# Thin Structure of Near-Field Emission of Semiconductor Laser

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1. Introduction

Results of SNOM measurements analysis of a near-field structure of the semiconductor laser emission are presented. In contrast to papers in this area [1-3] we have achieved a higher resolution that makes it possible to observe thin inhomogeneities of near-field laser emission, which are likely related to nano-scale inhomogeneities of the emitting laser surface. To achieve such a resolution, a small-aperture probe [4] has been used in a SNOM system. The microscope resolution is determined by the size of the probe aperture (~50-100 nm), which is much smaller than the wavelength of light. It was possible to discern in SNOM laser emission images small, comparable to the probe size, inhomogeneities of structure, the true size of which is inevitable smoothed by the probe transfer function and the true magnitude is inevitable decreased. To retrieve the true structure of near-field laser emission, a method that has been worked out [5] was used. Measurements results have been processed taking into account the probe transfer function and image deconvolution method based on the Tikhonov's theory of ill-posed problems [6] is applied to retrieve images distorted by the instrument transfer function influence. Using this approach, in the SNOM measurements small (3-4%) variations with a spatial size of about 50 nm have been discerned.

2. Image deconvolution and numerical modelling

If a 2-D distribution of SNOM signal is measured, then it can be (at least, approximately) expressed as 2-D convolution of true distribution and probe transfer function

$$z_{\mathrm{m}}(x,y)=\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}K(x-s,y-t)z(s,t)dsdt \qquad (1)$$

where the kernel $K(w,W)$ is the transfer function, $z_{\mathrm{m}}(x,y)$ is the measured signal, $z(s,t)$ is the true distribution to be found. The solution of (1) relative to $z(s,t)$ make it possible to retrieve the surface image with a higher resolution.

The key part of the approach developed in [5] is a method of determination of the transfer function in (1) from the image of a structure that contains small (much less than the size of aperture) details. These details can be considered as δ-function, so one has from (1) $z_m(x,y) = K(x,y)$. The probe transfer function has been determined from the analysis of a test structure (thin vanadium film (<10 nm) on the quartz partially etched to the substrate), and it was obtained that the corresponding kernel can be well approximated by the 2-D Gauss distribution with half-width parameters $\sigma_x = \sigma_y = \sigma \cong 70$ nm. The achieved (after the deconvolution) resolution $\sigma_r \cong 20$ nm (or about 0.045 of the SNOM wavelength) has been determined by the Gaussian approximation of smallest details of the retrieved image.

In this paper this same method of image deconvolution is used to retrieve a structure of near-field semiconductor laser emission. An important advantage of the considered method is its convergence (in $W_2^2$–space, and, hence, uniformly [6]) of the approximate solution to an exact solution at the decrease of measurement errors. The value of the measurement error parameter $\delta z$ (estimated in $L_2$- space) is the only parameter of the Tikhonov's method of the generalized discrepancy. It determines a quality of the retrieval by implicit relation with the regularization parameter, on which depends an extent of the smoothing of an approximate solution. At $\delta z \to 0$ the retrieved distribution converges uniformly to the exact one. So, there is no need in the use of large statistical ensembles to obtain an representative estimation of the accuracy of retrieval as it is necessary in other methods with an integral or mean-square convergence – it is enough to make a numerical modeling for typical and, may be, for extreme distributions.

It is well known that the accuracy of the retrieval in ill-posed problems can be determined on the basis of the numerical simulation only using the closed-circuit scheme: at first, an initial distribution is given, then, using this distribution, an exact left side of (1) is calculated, then a random error is added to obtain "measurements data" and, finally, the equation (1) is solved and results are compared with the initial distribution.

The results of numerical modelling at two values of $\delta z$ are shown in Fig.1,2. The error level for the case shown in Fig.2 (left) is close to this in real SNOM experiment. The retrieval results shown in Fig.4 (right) are obtained for the error level 4 times less. One can see the convergence to the exact solution at the decrease of the assumed level of measurement errors, so there is a real possibility to overcome the resolution limit related to the smoothing property of the probe transfer function.

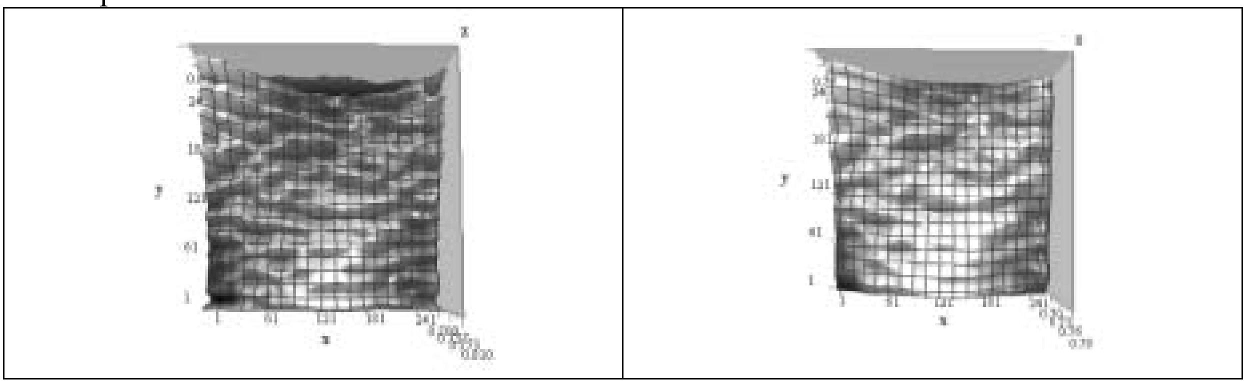

*Fig. 1. Numerical modelling. Initial SNOM image z(x,y) (leftr) and calculated "measurement data" $z_m(x,y)$ in (1) (right).*

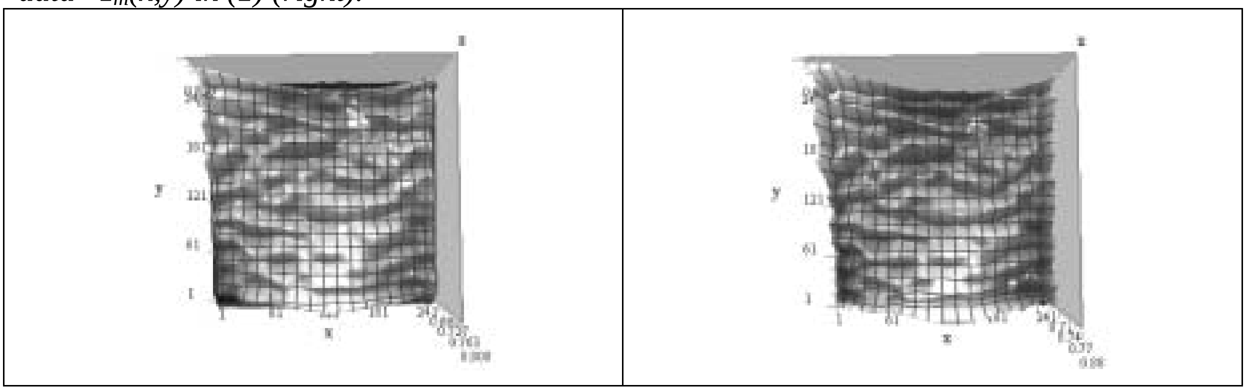

*Fig. 2.Rresults of retrieval by "measurement data"(see in Fig.1, right) at the real SNOM error level (left) and at 4 times less error level (right).*

3. Measurements and processing

Using SNOM microscopy and image deconvolution the semiconductor injection laser with quantum walls has been studied. It has a current threshold of 0.5 A, quantum efficiency of 27% at power of 0.2 W on the wavelength $\lambda$=961 nm. The working width of the active region of the laser consisted 100 μm. The laser scheme is shown in Fig.3. Results of SNOM measurements in collection mode of the near-field (the probe-surface distance $h \leq 5$ nm $\ll \lambda$) laser emission are shown in Fig.4 (left). There are small (practically invisible) spatial variations of the emission in this image, but taking into account the averaging over the probe transfer function footprint, after the image deconvolution, we have obtained the true emission distribution shown in Fig.4 (central). The variations in this reconstructed image are much more pronounced (about 3-4%). The size of spatial variations of the laser emission is about 50 nm, and these variations are most likely related to nano-scale inhomogeneities of the emitting surface, a structure of which measured by an atomic-force microscope is shown in Fig.4 (right).

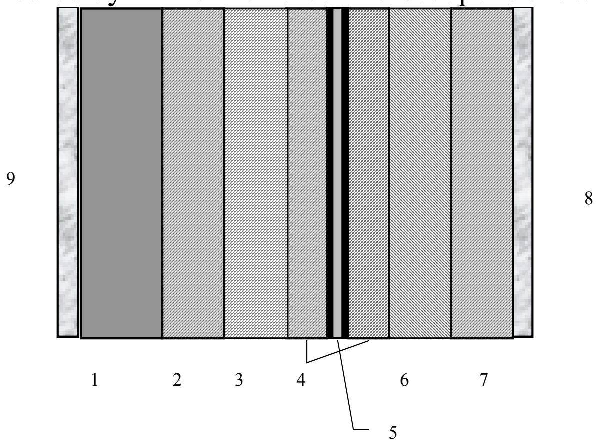


*Fig3. Structure of the laser. 1 – substrate $n^+$ - GaAs, 2 – buffer layer GaAs (550 nm), 3- bounding layer n - InGaP (500 nm), 4 – waveguide layers GaAs (300 nm), 5 – active region consisting of two quantum walls InAs (8 nm) and separating layer GaAs (80 nm), 6 – bounding layer p – InGaP (500 nm), 7 – contact layer $p^+$ - GaAs, 8,9 – ohmic Au contacts to n and p – type of GaAs respectively*

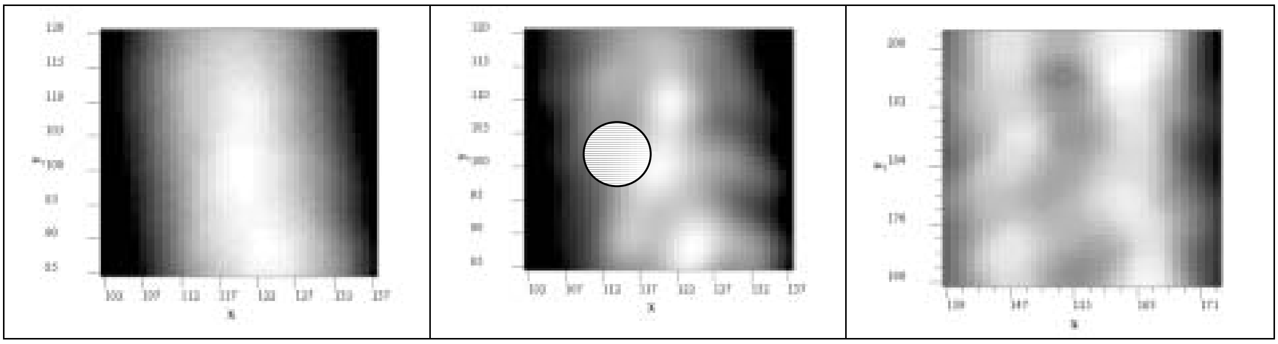

*Fig.4. Initial (left) and reconstructed (central) SNOM-images of near-field laser emission. The circle in the reconstructed image marks the probe pattern footprint. The pixel size is 10 nm. Right - relief of the laser emitting surface measured by atomic-force microscope (pixel size is 4,3 nm).*

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