Eigenmode analysis of phase-locked VCSEL-arrays using spatial coherence measurements

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***Abstract*—We study the cavity mode structure of a 2x2 phase-locked VCSEL-array using the modal coherence theory developed by Wolf and Agarwal, coupled mode theory, and spatial coherence measurements. The eigenmode content is derived as a function of the injected current, revealing the impact of spatial hole burning and spontaneous emission coupling.**

Keywords-Vertical cavity surface emitting laser (VCSEL); eigenmode analysis; coherence; phase-locking.

I. Introduction

Arrays of phase-locked, vertical cavity surface emitting lasers (VCSELs) constitute wide aperture, coherent light sources whose design can profit from concepts related to photonic crystals [1]. In particular, phased-locked arrays of VCSELs are very attractive means for obtaining higher power beams with a high degree of spatial coherence. From a more fundamental point of view, these devices provide an interesting system for investigating partially coherent light sources.

The spatial coherence of VCSEL-arrays is traditionnally evaluated using measurements of their far field pattern, completed by model calculation of supermodes [2]. However, far field patterns give only an indication about the global coherence of the array. This coherence analysis can be refined by measuring and resolving the contribution of each mode to the emission spectrum. A more complete evaluation demonstrated recently consists in measuring the spatial degree of coherence of each VCSEL pair by performing Young's interference experiments [3]. Remarkably, the mode structure can be analyzed using the mutual coherence function, based on the modal coherence theory discussed by Wolf and Agarwal [4]. This approach is of great interest since it allows to extract the parameters of the lasing supermodes, including their corresponding relative power distribution. Here, we apply this analysis method to a 2x2 VCSEL-array and compare it with a simulation model based on coupled mode theory.

II. Theory

We consider two different approaches to identify the spatial distribution of the modes in a VCSEL-array. The first method is an eigenmode analysis relying on modal coherence theory [4], whereas the second method employs Couple Mode Theory (CMT) which allows to calculate the spatial mode distribution [5].

A. Eigenmode Analysis

The modal coherence theory is based on the fact that the optical field $V(\mathbf{r},t)$ can be represented as an expansion of the eigenmodes ψ_n :

$$V(\mathbf{r},t) = \sum_n \alpha_n(\upsilon)\psi_n(\mathbf{r},\upsilon)e^{i2\pi\upsilon t}\,. \tag{1}$$

Wolf and Agarwal demonstrated in the spectral domain that the mode functions are eigenmodes of the homogeneous Fredholm integral [4]. However, under quasi-monochromatic conditions, an analogous expression can be formulated in the space domain:

$$\int \Gamma(\mathbf{r_1},\mathbf{r_2})\psi_n(\mathbf{r_1},\upsilon)d^3r_1 = \lambda_n(\upsilon)\psi_n(\mathbf{r_2},\upsilon)\,. \tag{2}$$

where the variables $\mathbf{r_1}$ and $\mathbf{r_2}$ correspond to the vector positions and υ to a fixed frequency. $\Gamma(\mathbf{r_1},\mathbf{r_2})$ is the mutual coherence function of two point sources located at the positions $\mathbf{r_1}$ and $\mathbf{r_2}$, assuming zero time delay. ψ_n is the mode function of the eigenmode n and λ_n is the corresponding eigenvalue.

Considering each VCSEL of the array as a point source, the problem reduces to a linear secular equation system. In the case of a 2x2 VCSEL-array, we obtain

$$\begin{pmatrix} \Gamma_{11} & \Gamma_{12}^* & \Gamma_{13}^* & \Gamma_{14}^* \\ \Gamma_{12} & \Gamma_{22} & \Gamma_{23}^* & \Gamma_{24}^* \\ \Gamma_{13} & \Gamma_{23} & \Gamma_{33} & \Gamma_{34}^* \\ \Gamma_{14} & \Gamma_{24} & \Gamma_{34} & \Gamma_{44} \end{pmatrix} \begin{pmatrix} \psi_n^{(1)}(\upsilon) \\ \psi_n^{(2)}(\upsilon) \\ \psi_n^{(3)}(\upsilon) \\ \psi_n^{(4)}(\upsilon) \end{pmatrix} = \lambda \begin{pmatrix} \psi_n^{(1)}(\upsilon) \\ \psi_n^{(2)}(\upsilon) \\ \psi_n^{(3)}(\upsilon) \\ \psi_n^{(4)}(\upsilon) \end{pmatrix}. \tag{3}$$

Clearly, measurements of the coherence function $\Gamma_{ij} = \Gamma(\mathbf{r_i},\mathbf{r_j})$ of all VCSEL pairs i and j (with i,j=1,2,3,4) can yield the eigenmode content $\psi_n^{(k)}$ where n can vary between one and four depending on how many eigenmodes are present in the structure. The exponent (k) indicates the eigenmode value at VCSEL location k (k=1,2,3,4). The intensities of the eigenmodes are given by their corresponding eigenvalue λ.

B. Coupled Mode Theory

CMT assumes weak coupling between the VCSELs, and of allows determining the supermodes of the VCSEL-array [5]. The mode amplitudes of a uniform 2x2 VCSEL-array in the near field derived by CMT are shown in Fig. 1(a). The in-phase mode ψ_1 corresponds to the highest loss mode. The medium loss modes are ψ_2 and ψ_3. Both have the same symmetry properties and are degenerate in terms of frequency and losses. The out-of-phase mode ψ_4**,** with alternating amplitude sign at adjacent VCSEL sites, is the lowest loss mode. Figure 1(b) depicts the corresponding far field patterns.

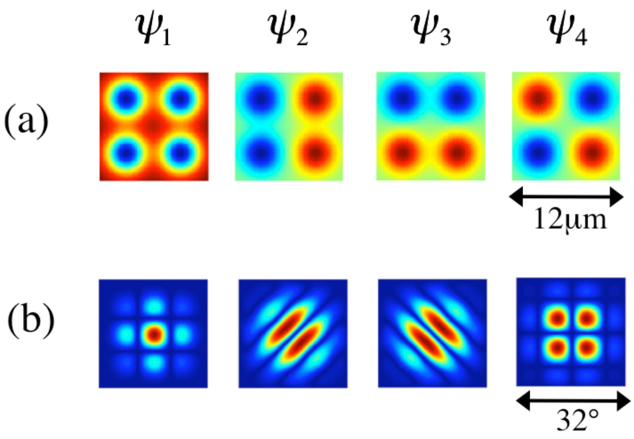

Figure 1. Calculated mode using CMT for an ideal, uniform 2x2 VCSEL-array: (a) near field amplitudes, (b) corresponding far field intensities.

III. Results

Close to threshold, typical phase-locked arrays of VCSELs oscillate at the highest order supermode due to its lowest cavity losses [2]. Lower order supermodes are excited at higher excitation levels due to spatial hole burning. By using the method based on coherence theory, we were able to extract the relative intensities of all lasing supermodes. The experiments were performed with an electrically pumped VCSEL-array fabricated using Bragg-mirror patterning [1,2], emitting at 955nm wavelength. It employs strained InGaAs/AlGaAs quantum wells as the gain medium and GaAs/AlGaAs distributed Bragg reflectors (DBRs). Each square-shaped VCSEL element has a size of 4x4μm^2 and the array pitch is 6.25μm. The threshold current was I_{th}=40mA.

The mutual coherence function of each pair of VCSELs within the array was measured by interefering the two corresponding near field spots using the spatial light modulator system described in [3]. Based on these measurements, equation (3) was then solved, yielding the eigenvalues and the eigenfunctions representing the array supermodes.

The eigenvalues λ, representing the relative supermode powers, are depicted by the histograms in Fig. 4 for three diode currents above threshold . The derived supermode amplitude patterns of the modes ψ_i with i = 1,2,3,4 are shown in the insets, and the total measured far field patterns are shown on the right panel. We note that the extracted near field patterns show distinct localization of the optical field, with complementary intensities of the supermodes at different array sites. This demonstrates the effect of spatial hole burning, which depletes the gain at the higher intensity peaks of each mode. The intensity of the highest order supermode is the highest at all currents, but increases with increasing pump level. This improved single mode operation results from the absence of perfect clamping of the modal gain above threshold, due to the significant coupling of spontaneous emission into the cavity mode.

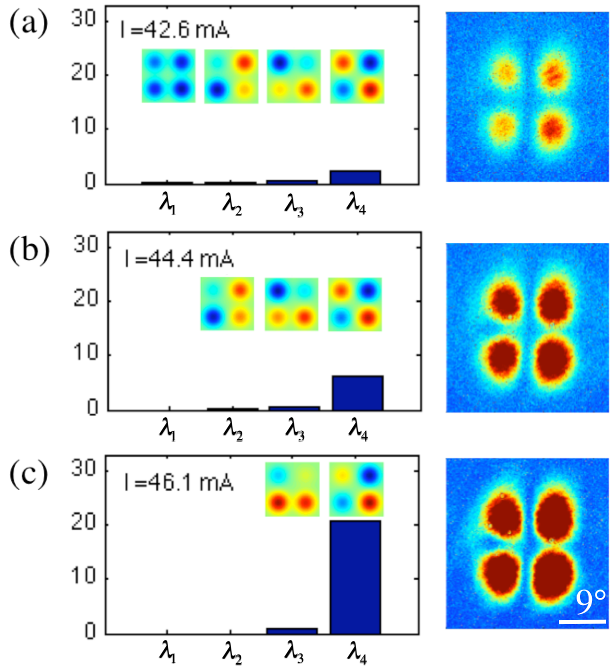

Figure 2. Histograms of normalized eigenmode intensities (λ_i ; i=1,2,3,4) including the representation of each eigenmode amplitude distribution for three different injection currents above threshold. The corresponding measured far field patterns are displayed on the right panel.

IV. Conclusion

We presented a modal coherence theory, which allows extracting the spatial mode distributions and the relative intensities of the lasing modes in a multimode laser cavity based on spatial coherence measurements. The method was applied to a phase-locked array of VCSELs. This approach makes possible the quantitative analysis of the mode content in such VCSELs and the assessment of new cavity designs for improved single mode operation.

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