# Beam divergence and waist measurements of laser diodes by near-field scanning optical microscopy

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We demonstrate the use of near-field scanning optical microscopy (NSOM) for the measurement of the beam properties of single quantum well, graded index separate confinement heterojunction ridge laser diodes. Using NSOM, we measure the field intensity in the transverse plane at near field and as a function of distance from the facet. The divergence of the laser beam and the beam waists in vertical and lateral dimensions are directly measured and the astigmatism of the mode is determined. In the near field, we observe a nearly ideal Gaussian shape in the vertical dimension which is consistent with the beam divergence as measured in the far field. In the lateral dimension, the beam shape deviates from the ideal Gaussian since the mesa structure of the laser diode provides an effective step-index waveguide. The non-Gaussian structure of the mode is also observed in the beam divergence properties. © *1997 American Institute of Physics.* [S0003-6951(97)01406-X]

Near-field scanning optical microscopy and spectroscopy (NSOM) is a technique[1,2] where a small optical probe is placed within a fraction of a wavelength of a sample and scanned over the surface.[3] Typically an aluminum coated, tapered, single-mode optical fiber is used as the tiny aperture through which the light is coupled and yields a spatial resolution of the order of the tip size (~100 nm). The application of near-field imaging and spectroscopy to optoelectronic devices and laser diodes provides subwavelength information on device structure, performance, and output properties.[4–8] The emission profile is obtained by coupling the emitted radiation into the fiber-tip (collection mode). In excitation mode, the fiber tip can be used as a local, tunable optical source allowing for near-field optical beam induced current (NOBIC) measurements.[4,5] The location of the active region relative to the mesa and optical mode of a laser diode can be determined in this way. We directly measure the optical beam waist and astigmatism of high power strained (In,Ga)As quantum well lasers using the near-field tip to collect the output of the laser diode at various heights above the device facet.

We studied high power strained (In,Ga)As graded-index separate confinement heterojunction (GRINSCH) laser diodes.[9] These devices emit an nearly diffraction limited single lobe at 980 nm and are designed to pump Erbium doped fiber amplifiers. The structure consists of a single InGaAs quantum well sandwiched in a symmetrical waveguide of graded AlGaAs cladding layers with parabolic refractive index variation. In the vertical dimension (along the crystal growth), the graded index of refraction provides guiding of the optical field. In the lateral dimension, a 5-$\mu$m-wide ridge is defined by wet etching to provide a step index of refraction for optical guiding. The cavity facets are dielectric coated for front and rear reflectivities of 0.1 and 0.9, respectively. The laser output is typically coupled into a single-mode optical fiber, therefore, it is critical to have a good quality single mode beam. The beam property that usually has the most dramatic impact on how well a diode laser's output may be collimated or focused is astigmatism. Even when correctional optics are used, there is typically a residual astigmatism in the order of few $\mu$m, because of the statistical variations from laser to laser. Furthermore, with temperature and pump current variations, the beam properties may change resulting in loss of coupled power. High resolution and accurate characterization of the beam properties is, therefore, crucial for the design and optimization of laser diodes and related optical components. Beam properties are typically characterized in the far field using knife-edge scan techniques, with beam waist profiles deduced under the assumption of Gaussian fields and with knowledge of the properties of the collimating optics. The advantage of the NSOM technique is that both the lateral and axial position of the beam waist relative to the device structure can be determined with high resolution, while also yielding accurate astigmatism values. Our measurements of the beam waist represent, to the best of our knowledge, the first direct determination of laser diode astigmatism.

The laser diode is mounted facet up on a piezo actuated flexure stage and scanned in the $\hat{x}$-$\hat{y}$ plane beneath the probe tip. Figure 1 shows an image of the sample topography in greyscale obtained using shear force with the emission intensity measured in collection mode superimposed as constant intensity contours. The laser emission profile is centered under the mesa and over the active region as determined by NOBIC measurements.[4,5] Slight distortion at the edge of the emission profile is believed to be due to the deep mesa etch. This image is typical of the mode structure of the device up to 200 mA.

Figure 2 shows the lateral (in the plane of the layer structure) and vertical (in the growth direction) profiles of the mode intensity as measured in the near field. In the vertical dimension, the measured profile is nearly an ideal Gaussian. The Gaussian mode shape agrees with the solution for a graded-index waveguide.[10] In the lateral dimension, the measured profile shows a slight deviation from a Gaussian as

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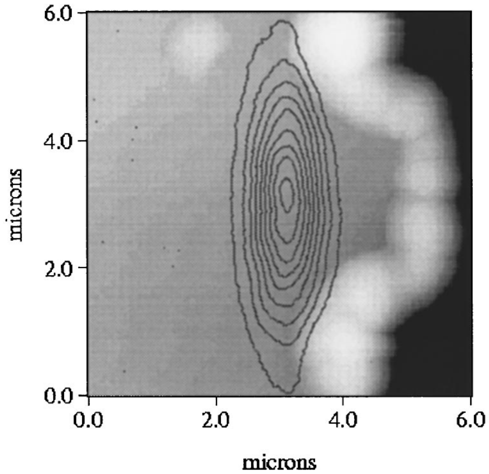


FIG. 1. Near-field collection mode image of the GRINSCH laser diode emission intensity (constant intensity contours) superimposed on the topographical shear-force image (greyscale). The metal contact on top of the mesa slightly protrudes over the facet of the device, yielding the brighter topographic regions.

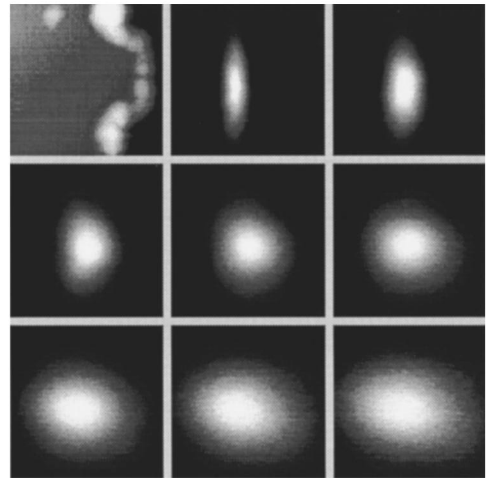

FIG. 3. Images of the beam propagation from the near field to 7 $\mu$m from the laser diode taken in 1 $\mu$m steps. The top left image is the topography to provide the physical orientation for the laser emission images given in left to right sequence. All images are 6×6 $\mu$m. The greyscale for each image is chosen to maximize contrast.

expected from a step index waveguide formed by the mesa-etched ridge structure. In this case, the solution to the wave equation for the electric field for a step change in the index of refraction is a cosine function with matching at the waveguide boundaries to an exponentially decaying function. As discussed below, although the intensity distribution is similar to a Gaussian, the beam divergence properties demonstrate significant non-Gaussian properties in the lateral direction.

Figure 3 is a series of high-resolution images of the laser mode intensity collected with the near-field probe as a function of height above the laser diode back facet. The laser is operated at a current of 100 mA. The first image was taken in the near field ($z \sim 10$ nm). Each successive image is 1 $\mu$m further from the facet with the last image at 7 $\mu$m from the surface. As expected, the spreading of the beam is much faster in the vertical than the lateral dimension. The elliptical beam at the facet becomes a nearly circular beam at a height of 4 $\mu$m. From this series of scans, we determine the variation of the spot size of the mode along the optical axis. Figure 4 shows the spot size measurements as determined from the $1/e^2$ intensity points of Gaussian fits to the measured beam profiles. The spot sizes in the lateral and vertical dimensions are shown by squares and circles, respectively. The position of the laser facet is set to the origin of the $x$ axis. On the same figure, solid lines show the fits of the spot

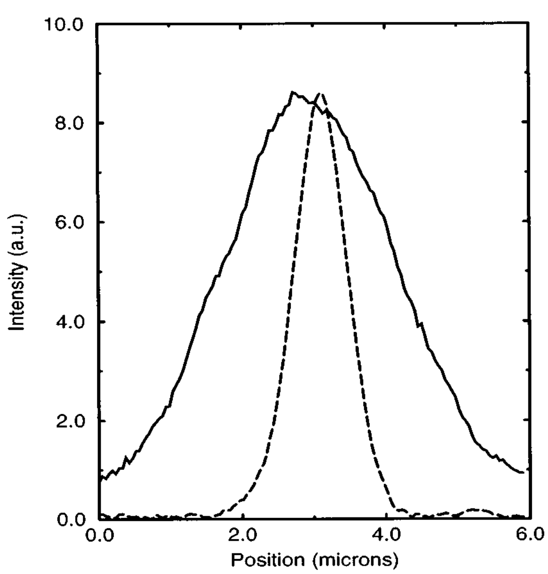


FIG. 2. Vertical (in the film growth direction) and lateral (in the plane of the layer structure) cross sections of the laser mode as measured in the near field are shown as dashed and solid lines, respectively. The position axis corresponds to that of Fig. 1.

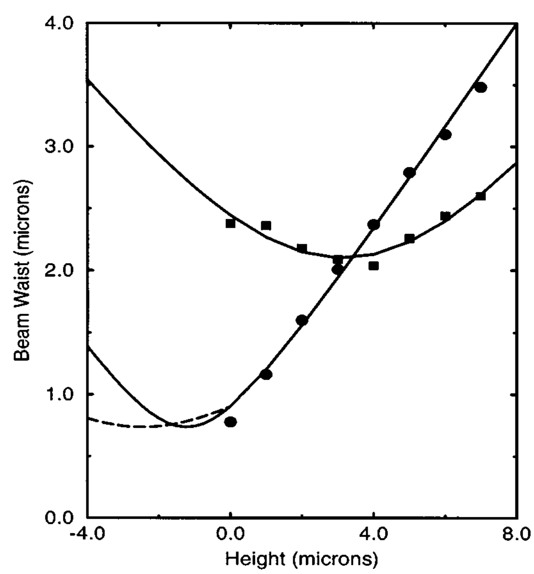


FIG. 4. Experimental measurements of the lateral (squares) and vertical (circles) spot size dependence on height above the laser diode facet. The spot sizes are determined by assuming and fitting a Gaussian distribution. Solid lines show the fit to the beam divergence as explained in the text. The beam divergence fits are extended into the device to make the astigmatism more evident. The dashed line is the vertical divergence fit with the dielectric interface of the laser diode mirror represented as an index of refraction $n = 2$.

size variation along the optical axis to a propagating Gaussian beam given by[10]

$$w^2(z) = w_0^2\left[1 + \left(\frac{z}{z_0}\right)^2\right]. \tag{1}$$

The fit for the vertical axis makes use of a beam waist, $w_0 = 0.736$ $\mu$m, derived from the asymptotic divergence angle of the optical field measured in the far field consistent with a pure Gaussian beam. The minimum position, $z = 0$, and the confocal parameter $2z_0$ are the two independent parameters. The derived confocal parameter matches closely with that expected from the beam waist for a pure Hermite–Gaussian beam satisfying $z_0 = \pi w_0^2/\lambda$. The match between the beam waists calculated from the far-field divergence angle and obtained by fitting the direct measurements of spot size in the near field is within 1%. For the lateral dimension, the beam waist ($w_0$), its position ($z = 0$), and the confocal parameter ($2z_0$) are used as independent variables to fit the experimental data. The derived values from the fit for the lateral beam waist and the confocal parameter suggest a non-Gaussian propagating field. In this case, the value of the confocal parameter obtained from the fit to the experimental data is only approximately 1/3 of what is expected from a Gaussian beam with a beam waist $w_0 = 2.1$ $\mu$m. If the fit is done with the beam waist set to the value derived from the far-field measurements, the curvature seen in the experimental data cannot be matched.

Along the axis of propagation, we observe a monotonically diverging beam for the vertical dimension. By extrapolating the spot size curve to negative $z$ values, we obtain the beam waist position for the vertical dimension at approximately 1 $\mu$m below the facet. When we consider the refractive index change at the facet, we observe that the beam waist remains the same while its position moves further into the device. In Fig. 4, dashed lines show the extrapolated spot size for a refractive index of 2—an approximate effective value considering the indices of the facet coating. The beam profile in the lateral dimension, however, exhibits a minimum in the waist diameter at approximately 3 $\mu$m from the facet resulting in an astigmatism value of about 4 $\mu$m. Although the astigmatism of this specific device was not characterized by far-field methods, the astigmatism measured by NSOM is consistent with previous results.[9] These direct measurements of the beam waists can be used to construct the phase front at the laser facet which in turn provides information about the thermal distribution in the device structure. Similar measurements at various drive current and operating temperature conditions to study the variation of phase front and to analyze the effect of thermal distribution on the beam quality are underway.

In summary, the high-resolution imaging capabilities of NSOM provide a direct way of characterizing the beam properties of semiconductor lasers. This measurement of the beam waist represents, to the best of our knowledge, the first high-resolution direct measurement of laser diode astigmatism. We expect that this new capability will provide a useful tool for laser diode design and optimization.

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