Light-induced expansion of fiber tips in near-field scanning optical microscopy

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The emission profiles of laser diodes working at 780 nm and 1300 nm are studied by near-field scanning optical microscopy. As the near-field probe is scanned across the laser mirror facet, the laser emission induces a transient expansion of the probe tip which is monitored using shear force microscopy. The thermal expansion of the tips reaches absolute values of up to 100 nm per mW of emitted laser power. A fully metallized near-field probe tip is shown to serve as a local bolometer with a spatial resolution of better than 1 μm. © *1996 American Institute of Physics.* [S0003-6951(96)03729-1]

Near-field scanning optical microscopy (NSOM)[1,2] offers unique new opportunities for studying the static and dynamic optical properties of nanostructures. Subwavelength optical resolution as good as $\lambda/20$ is achieved by transmitting light through a nanometer-sized aperture located at the end of a suitable probe tip. In the current stage of development of the technique, a tapered single mode optical fiber with a lateral metal cladding and an uncoated end face is used as the light probe. In most experiments, samples located in the near field of such a tip have been illuminated through the fiber in order to record a high-resolution image (illumination mode). However, the fiber tip can also be used to collect light emitted by the sample with high spatial resolution. This collection mode has been applied in recent measurements where the near-field intensity distribution of laser diodes was studied.[3]

The interaction between the fiber tip and the sample as well as the local intensity distribution determine the image recorded with a NSOM. In particular, absorption of light in the fiber tip and/or its coating leads to thermal expansion of the probe, a mechanism that changes the probe geometry and thus directly affects image formation. In the literature, this effect has only been studied in the illumination mode via thermal changes of the transmitted intensity or the coating reflectivity.[4,5] In this letter, we study NSOM image formation in the collection mode using semiconductor lasers as light-emitting samples. We demonstrate that heating of the fiber tip by absorption of light from the sample leads to severe changes of NSOM images, in particular in the shear force mode where the topography of the sample is monitored. The thermal expansion of fiber tips with a 100 nm thick aluminium coating is proportional to the absorbed optical power and has values of 100 and 20 nm per mW for emission wavelengths of 780 and 1300 nm, respectively. These experiments allow us to directly measure the maximum emission intensity of the sample that can be monitored in collection mode NSOM experiments without destruction of the probe tip.

The near-field scanning optical microscope is based on a commercial instrument (Topometrix Aurora). Probe tips with a cone angle of 10° were pulled from single-mode optical fibers in a commercial CO_2 laser-based fiber puller and then coated with 50–100 nm aluminum. The diameter of the uncoated tips was less than 50 nm. Shear force images recorded with these uncoated tips gave a lateral topographic resolution of better than 20 nm. The optical resolution of the aluminium coated tips was tested using a standard AFM grating and was better than 50 nm. A shear force setup[6,7] was used for tip-sample distance regulation. Experiments were performed at a tip-sample separation of 5 ± 1 nm. Two kinds of commercial shallow stripe multiple-quantum-well (MQW) laser diodes were used in the experiments, a 5 mW GaAs/AlGaAs diode emitting at 780 nm (Hitachi HL 7843 MG) and a 10 mW InGaAsP diode working at 1300 nm (HL 1326 MF). The geometry of the 780 nm laser heterostructure consists of a 2 μm *n*-doped AlGaAs cladding layer, the active MQW layers, a *p*-doped AlGaAs layer and a GaAs cap layer. The laser diodes were mounted on an *xyz*-piezo translator and scanned relative to the probe tip. The laser output transmitted through the tip was detected with a photomultiplier or photodiode. The piezoscanner was software linearized and calibrated against a standard AFM grating with a calibration error of less than $\pm5\%$.

NSOM images of the laser emission are shown in Fig. 1. At injection currents above the lasing threshold of 18 mA, the emission profiles are elliptical in shape. In the transverse direction, i.e., perpendicular to the active layer, the width of the near-field profile is 0.70 ± 0.05 μm (FWHM). Within experimental error this width is independent of the injection current, as expected for an index-guided structure. The near-field transverse mode profiles are in agreement with the far-field beam divergence angle $\theta_\perp = 24°$ as has been verified by Fourier transformation of the near-field data. In the lateral direction, the width of the gain-guided optical mode depends on the injection current. The near-field images in Fig. 1 illustrate a pronounced narrowing of the lateral profile as a function of current below threshold. At $I=12$ mA, the width is 4.5 μm and decreases to 2.7 μm at 17 mA whereas the narrowing is much weaker at higher currents [Fig. 1(c)]. The lateral dimension of the near-field profile of 2.7 μm is consistent with the corresponding far-field angle $\theta_\parallel = 10°$. Above threshold, the observed near-field profile is Gaussian

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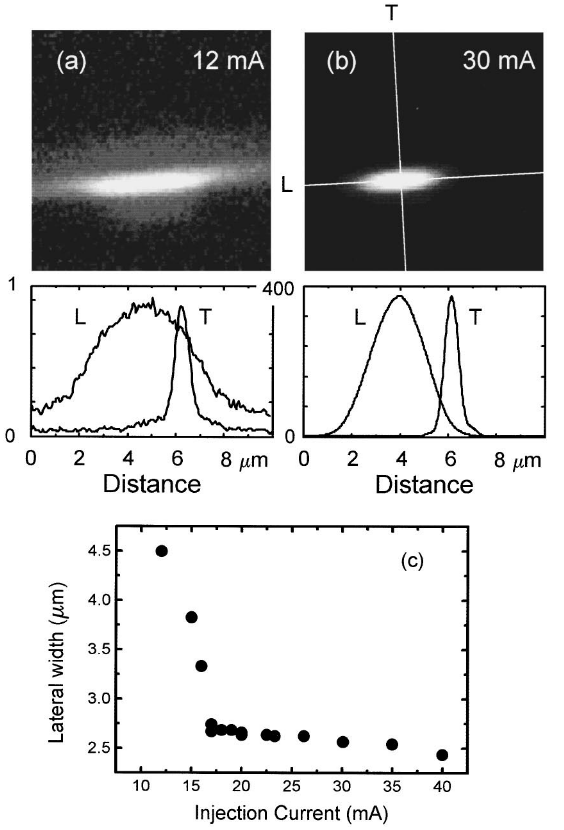

FIG. 1. NSOM images (size 10 μm×10 μm) of the near-field emission of a 780 nm MQW GaAs/AlGaAs laser diode for injection currents of (a) 12 mA (below the laser threshold) and (b) 30 mA (above threshold). Intensity profiles in lateral (L) and transverse (T) direction are shown below each image. Below the lasing threshold, the emission from the active layer is surrounded by weak electroluminescence from the neighboring p- and n-doped AlGaAs layers. (c) Full width at half maximum of the emission profile in lateral direction vs injection current. A strong reduction of the width with increasing current is observed up to the lasing threshold at 18 mA.

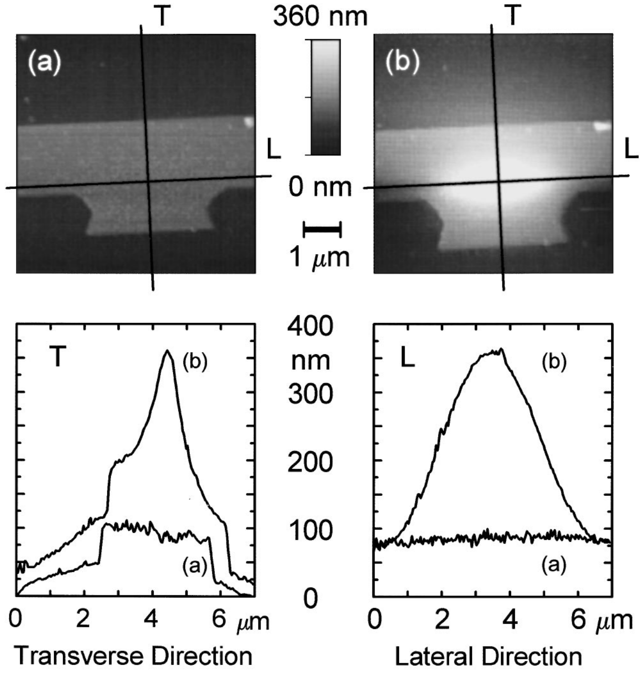

FIG. 2. Shear force images of the surface of a 780 nm MQW AlGaAs laser diode. (a) Data recorded with an uncoated fiber tip at $I=40$ mA, reflecting the undistorted topography of the laser diode. (b) Same experiment with an Al-coated tip for $I=40$ mA. This image shows a retraction of the z-piezo at the location of the laser mode. This results from light absorption in the aluminum coating of the probe tip leading to a local heating and a thermal expansion of the tip. Below the two-dimensional shear force images, cross sections are shown along the transverse, T, direction (left-hand side) and along the lateral, L, direction (right hand side). In each image, cross sections are compared for an uncoated (a) and a fully metallized (b) fiber probe. Note the expansion of the fiber probe as it is scanned across the laser mode. The tip expansion closely follows the local intensity of the optical mode.

shaped, typical for the lowest order mode in a gain-guided structure.[8] The optical mode is located at the center of the p-doped layer, i.e., at the center of the gain profile. The detected intensity in the maximum of the near-field emission profile increases linearly with the far-field laser emission in the absence of the probe tip. A change in lasing threshold due to the presence of the metallized probe tip could not be detected.

Next, we present shear force images that were recorded simultaneously with the near-field data. In the shear force mode, the probe tip is scanned at a constant distance relative to the sample and the voltage across the z-piezo translator, i.e., a quantity proportional to the vertical elongation of the sample, is recorded at each point. In this way, the topography of the sample can be monitored. Such measurements were performed with an uncoated fiber tip, without metal cladding, with the standard fiber tip described above, and with a fully metallized, optically opaque tip. Experiments with the uncoated tip show practically no variation of the surface topography with change in injection current from 0 to 40 mA. In Fig. 2(a), we present a shear force image which was measured with the uncoated tip for an injection current of 40 mA. The geometry of the laser heterostructure is well resolved in this image. Below the two-dimensional shear force images, cross sections are shown along the transverse, T, direction (left-hand side) and along the lateral, L, direction (right-hand side). Analysis of the height profile along the T direction on the laser facet shows that a possible local expansion in the center of the optical mode is less than 8 nm.

With the standard and the fully metallized fiber tips, we observe a completely different behavior. Below the laser threshold, images similar to Fig. 2(a) are recorded whereas a bell-shaped elevated structure with dimensions of about 3 μm×1 μm is found above threshold. The overall dimension and the orientation of the elevated area is close to that of the near-field intensity pattern. In Fig. 2(b), we present an image recorded with the optically opaque tip for an injection current of 40 mA [same value as in Fig. 2(a)]. The cross sections along the L and T direction in Fig. 2 demonstrate that the maximum vertical elongation of 280 nm occurs at the center of the laser . The elongation changes strongly with injection current, i.e., with the optical power emitted by the diode. In Fig. 3(a), this quantity is plotted as a function of laser power for the three different fiber tips. The strongest change of vertical geometry is found for the fully metallized tip where an elongation of 90 nm per mW of total emitted power is observed. For the standard tip with an uncoated front face, the effect is weaker (24 nm per mW) and a negligible elongation is found for the uncoated tip. A similar behavior was found with a diode laser emitting at 1300 nm [Fig. 3(b)]. Here, the absolute elongation of the metallized

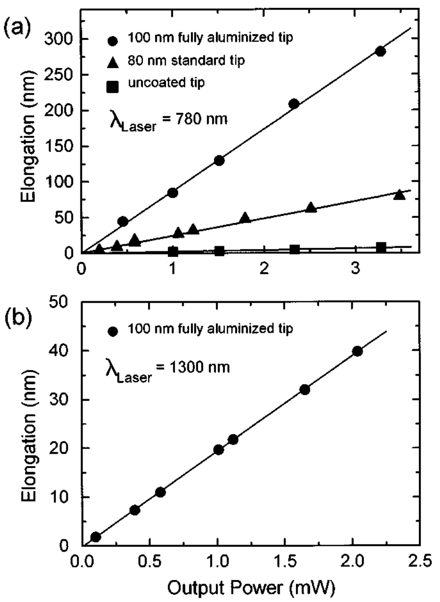

FIG. 3. Expansion of aluminum-coated fiber tips through diode laser light absorption as a function of laser power. (a) Results for a 780 nm MQW AlGaAs laser diode for different probe tips. (b) Results for a 1300 nm MQW InGaAsP laser diode for a fully metallized tip.

tip is smaller, giving a slope of 20 nm per mW. We note that additional emission apart from the laser mode, as has recently been reported in a NSOM study of a 1550 nm MQW InGaAsP laser diode,[3] was not observed.

An increase of the output power of the 780 nm laser beyond 3 mW resulted in damage of the fully metallized tips. This damage was noted by a drastic increase in the optical tip transmission. Damage occurred in the center of the optical mode profile and lead to craters in the laser facet with a depth of about 50 nm and a width of several hundred nanometers. Recent experiments on light-induced local heating of fiber tips[5] suggest that tip damage results from a local melting of the aluminum coating. Preliminary experiments with gold-coated tips indicate that the higher thermal conductivity of the gold coating results in higher damage thresholds.[9]

Two different mechanisms can lead to the vertical elongation in the shear force images: (i) Radiationless surface recombination and/or reabsorption of laser light close to the laser facet result in a substantial heating of the emitting area and thus, in a thermally induced elevation of this part of the surface. This mechanism was invoked to interpret recent shear force data recorded with a 1550 nm MQW InGaAsP laser diode.[3] In our experiments, thermal expansion of the laser facet makes a negligible contribution to the measured vertical elongation. This is evident from the absence of any elongation in the measurements with the uncoated fiber tip at injection currents well above the lasing threshold, i.e., for milliwatt optical output power [Fig. 2(a)]. (ii) Partial absorption of the laser emission in the metal cladding and, to a much smaller extent, in the quartz core of the fiber tip results in an increase of temperature, a concomitant expansion of the probe and an elongation in the shear force image. Our measurements with the different fiber tips give direct evidence of this effect. For the uncoated fiber probe, absorption in the tip and thus, expansion does not occur [squares in Fig. 3(a)]. On the other hand, maximum absorption occurs in the fully metallized tip. (From the tip diameter and the reflectivity of aluminum we estimate that about 0.1% of the total laser output is absorbed in the probe tip.) In this case, we observe the strongest retraction of the z-piezo scanner which changes linearly with the output power of the laser (circles in Fig. 3). At a wavelength of 1300 nm, the reflectivity of aluminum at 1300 nm is 97% vs 87% at 780 nm and the amount of absorbed light is reduced by approximately a factor of 5. This results in a smaller tip expansion coefficient of 20 nm per mW [Fig. 3(b)]. For standard fiber tips with an uncoated front face, transmission through the fiber reduces the absorption and the thermal expansion [triangles in Fig. 3(a)].

The shear force images of Fig. 2 directly reflect the expansion and contraction of the tip during its motion across the laser facet. Expansion line profiles in lateral and transverse direction are reasonably well represented by Gaussian shapes with widths of about 3 μm in lateral and 1 μm in transverse direction. We conclude from the high spatial resolution in the transverse direction that the absorbing region is located at the very end of the fiber with a length restricted to about 1 μm. The symmetric shape of the tip expansion profile in the lateral direction indicates that the time scale of the temperature equilibration within the fiber tip is fast relative to the scan speed of the piezo. In our experiments, the scan speed was 4 μm/s and we can estimate an upper limit of the equilibration time of 20 ms. In fact, this upper limit of 20 ms is close to the value for the thermal equilibration constant for aluminum coated fiber probes of 10 ms obtained by La Rosa *et al.*[4] A fully metallized fiber tip thus serves as a local bolometer with a high spatial resolution of 1 μm and a sensity of about 0.1 nm per μW at $\lambda = 780$ nm.

In conclusion, the emission profiles of semiconductor laser diodes were studied by near-field scanning optical microscopy. We have demonstrated that absorption of light from the sample in probe tips with metal claddings influences image formation significantly, in particular in the shear force mode. The thermal expansion of the probe tips has values of up to 100 nm per milliwatt of laser power and allows to monitor the emitting area in shear force images. Due to the strongly localized heating at the front face of the tip, a fully metallized probe tip can serve as a microscopic bolometer with a spatial resolution of better than 1 μm.

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