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Theoretical and Experimental Study of Near-Field Beam Properties of High Power Laser Diodes

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Abstract— **We present laser beam astigmatism results obtained by Near-field Scanning Optical Microscopy. Measurements made with this technique on the high reflecting facet of a Graded Index Separate Confinement Heterojunction laser diode indicate the lateral beam waist is outside of the device structure, seemingly in contradiction to far-field measurements made on the low reflecting output facet of the device. Our attempts to resolve the discrepancy by invoking thermal lensing due to a temperature gradient across the mirror facet is capable of partly generating the focusing required to explain the difference in observed beam waist position for the two separate measurements. Simulations which include inhomogeneities along the length of the device cavity may resolve the apparent discrepancy. This paper is eligible for best student paper.**

Keywords— **near-field scanning optical microscopy, astigmatism, laser diode**

I. Introduction

RECENTLY , using near-field scanning optical microscopy (NSOM) we observed focusing of the laser mode in the lateral dimension (in the plane of the p-n junction) outside of the device structure for a high power laser diode.[1]. The devices we studied are graded-index separate confinement heterojunction (GRINSCH) lasers diodes. These devices emit a nearly diffraction limited single lobe at 980 nm and are designed to pump Erbium doped fiber amplifiers for use in long distance telecommunication systems. The devices we studied were designed to be index guided in the lateral dimension. However, while predominately index guided, previous simulations and experimental evidence suggest that during high power output gain guiding contributes to the waveguiding of the laser mode.[2] Consistently, far-field studies on the low reflecting, output facet of similar devices show the lateral beam waist to be inside of the laser cavity as is expected for gain-guided devices.[3] Unlike the far-field studies, our NSOM results on the beam astigmatism of GRINSCH lasers diodes were carried out on the high reflecting facet of the device and found the device focusing outside of the mirror facet. In an effort to reconcile these facts, we have tried to simulate focusing of the laser mode outside of the laser cavity by means of an optical field induced temperature gradient on the high reflecting dielectric mirror stack.

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II. Device

We studied high power strained (In,Ga)As graded-index separate confinement heterojunction laser diodes. These devices emit a 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 5μm 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.

III. Experiment

Near-field scanning optical microscopy and spectroscopy (NSOM) is a technique [4][5] where a small optical probe is placed within a fraction of a wavelength of a sample and scanned over the surface.[6] 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 order the tip size ($\sim$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.[7][8] The emission profile is obtained by coupling the emitted radiation into the fiber-tip. We directly measure the optical

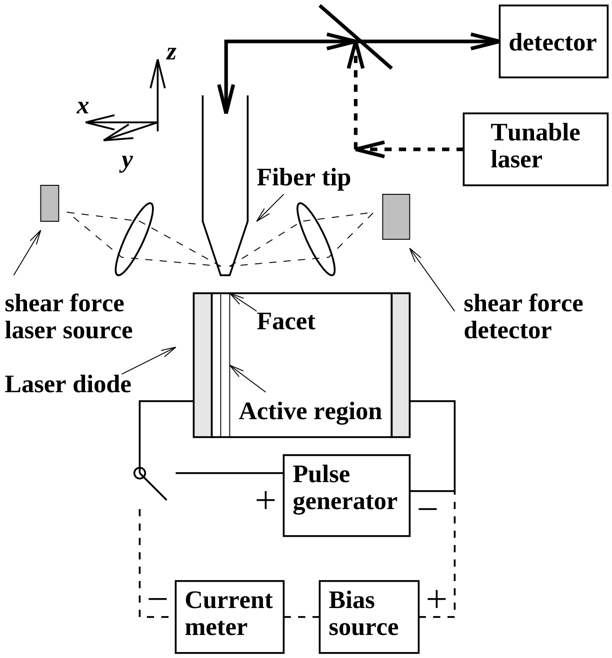

Fig. 1. Schematic of the experimental set-up.

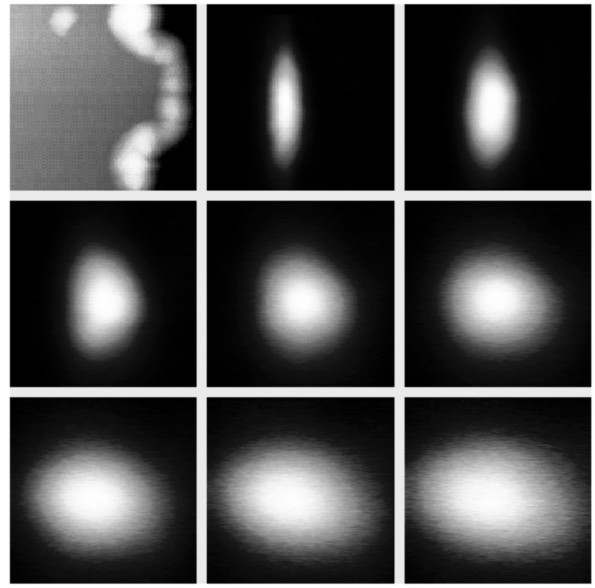

Fig. 2. Images of the beam propagation from the near-field to 7μm from the laser diode taken in 1μm steps. The top left image is the topography to provide the physical orientation for the laser emission images given in left to right sequence. All images are 6x6μm. The greyscale for each image is chosen to maximize contrast.

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.

The GRINSCH laser diode was mounted with its high reflecting mirror pointing up on a piezo actuated positioning stage and scanned beneath the probe of a near-field scanning optical microscope. Figure 1 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 1μm further from the facet with the last image at 7μm 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 4μm. From this series of scans we determine the variation of the spot size of the mode along the optical axis. Figure 2 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.

IV. Discussion

Previous studies of the astigmatism of these high power GRINSCH laser diodes found the devices typically have astigmatisms of 2-4 microns.[2] The far-field results find the lateral beam waist for the low reflecting facet occurring inside the device relative to the position of the vertical beam waist. With strong index guiding in the vertical dimension which is responsible for the vertical waist being fixed at the end of the heterojunction waveguide, the point at which the dielectric mirror stack begins, the lateral waist is expected to be inside the laser cavity.

Although these GRINSCH lasers were intended to be index guided in the lateral dimension, it was previously found that index guiding alone is not enough to confine the optical mode at high output powers. For a gain guided device, one expects to find the beam waist for both facets to occur inside of the device structure. However, carrier density inhomogeneity and temperature variations along the length of the cavity will probably result in different beam propagation parameters for the two output facets.[9]

Our NSOM studies of these devices have been mainly limited to studying the optical beam which exits the device through the high reflecting mirror due to difficulties probing the extremely high power density which exists at the low reflecting mirror facet. The continuous-wave power density on the output facet of the GRINSCH laser diodes is approximately 2 MW/cm^2. The NSOM tips are unable to probe this intense laser field. The high optical field damages the metal film of the NSOM probe which provides optical confinement for the probe and hence the high resolution.

In an effort to reconcile the differences observed for the laser output from the two different mirror facets, we have begun to simulate focusing of the laser mode by an index variation across the mirror facet induced by the incident optical field. We have simulated the waveguide mode of the GRINSCH laser diode being focussed by the high reflecting dielectric stack due to a real index of refraction variation proportional to the local laser mode intensity. The focusing of the laser mode by a laterally graded index profile will have a more significant effect for the high reflecting facet due to the greater optical path length than that of the low reflecting facet.

In our model we stipulate that the beam focuses outside the cavity due to the heating of the dielectric mirror stack and consequently the variation in the refractive indices of the materials forming the stack. Such a graded index object might act as a thin lens and bend the phase front towards a focal point outside of the facet. We have applied the basic tools of Fourier optics to propagate the laser beam through the graded-index mirror and then in air.[10] It was assumed that the index variation due to heating is about the same shape as the mode, which is actually the source of the heating.

In figure 3 we compare the laser mode spot size along the optical axis as given by our simulation with the data collected by NSOM. The lateral beam spot size from the NSOM studies are plotted as squares while the simulation results are shown as triangles. For the simulation we required the initial waveguide mode have a spot size at the surface consistent with the NSOM data. Using the simulation, we tried to achieve a waist minimum at the same point along the optical axis at which the waist minimum is observed by the NSOM experiments. In order to achieve a focus at 4 microns from the laser facet, we see that the resultant beam has a smaller beam waist than found by NSOM. Of greater significance, a maximum in the index variation of 5% was necessary to achieve these results. Such a real refractive index variation requires facet temperatures an order of magnitude greater than is reasonably expected.

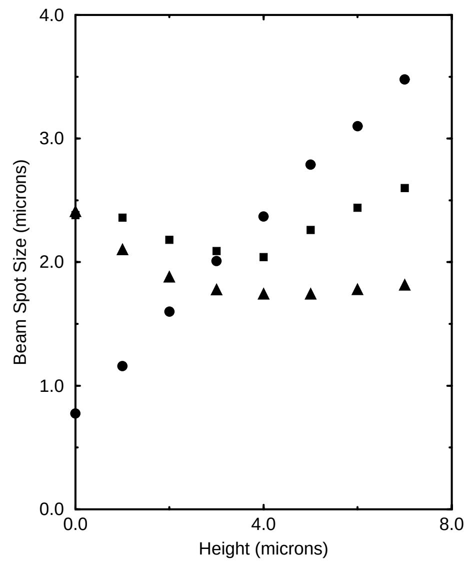

Fig. 3. Experimental measurements of the lateral (squares) and vertical (circles) spot size dependence on height above the laser diode facet. The spot sizes are determined by assuming and fitting a Gaussian distribution. Simulated data of the focusing effects of the graded index mirror facet are shown as triangles.

V. Conclusions

We have measured the position of the lateral beam waist of a GRINSCH laser diode for the high reflecting mirror facet by NSOM. Measurements made with this technique indicate the lateral beam waist is outside of the device structure, seemingly in contradiction to far-field measurements made on the low reflecting output facet of the device. Thermal lensing due to a temperature gradient across the mirror facet is incapable of generating the focusing required to explain the difference in observed beam waist position for the two separate measurements. In order to make a direct comparison with far-field results, we hope to obtain lateral beam waist measurements by NSOM for the low reflecting facet by driving the laser diode at very low duty cycles with pulse length significantly shorter than the heating cycle of the probe. Further simulations may be able to explain the apparent discrepancy if inhomogeneities in temperature or carrier concentration along the cavity are included.

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