirror reflectivities ρ_1, ρ_2	0.995
Longitudinal confinement factor Γ_z	0.05
Nonlinear gain parameter γ, cm^3	$5*10^{-17}$

3. Results of modeling

We have studied the effects of diffusion coefficient and pumping geometry on spatial hole burning in VCSEL under pseudorandom pulsed modulation for bit-rate at 2.5 Gb/s. The most interest and important results are as follows. The only fundamental transverse mode HE_{11} exists in alone binary "one" surrounded by binary "zeros". If the current pulse continues for a longer time (i.e. if few binary "ones" are transmitted in a row), the mode composition is considerably enriched by additional transverse modes - TM_{01}, HE_{21} and TE_{01} (fig. 1, *a*). The modes HE_{11}, TM_{01}, HE_{21} and TE_{01} are marked as 0,1,2 and 3, respectively. T.O. stands for total laser output.

This mode dynamics is exhibited because of bigger gain coefficient for fundamental mode then for the other ones (in initial part of long pulse) and due to existence of essential spatial hole burning in the remaining part of the pulse. The rising of diffusion coefficient leads to depletion of mode spectrum (fig. 1, *b*). It is caused by smoothing of carrier density profile



F i g. 1. The segment of pseudorandom sequence of lasing power

and, consequently, by decrease the effects of spatial hole burning in central region of VCSEL on exciting of additional transverse mode.

4. Conclusion

The composition of binary "ones" for pseudorandom sequence of pulses emitted by VCSEL may be quite different due to delay in exciting the side modes with respect to the fundamental mode excitation. Most likely, this phenomenon may be the reason of pronounced mode partition-noise in long-haul communication systems and have to be accounted for VCSEL's application in such systems.

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ДИНАМИКА VCSEL ЛАЗЕРА С ПЕРИОДИЧЕСКОЙ МОДУЛЯЦИЕЙ АЗИМУТА ПОЛЯРИЗАЦИИ

А. П. Войтович, А. М. Кульминский, Ю. В. Лойко

Институт молекулярной и атомной физики НАН Беларуси, г. Минск

В последнее время большое внимание уделяется исследованию полупроводниковых поверхностно излучающих лазеров с вертикальным резонатором (VCSEL). Такие лазеры малогабаритны, просты в эксплуатации и их динамика легко контролируется, что является несомненным преимуществом в системах обработки и передачи информации. Характерной особенностью VCSEL-лазеров является их чувствительность к поляризации генерируемого излучения, корректно учитываемая в рамках модели векторных скоростных уравнений [1].