PHYSICAL REVIEW A, VOLUME 64, 031803(R)

Spatially inhomogeneously polarized transverse modes in vertical-cavity surface-emitting lasers

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(Received 17 October 2000; published 20 August 2001)

We demonstrate spatially nonuniform polarization of the fundamental transverse mode in a vertical-cavity surface-emitting laser. Using a vectorial electromagnetic model, we find orthogonal linearly polarized components in the field of a solitary mode. We give experimental evidence for our predictions by polarization-resolved near-field measurements: the fundamental transverse mode contains a four-lobed intensity distribution in one linear polarization direction that is weaker than the dominant orthogonally polarized Gaussian-shaped distribution by 35 dB in excellent agreement between experiment and model.

DOI: 10.1103/PhysRevA.64.031803 PACS number(s): 42.55.Px, 42.25.Ja, 42.60.Da, 42.60.Jf

The commonly used approach to determine eigenmodes of optical resonators is based on a scalar description of the electromagnetic field [1]. To obtain cavity solutions within the framework of the scalar paraxial approximation, it is necessary to assume a uniform linear polarization of the field vector in any cross section of the spatially extended mode. However, it has been shown that a homogeneous linear polarization is only compatible with infinitely extended plane waves, whereas beams of finite size or nonplanar wave fronts require components of the field vector along the beam's main propagation axis (''longitudinal polarization'') and orthogonal to the dominant linear polarization direction (''cross polarization'') to maintain consistency with the transverse nature of electromagnetic waves as a basic result of Maxwell's equations [2,3]. This phenomenon has been addressed for the case of radiating spherical particles [4], illuminated pinholes [2], and Gaussian-Maxwell-beams of gas lasers [5,6], where nonuniform distributions of the electric-field vector have been predicted and observed. The power ratio between the weak cross-polarization component and the total power in the propagating TEM_{00}-mode of an Ar-ion laser has been measured to be only 10^{-11} [6]. Thus, the effect is usually assumed as negligible and transverse modes are regarded as spatially homogeneously polarized. This assumption has also been adopted for transverse modes in vertical-cavity surface-emitting lasers (VCSELs) [7], a special type of semiconductor laser whose polarization properties have attracted broad interest [8–10]. Numerous investigations of polarization related phenomena have been conducted [11–15], but thorough studies of spatial variations in the polarization of a solitary transverse mode in a VCSEL are up to now missing. Instead, it has been initially assumed that the polarization state of the emitted light is well described by a single set of Stokes parameters for each transverse mode [16,17].

In this work, we demonstrate the transverse modes' vectorial character. In particular, we use a joint theoretical and experimental approach to analyze the spatial distribution of the polarization vector in the near field of a VCSEL's solitary cavity mode. For the computation of the modes we apply the model of [18] based on mode expansion and coupled-mode theory. We expand the vectorial electromagnetic field in terms of the continuous basis of the TE and TM free space modes labeled by the transverse wave vector k [19]. The refractive index perturbation introduced by the device structure leads to a coupling between the expansion modes and via coupled-mode theory [20] it is possible to define a relation for the electric field at any two longitudinal positions z of the resonator. The boundary condition is given by the demand for self-consistency between backward and forward propagating waves at two arbitrary values of z and defines a simple eigenvalue problem: eigenvalues are related to the threshold gain and lasing frequency of the modes, while the corresponding eigenvectors give the distribution of the expansion coefficients over k and thus allow the reconstruction of the vectorial field.

We apply this model to particular structures that are available to us for experimental verification. The devices are oxide-confined AlGaAs VCSELs provided by Honeywell, Inc. They have oxide apertures of 3-μm diameter and emit at wavelengths of $\lambda \approx 845$ nm. For these devices, we calculate the complex vectorial field of the cavity solutions and so obtain complete information on the polarization state. In the following, we depict the vectorial fields by plotting the three Cartesian field components (E_x, E_y, E_z) because their particular shapes allow a very sensitive experimental investigation of the polarization state.

In Fig. 1, we present the calculated intensity distribution in the near-field of the fundamental transverse mode. We obtain two vectorial solutions, labeled as even and odd, which are degenerate in frequency and gain due to the circular symmetry and isotropy initially assumed in the model. They both possess a nonzero z component as a consequence of $k \neq 0$ contributions in the field expansion. Moreover, both solutions simultaneously contain unequal components x and y, indicating that the modes' polarizations are spatially inhomogeneously distributed. The dominant components have a Gaussian-like intensity profile, while the weaker components have a characteristic four-lobed profile.

In order to explain the origin of these spatial structures, we explicitly derive the expressions of the field expansion

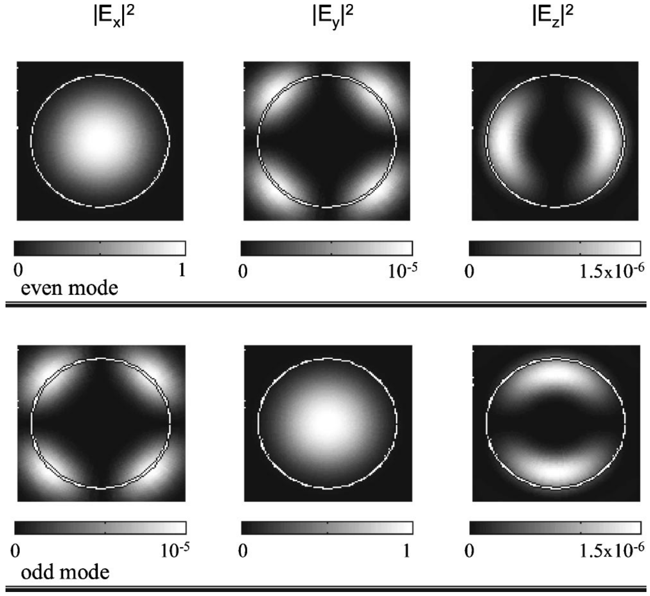

FIG. 1. Computed squared field components of the two degenerate fundamental mode solutions encoded in a linear gray scale as depicted on bottom of each image. Upper (lower) part: even (odd)-mode expansion. The white circle indicates the oxide aperture of 3-μm diameter.

for $E_x(r,\phi,z)$ and $E_y(r,\phi,z)$. In the case of the fundamental mode in an isotropic and circularly symmetric laser, the expansion modes of different azimuthal order m are uncoupled and the transverse fields are written as [19]

$$E_x=\int \mathrm{d}k\,[J_0 f_0(A^{\mathrm{TE}}+A^{\mathrm{TM}})+J_2 f_2(A^{\mathrm{TE}}-A^{\mathrm{TM}})], \tag{0.1}$$

$$E_y=\int \mathrm{d}k\,[J_0 g_0(A^{\mathrm{TE}}+A^{\mathrm{TM}})-J_2 g_2(A^{\mathrm{TE}}-A^{\mathrm{TM}})],$$

where k is the transverse component of the wave vector, $A^{\mathrm{TE}}(k,z)$ and $A^{\mathrm{TM}}(k,z)$ are the complex expansion coefficients, and $J_m(kr)$ is the Bessel function of order m, with r as the radial coordinate. The functions $f_m(\phi)$ and $g_m(\phi)$ are

$$f_m(\phi)=\begin{cases}\cos(m\phi)\\ \sin(m\phi)\end{cases};\quad g_m(\phi)=\begin{cases}-\sin(m\phi) & \text{even}\\ \cos(m\phi) & \text{odd}\end{cases} \tag{0.2}$$

being ϕ the azimuthal coordinate. The contributions f_0 and g_0 in (0.1) have no azimuthal variation and result in Gaussian-like distributions. Moreover, $g_0=0$ in the even mode expansion and $f_0=0$ in the odd mode expansion. Due to sin(2ϕ) and cos(2ϕ), f_2 and g_2 correspond to four-lobed distributions mutually rotated by 45°. The ratio between the weights ($A^{\mathrm{TE}}-A^{\mathrm{TM}}$) and ($A^{\mathrm{TE}}+A^{\mathrm{TM}}$) determines the ratio between E_x and E_y and therefore the deviation from a uniform linear polarization state. When $A^{\mathrm{TE}}=A^{\mathrm{TM}}$, the field is homogeneously linearly polarized. This condition is fulfilled only for $k=0$, where TE and TM modes are degenerate due

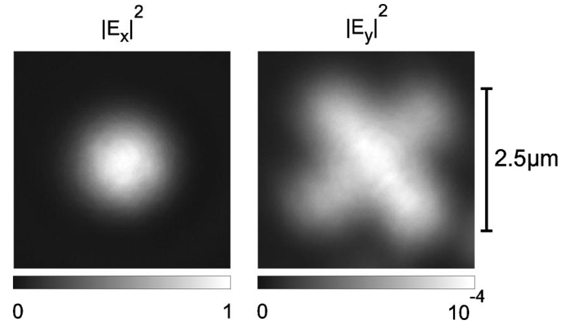

FIG. 2. Experimentally obtained polarization resolved near-field images. The gray scales are separately normalized to the intensity maxima in each polarization.

to degenerate Bragg-mirror reflectivities and mode-coupling coefficients. Any confined mode, however, is characterized by a k-distribution with nonvanishing contributions at $k\neq 0$ ($A^{\mathrm{TE}}\neq A^{\mathrm{TM}}$) and therefore is inherently inhomogeneously polarized. Consequently, the approximation of homogeneously linearly polarized modes is certainly good for the fundamental transverse mode in large diameter VCSELs with weak guiding mechanisms where the distribution of the expansion coefficients is narrow and peaked around $k=0$. In contrast, we expect the effect of inhomogeneous polarization to become observable in the case of small aperture oxide-confined VCSELs, where the optical field is more tightly confined and the modes have a broader k-distribution of the expansion coefficients with higher k-values involved. Thus, the spatially nonuniform polarization of the modes is a direct consequence of the VCSEL cavity and characteristic for the fields of all confined modes.

In order to give experimental evidence for our theoretical predictions, we have performed polarization resolved spatiospectral measurements on our VCSELs. Using a Glan-Thompson polarizer with an extinction ration of 40 dB and a high-resolution high-sensitivity CCD camera we have recorded images of the VCSEL near fields projected onto orthogonal axes of linear polarization, x and y, analogous to Fig. 1. The resulting images are displayed in Fig. 2. The left part of Fig. 2 contains the Gaussian-shaped x-polarized component of the total near field, which in our laser is the stronger component. In the right part of Fig. 2, we present the projection of the near field onto the orthogonal y-polarization axis. In this near-field image one clearly recognizes a characteristic four-lobed distribution similar as that of the even mode in Fig. 1, superimposed with an additional central spot. In principle, the four-lobed part of the distribution could be a second order transverse mode. To exclude this we have performed spatiospectral measurements of the y-polarization by combining a 1-m Czerny-Turner spectrometer and the CCD camera (details on the setup are given in [15]). We present these results in Fig. 3 where the upper part is the spectrally resolved near-field image: the cavity modes are separated along the horizontal axis according to their spectral splitting. Since the dispersion of the used grating is too small to also resolve the spectral width of the individual modes, their spatial distributions are reproduced in both transverse directions without noticeable distortion. The lower part of the figure

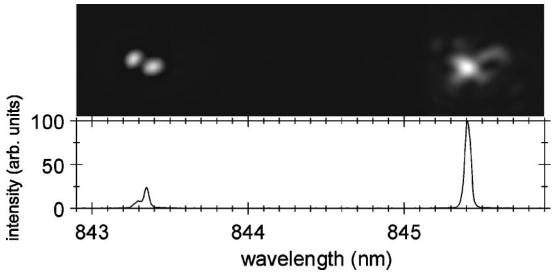

FIG. 3. Upper part: spectrally resolved image of the *y*-polarized near field. The first order mode has been selectively enhanced by applying a nonlinear intensity scale. Lower part: optical spectrum.

contains the corresponding nonspatially resolved optical spectrum. At $\lambda = 845.4$ nm we observe the four-lobed distribution of Fig. 2. In VCSELs, higher-order transverse modes oscillate at lower wavelengths due to the refractive index profile and planar mirrors [21]: the first-order transverse mode at $\lambda = 843.3$ nm is separated by $\Delta\lambda = -2.1$ nm in agreement with our model. The second order transverse mode with a four-lobed near field has been observed at even lower wavelengths $\lambda = 841.0$ nm in agreement with the model but only at very high pumping. The four-lobed distribution at $\lambda = 845.4$ nm, in contrast, is present at any injection current which is evidence that the *y*-polarized part of Fig. 2 indeed is the weak vectorial component of the even fundamental mode. Superimposed to the four-lobed distribution, however, there is an additional central spot (cf. Fig. 2). We have proven that this spot is *not* a residual part of the Gaussian distribution in the strong *x*-polarization by adding one additional polarizer along the *y*-polarization without further weakening the central spot. Thus we conclude, that the central spot is the Gaussian *y* component of the weakly excited odd fundamental mode.

In real lasers, the even and odd fundamental mode are split by birefringence, because their dominant components are orthogonally polarized. We have been able to measure this mode splitting by using a scanning Fabry-Perot interferometer. In our lasers, the splitting amounts to only $\Delta\nu = 2$ GHz corresponding to $\Delta\lambda = 0.005$ nm at $\lambda = 850$ nm, which is below the resolution of the spatiospectral measurement. Thus, the even mode's four-lobed distribution and the odd mode's Gaussian component are not resolved in Fig. 3. Birefringence also affects the power partition into orthogonal polarizations. In order to quantitatively estimate the power ratio of one mode's vectorial components in the device under investigation, we have included within the model an anisotropy. It determines the measured birefringence and can originate either residually or intentionally, as e.g., by stress resulting in gain anisotropy or dichroism [22,23]. The birefringence serves to select the lasing mode by lifting the degeneracy between the even and odd solutions, but has no influence on their spatial distribution. A further effect of birefringence is an enhancement of the weak vectorial components of each mode by a factor of 20, resulting in a ratio of the peak power densities of the *x* and *y* components for the lasing mode of 37 dB. This ratio is in quantitative agreement with the experimental observations, 36 ± 2 dB.

Inhomogeneous polarization of laser modes has been reported before. Indeed, the four-lobed intensity distribution observed in an Ar-ion laser [6] closely resembles the present results. However, the ratio between weak and strong polarization components in the Ar-ion laser was 10^{-11}, which is weaker by more than seven orders of magnitude than in the VCSELs. The physical origin for the particular strength of the effect in the VCSEL is the difference in both, the reflection coefficients of the multilayer Bragg-mirrors and the coupling coefficients of the expansion modes for TE and TM polarized light, mostly caused by the oxide layer. Both structural elements are not present in gas lasers.

The remarkably high degree of inhomogeneous polarization in VCSELs implies direct technological consequences: many applications require a high power ratio between orthogonal linear polarization components, i.e., a high degree of polarization purity. In real-world VCSELs, the polarization ratio rarely exceeds 25 dB due to the contributions of nonlasing modes of different polarization direction and unpolarized spontaneous emission. As an important result of the present investigation, the fundamental limit for the polarization purity even of a perfectly single-mode VCSEL is determined by deviations from the linear polarization state of the solitary mode. The polarization purity of a single mode strongly depends on the cavity structure via its guiding effect on the optical field and amounts to ≈ 35 dB in the device under analysis.

The quantitative agreement between the theoretical predictions and the experimental observations for the fundamental transverse mode is strong evidence for the validity of the applied model. As a general result, the vectorial model predicts that *all* transverse modes are spatially inhomogeneously polarized. An experimental analysis of these profiles remains a task for future work.

In conclusion, we have demonstrated that transverse modes in VCSELs are inherently inhomogeneously polarized. The strength of the deviation from a spatially uniform polarization depends on the device characteristics and increases with tight optical confinement. In the case of the fundamental transverse mode, the optical field consists of a Gaussian-shaped component in the strong polarization and a four-lobed distribution in the weaker orthogonal one. The observed effect is more than seven orders of magnitude stronger than former reports from gas lasers as a consequence of the particular cavity structure of oxide-confined VCSELs. Thus, our results of spatially nonuniform polarization shed new light on all polarization involved quantum optical phenomena in VCSELs.

We gratefully acknowledge H. Joch of Honeywell Germany and J. Tatum of Honeywell USA for providing us with their excellent lasers and for valuable structural information. The activity reported has been carried out in the framework of the Vigoni project (DAAD/CRUI). The Torino group acknowledges the support of MADESS II (Progetto Finalizzato of Italian CNR). The Darmstadt group acknowledges funding by Deutsche Forschungsgemeinschaft (EL 105/10).

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