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Polarization switching mechanism in surface-emitting semiconductor lasers

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ABSTRACT

Within the scope of the earlier proposed approach to the description of polarization dependences in VCSEL based on analysis of the experimental and theoretical data, an explicit expression for the function describing the relationship between the amplification anisotropy and the current density is suggested. The conducted numerical calculations support the peculiarities of the polarization switching (PS) process and enable one to explain the effect of the PS point anomalous shift when the current variation rate is high. A special attention is given to a fairly clear physical interpretation of the formation of polarization radiation in VCSEL.

1. Introduction

The effect of quick switching of one linear polarization to the orthogonal polarization in the output radiation of injection semiconductor lasers has been known for a fairly long time [1,2], still being exotic to some extent due to its rather hard realization conditions. However, even at such conditions polarization switching (PS), owing to its hysteresis character, has found wide applications in various devices developed for optoelectronic systems [3].

Interest to this phenomenon has increased greatly since revealing of «spontaneous» PS in vertical cavity surface-emitting lasers (VCSEL) [4,5], when PS occurs due to variations in the injection current. Many works associated with this problem have been published during a period of about twenty years and, nevertheless, it remains of a particular importance [6–9] as VCSEL, and PS in particular, have numerous applications [7–9]. But the PS effect is very unwanted for the majority of optoelectronic systems because of their polarization sensitivity. Different methods to suppress PS have been developed (e.g., [7,10]). However, they are associated with sophistication of the VCSEL production technology and, to some or other extent, affect the output parameters diminishing the source advantages inherent in VCSEL.

The PS effect is important because it illustrates instabilities occurring in nonlinear systems – many attempts were undertaken to interpret this effect as some phase transition (e.g., see [11]), though these attempts little contributed to better understanding of its mechanism.

At the present time, the most commonly used approach to interpretation of the PS effect is based on the polarizations modes approach (PMA) assuming that, due to anisotropy of gain and/or loss, two independent polarization modes are formed in a semiconductor laser. When this anisotropy is relatively high, as is usual in end-pumped semiconductor lasers, one of

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the modes becomes dominant and the output radiation is linearly polarized [12]. In VCSEL such anisotropy is low, being induced by the electrooptic, elastooptic, and thermal processes [6] during their production or operation, and at the particular conditions the concurrence of these modes is liable to lead to polarization instability and to the PS effects. The approach has attracted much attention since publication of the works [13,14], where the authors had developed the so-called Spin Flip Model (SFM) for the case of VCSEL with a QW active layer. SFM is a microscopic model, according to which the generation process is realized by a system of two spin subsystems whose interaction is described by the phenomenological parameter of the spin relaxation rate. As a result of concurrent radiations from the subsystems, two orthogonal linearly-polarized modes are stable, and their concurrence leads to dominance of the only one of them. Still there are some instability regions, where SP can occur.

SFM is very popular because it offers explanation [14] for numerous effects accompanying PS (both types of PS, bistability, hysteresis, etc.). Nevertheless, many effects of PS may be explained from the viewpoint of the phenomenological theory that is based on rate equations, if we distinguish self- and cross-saturation of orthogonal modes [15]. But the introduction of saturation effects into SFM [16], in principle, gives similar results [15]. Despite wide applications of the above-mentioned models, they are not free from some intrinsic contradictions and both fail to describe fully all the phenomena associated with SP.

The main disadvantage of SFM, and of PMA as a whole, is the introduction of the polarization mode phases as net, i.e. rigorously defined, parameters [13,14]. SFM was formed as a direct analog of a theory of gas lasers [13] characterized by slow phase relaxation. For semiconductor lasers, fast phase relaxation (dealt with in greater detail further in the text) is the case, and the rigorously defined mode phases may be considered as an asymptotic approximation, i.e. as a limit for the quasi-stationary state. Properly speaking, the introduction of two orthogonal linearly polarized modes in SFM is just associated with the limiting transition to the stable state. However, the admitted assumption of the phase definiteness results in the fact that in the region of SP the dynamic states of elliptic polarization should be formed [17,18], though they are hardly detected as the obtained data afford no unambiguous interpretation [18,19].

SFM has been extended and refined due to the introduction of a complex medium susceptibility [20]. Unfortunately, this leads to a considerable complication of the equations [21,22] containing numerous parameters the definition of which is problematic. Because of this, much favor holds a microscopic model of PMA using an asymmetric scheme of nonlinear effects [15], with the self- and cross-saturation factors considered as system's parameters. But it should be noted that the calculation results are differing considerably [23]. Moreover, as demonstrated by the detailed studies, the results have different spectral dependences [24] and are also dependent on the pump pulse energy [25], i.e. they are the function of the process as well.

These intrinsic contradictions affect the effectiveness of the approaches developed with the use of PMA. Nonlinear coupling of polarization modes has been introduced in terms of the induced nonlinear anisotropy [26]. Besides, some other corrections and supplements to the initial models have been suggested, though in several cases (e.g., see [27]) the experimental results were described inadequately.

The fundamentally different approach to the description of PS – the polarization components approach (PCA) – has been based on the idea of the incoherent nonpolarized spontaneous radiation sequentially amplified in an active medium with anisotropic gain and/or loss factors. Within the scope of this approach, the PS process is considered as a sequential deterministic transition from one linearly polarized state to the orthogonal state by means of a chain of partially polarized states rather than a process resultant from concurrence of two orthogonally polarized modes. In the works [28,29], with the use of this approach, the possibility to describe the principal effects accompanying PS has been demonstrated and their fairly simple physical interpretation has been presented. In more recent works [30] it has been shown that PCA may be used to study the spectral and statistical characteristics in the region of PS. In other words, the applicability of PCA is proven. Now the applicability limits of this approach for the description of the formation of polarized radiation in VCSEL should be examined.

The article is organized as follow. Section 1 presents the development of a theoretical model based on PCA; based on analysis of the literature data, we introduce the function that, in the explicit form, describes gain anisotropy depending on the injection current density. Section 2 is devoted to the numerical results obtained for the stationary approximation as well as for the case when the current increases at the constant rate. For the last case it was shown that besides the natural shift of PS point in the greater current range (that leads to hysterics phenomena) there is an effect of a reverse PS point shift for high rate of the current increases.

2. Theoretical model

PCA has been considered in detail as applied to dye lasers in [31–33]. Here we deal with the main points and the requirements enabling one to describe PCA as a basic method for the description of lasing in semiconductor injection lasers, as a whole, and surface-emitting lasers, in particular.

Using PCA, we first represent a plane monochromatic wave propagating along the axis z of a laboratory system with the coordinates as

$$\mathbf{E}(z,t) = \int_0^{\pi} \mathbf{e}_{\psi} E(\psi, z, t) \exp[i\phi(\psi, z, t)] d\psi \tag{1}$$