Near-field scanning optical microscopy of polarization bistable laser diodes

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TE/TM polarization bistability in a $\lambda=1.3\ \mu$m ridge-waveguide InGaAsP/InP bulk laser is studied by near-field scanning optical microscopy with an optical resolution of better than $\lambda/8$. The near-field mode profiles of TE and TM emission show different lateral widths and distinctly different mode center positions. This lateral shift is related to a nonuniform strain distribution along the active layer. Based on this strain gradient, we present a model that accounts for the hysteresislike current dependence of the polarization resolved laser output. © *1996 American Institute of Physics.* [S0003-6951(96)04143-5]

Switching processes in semiconductor lasers are important both from the viewpoint of nonlinear dynamics and for numerous applications in optoelectronics and optical communications. Recently, polarization switching has been observed in strained InGaAsP/InP laser diodes showing a TE and/or TM polarized emission in different regimes of injection current.[1,2] Bistability of the two laser modes and fast TE/TM switching in the gigahertz range have been studied in great detail[3,4] and were attributed to a nonlinear interaction of the two emission modes via gain saturation and to lateral waveguiding effects.

The polarization bistability was analyzed in terms of polarization-dependent nonlinear rate equation models.[5] These models give a stability criterion for polarization bistability, namely, nonlinear cross gain saturation has to be larger than self-saturation. Such models do not consider, however, possible spatial variations on the laser characteristics, such as, e.g., spatial hole burning, which may also be important for the polarization bistability.[6] Here, measurements of the near-field intensity distribution of the two modes with high spatial resolution should provide direct information. In this letter, we report the study of the spatial emission properties of polarization bistable InGaAsP/InP laser diodes by near-field scanning optical microscopy (NSOM) with a resolution of 150 nm. The experiments reveal a distinct asymmetry between the TE and TM near-field mode profiles that arises from a strain-induced lateral gain gradient within the active layer. This strain-induced asymmetry is shown to play a decisive role for the observed polarization bistability.

The structure of the 1.3 μm ridge-waveguide InGaAsP/InP laser is shown schematically in Fig. 1(a) and has been described in detail elsewhere.[6] The shape of the InP ridge is a slightly asymmetric trapezoid with a base length of 4 μm, and a thickness of 1 μm. The lattice mismatch of $\Delta a/a=10^{-3}$ between the 0.15-μm-thick active layer and the substrate results in a tensile biaxial strain of about 10^9 dyn/cm^2. The electric field vectors of the TE and TM waves are parallel to the lateral x axis and the transverse y axis, respectively. The near-field scanning optical microscope[7,8] is based on a commercial instrument (Topometrix). Fiber tips were pulled from nonpolarization-preserving single-mode optical fibers with an operating wavelength of 820 nm. Thermal expansion of the gold-coated tip was limited to less than 60 nm and did not affect the NSOM images.[9] The diameter of the tip aperture was kept at approximately 150 nm, resulting in an optical resolution of about $\lambda/8$ for $\lambda=1.3\ \mu$m. All experiments were performed in the collection mode, i.e., the laser emission was detected through the fiber tip. The laser diode is mounted on an xyz-piezo translator and scanned relative to probe tip. Stabilization of the tip to sample distance of 5 ± 1 nm was achieved using a shear-force feedback technique.[10] The location of the ridge on the laser structure

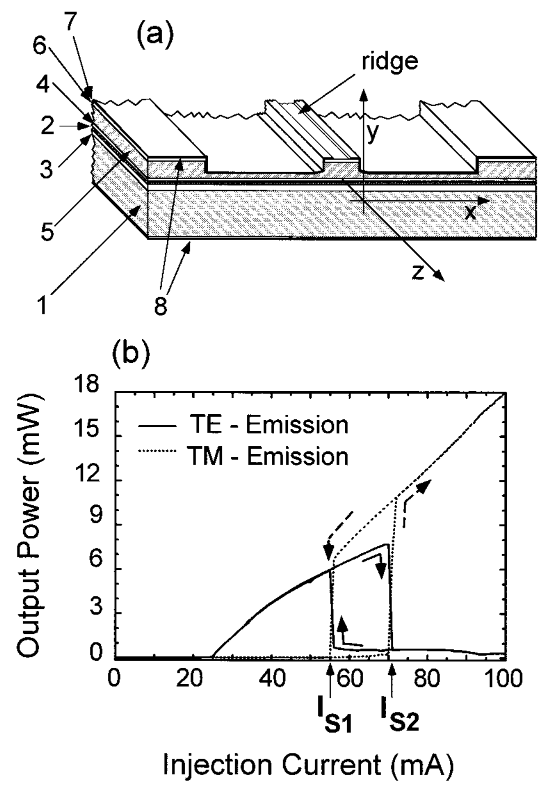

FIG. 1. (a) Schematic of the ridge-waveguide InGaAsP/InP laser used in the experiments. The device is grown on an n-InP substrate (1). It consists of an active InGaAsP layer (2) cladded by an Sn-doped InP buffer layer (3), an InGaAsP etch-stop layer (4), and a p-InP layer (5) inside the ridge. This is followed by a p^+-InGaAsP cap layer (6), a SiO_2 isolation (7), and a gold contact (8). (b) Polarization resolved optical output power vs injection current for an InGaAsP/InP ridge-waveguide laser at a temperature of 290 K.

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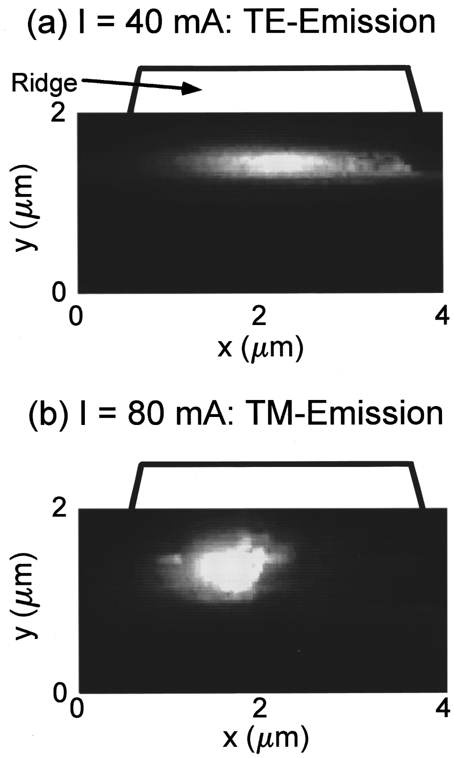

FIG. 2. Near-field emission profile for TE polarized laser output of the ridge-waveguide InGaAsP/InP laser at an injection current of 40 mA. The emission profile is elliptical in shape with a transverse width of 0.5 μm and a lateral width of 2.3 μm (FWHM). In the lateral direction, the emission is centered symmetrically relative to the ridge structure. (b) Near-field emission profile for TM polarized laser output at an injection current of 80 mA. The transverse width of the emission profile increases to 0.78 μm while the lateral width narrows to 1.6 μm. Note that the center of the TM mode profile shows a lateral shift of 0.7 μm relative to the TE profile.

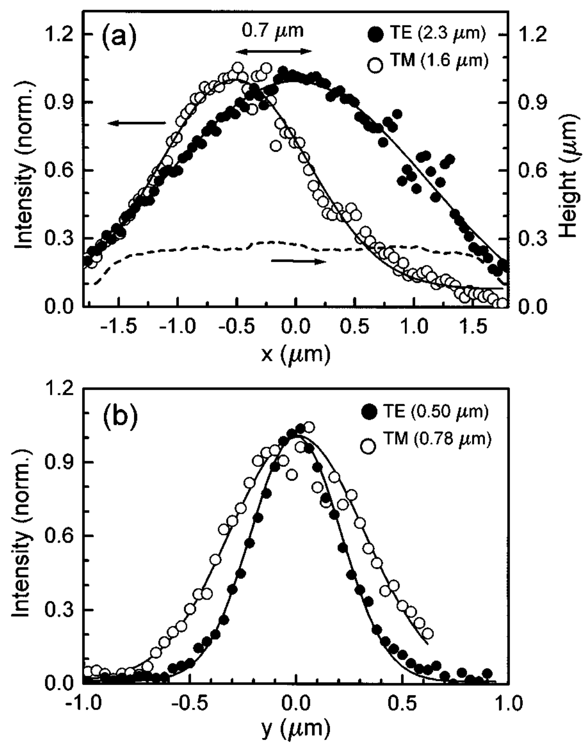

FIG. 3. Cross sections through the near-field emission profiles along the lateral (a) and transverse (b) direction TE ($I=40$ mA) and TM ($I=80$ mA) polarized laser ouput. Gaussian shaped fits through the experimental data are shown. Note the pronounced lateral shift of 0.7 μm of the center of the TM mode relative to that of the TE mode. The dotted curve shows the position of the ridge, as derived from a shear-force image.

was determined from shear-force images recorded simultaneously with the near-field data. During the NSOM measurements, the far-field polarization of the laser emission was constantly monitored and remained unchanged. Furthermore, the lasing thresholds of TE and TM emission were not altered by the fiber tip.

In Fig. 1(b), the polarization resolved far-field output power of the laser diode is plotted as a function of the injection current I ($P-I$ characteristics). Lasing starts at $I=25$ mA in the TE mode which dominates up to $I=72$ mA. At $I_{S1}=72$ mA the polarization of the laser emission switches abruptly from TE to TM and the laser remains in this mode at all higher currents. If the injection current is decreased below I_{S1}, the laser remains in the TM polarization, until it switches back to TE polarization at $I_{S2}=55$mA, showing hysteresislike power–current characteristics.

NSOM images (Fig. 2) of the laser emission were recorded for different injection currents I. In order to use lock-in detection, the injection current is modulated between 0 and I, using rectangular current pulses with a repetition rate of 3 kHz. In this way, we probe only the $P-I$ characteristics in the direction of increasing I in Fig. 1(b), i.e., the laser emits in TE polarization for all currents below I_{S1}. For $I=40$ mA [Fig. 2(a)], i.e., for TE emission well below the switching current I_{S1}, the emission profile is elliptical in shape with a transverse width of 0.50 μm [full width at half magnitude (FWHM)] and a lateral dimension of 2.3 μm. Along the lateral direction the maximum of the emission intensity is located at the center of the trapezoidal ridge. This is evident from Fig. 3(a), where a cross section through the TE profile along $y=0$, i.e., the lateral mode structure (solid circles), is compared to the topography of the ridge structure as obtained from the shear-force image (dashed line). In the shear-force mode, the probe is scanned at a constant distance to the sample, and the voltage across the z-piezo translator, i.e., a quantity proportional to the vertical elongation of the sample, is monitored.[10,12] The ridge structure extends from $x=-1.7$ to 1.7 μm and the TE mode is centered symmetrically at $x=0$. In the transverse direction [Fig. 3(b)], the maximum of the TE mode lies in the center of the active layer at $y=0$. Identical near-field emission profiles are observed for all currents between 35 and 70 mA. When the injection current is increased beyond the switching current I_{S1}, the laser emission changes from TE to TM polarization and the near-field intensity profile changes significantly. The maximum of the optical mode shifts in the lateral direction by as much as 0.7 μm to an off-center position under the ridge [Figs. 2(b) and 3(a)]. This pronounced asymmetric mode shift is evidenced in Fig. 3(a), where the lateral TE and TM near-field profiles are compared. The transverse width of the mode profile increases from 0.50 μm (TE emission, closed circles) to 0.76 μm (TM emission, open circles), while the lateral width decreases from 2.3 μm (TE) to 1.6 μm (TM) [Fig. 3(b)].

Similar results were obtained for several other polarization bistable 1.3 μm InGaAsP ridge-wave laser diodes. The lateral TE emission profile of the investigated diodes was located symmetrically at the center of the ridge, while the center of the TM emission showed a marked lateral shift. For the investigated diodes, this shift occurred in the direction towards $x<0$. A shift towards $x>0$ was not found experimentally. We also investigated a laser diode of the same composition that showed no polarization bistability but a gradual transition from pure TE to pure TM emission, with TE/TM mode coexistence in the intermediate current interval between 37 and 62 mA. For this diode, the maxima of both the TE and TM near-field profiles were located at the center of the ridge, i.e., the lateral shift was absent.

The observed lateral shift of the TM emission profile provides direct evidence for a variation of the TM gain coefficient along the lateral x axis. As long as the lateral gain profile is assumed to be symmetric with respect to $x=0$, the center of the optical mode should always be located at $x=0$. The lateral gain gradient is very likely to be caused by a nonuniform strain distribution along the x axis. Such a strain gradient is strongly suggested by measurements of the emission anisotropy at injection currents below the lasing threshold which show a systematic decrease of the degree of polarization in the direction of $x<0$.[13]

The dependence of the linear gain coefficients a and the carrier densities N_t at transparency for TE and TM polarization on the biaxial strain ϵ, is approximately given as[5,14]

$$a_{\mathrm{TE}}=a-b_{\mathrm{TE}}\epsilon, \quad N_{t\mathrm{TE}}=N_t+c_{\mathrm{TE}}\epsilon, \tag{1a}$$

$$a_{\mathrm{TM}}=a+b_{\mathrm{TM}}\epsilon, \quad N_{t\mathrm{TM}}=N_t-c_{\mathrm{TM}}\epsilon. \tag{1b}$$

Here, the biaxial strain ϵ is defined as $\epsilon=-\Delta a/a_{\mathrm{InGaAsP}}$, where $\Delta a=a_{\mathrm{InGaAsP}}-a_{\mathrm{InP}}$ is the difference between the lattice constants of the unstrained active layer and substrate materials, so that the tensile strain in our laser structure corresponds to positive values of ϵ of about 10^{-3}. The terms $a=2.5*10^{-16}$ cm^2, $N_t=1.4*10^{18}$ cm^{-3}, $b_{\mathrm{TE}}=1.5*10^{-14}$ cm^2, $b_{\mathrm{TM}}=3.5*10^{-14}$ cm^2, $c_{\mathrm{TE}}=3.2*10^{19}$ cm^{-3}, and $c_{\mathrm{TM}}=4.7*10^{19}$ cm^{-3} are material parameters.[14] We note that the strain dependence of the TM gain coefficient is significantly stronger than that for TE polarization. The threshold densities for lasing for TE and TM polarization are very similar, a necessary condition to observe polarization bistability.[5]

Within this model, the behavior observed in our experiments is explained in the following way. First, we conclude that our devices show an increase of tensile strain along the *negative x* axis which results mainly from the manufacturing process. At low injection currents, light emission starts in the TE mode since TM emission shows a smaller facet reflectivity and smaller transverse confinement factors. We found that an increase in current corresponds to an increase in TM gain. At the injection current I_{S1}, the effective gain for TM becomes larger than that for the TE polarization and TM emission builds up. A switching from TE to TM emission requires efficient mode competition, suppression of TE emission, and therefore sufficient spatial overlap of both modes. Eventually the TM mode is stabilized in the region of optimum TM gain, as observed experimentally. This leads to the observed spatial shift between TE and TM emission. The increase in local TM gain is connected with a decrease of the threshold carrier density for TM lasing. The reduced carrier density further stabilizes the TM emission and thus suppresses the TE emission. Due to this lateral shift of the TM emission, a reduction of the current to a value I_{S2} smaller than I_{S1} is required until the TE effective gain becomes larger than that for TM polarization and switching back to TE emission can occur.

This qualitative picture accounts for the hysteresis in the $P-I$ dependence and the observed lateral mode shift. It suggests that the shape of the $P-I$ characteristics depends strongly on the strain gradient along the active layer. This is supported by the experimental fact that the polarization-dependent $P-I$ curves vary drastically for different parameters during device processing, i.e., different strain distributions. It is important to note that the lateral separation of the TE and TM emission reduces the spatial overlap of the two modes and leads to a strong reduction of nonlinear cross saturation of the TE and TM gain, i.e., of the mutual carrier depletion due to laser action on the two modes.[5] Thus, this mechanism seems to play a minor role in our devices. A detailed theoretical analysis is under way to confirm the suggested qualitative model.

In summary, the polarization dependent near-field emission profiles of 1.3 μm ridge-waveguide InGaAsP/InP laser diodes were studied by near-field scanning optical microscopy (NSOM). The observed distinct lateral shift between the centers of the TE and TM mode profiles is the result of a nonuniform strain distribution along the active layer of the laser diode. Based on this lateral strain gradient, we presented a qualitative model that accounts for the hysteresislike current dependence of the polarization resolved laser output power. It will be of great interest to investigate the transient polarization-resolved mode evolution using time-resolved near-field scanning optical microscopy.

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