Scanning Microscopy of Near-Field Emission of Semiconductor Laser

K.P.Gaikovich, V.F.Dryakhlushin

Institute for Physics of Microstructures RAS, Nizhny Novgorod,GSP-105, Russia, 603950. E-mail: gai@ipm.sci-nnov.ru; phone: (8312)675037; fax: (8312)675553

ABSTRACT

Results of the study a thin near-field structure of the semiconductor laser emission using near-field optical microscopy (SNOM) are presented. Significant enhancement of resolution is achieved by deconvolution of measured 2-D images using Tikhonov's method. It made possible to detect the true nano-scale structure of inhomogeneities of a semiconductor laser emission.

Keywords: scanning near-field optical microscopy, semiconductor laser, deconvolution.

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. Then, to obtain yet better resolution, measurements results have been processed further taking into account the probe transfer function and image deconvolution method based on the Tikhonov's theory of ill-posed problems is applied to retrieve images distorted by the instrument transfer function influence. In [5-6] this method was applied for the rectification of the scanning near-field optical microscopy images of the etched vanadium surface and, also, for the microwave 2-D imaging of the subsurface dielectrical structures.

2. RECTIFICATION OF SNOM IMAGES. NUMERICAL MODELLING

This processing used results of our previous work [5], where image deconvolution method has been developed to restore SNOM images distorted by the probe transfer function influence. Under this influence the smoothing of the real picture takes place. If the transfer function is known (even approximately), it is possible to consider the inverse problem of the image rectification. This problem consists of the solution of integral Fredholm equation of the 1-st kind of the 2-D convolution type, which is a known ill-posed problem. In [5] an algorithm based on Tikhonov's method of generalized discrepancy has been worked out. 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:

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

The work reported in this paper was supported by the INTEL grant and by grants RFBR *No*. 03-02-17321, 01-02-16432.

where the kernel $K(w,W)$ is the transfer function, $z_m(x,y)$ 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

$$K(x,y) = \frac{4}{\pi\sigma_x\sigma_y}\exp[-4(\frac{x^2}{\sigma_x^y} + \frac{y^2}{\sigma_y^2})], \quad (2)$$

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 smallest details of the retrieved image.

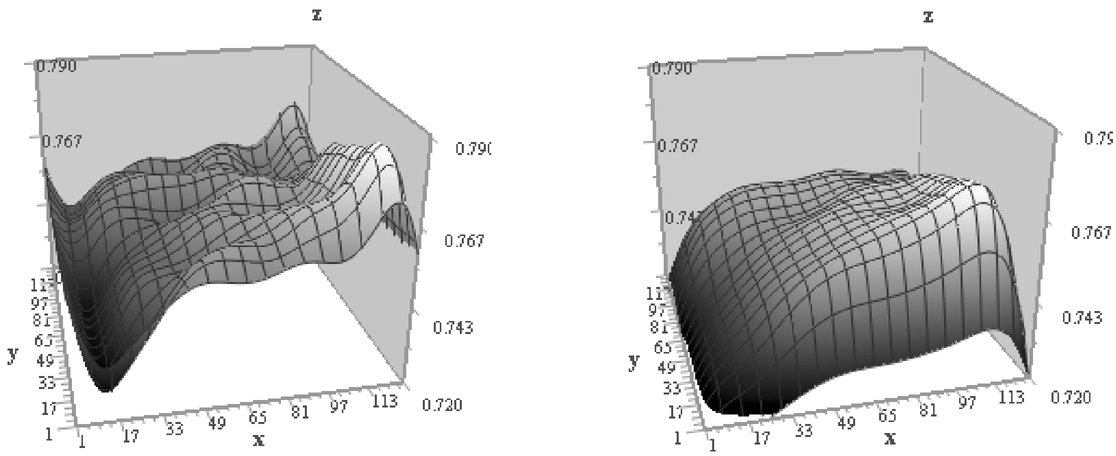

Fig. 1. Numerical modeling. Initial SNOM image z(x,y) (left)
and calculated "measurement data" $z_m(x,y)$ *in* (1) *(right). (in mV).The value of* σ *in (2) is assumed* σ =20 pixels.

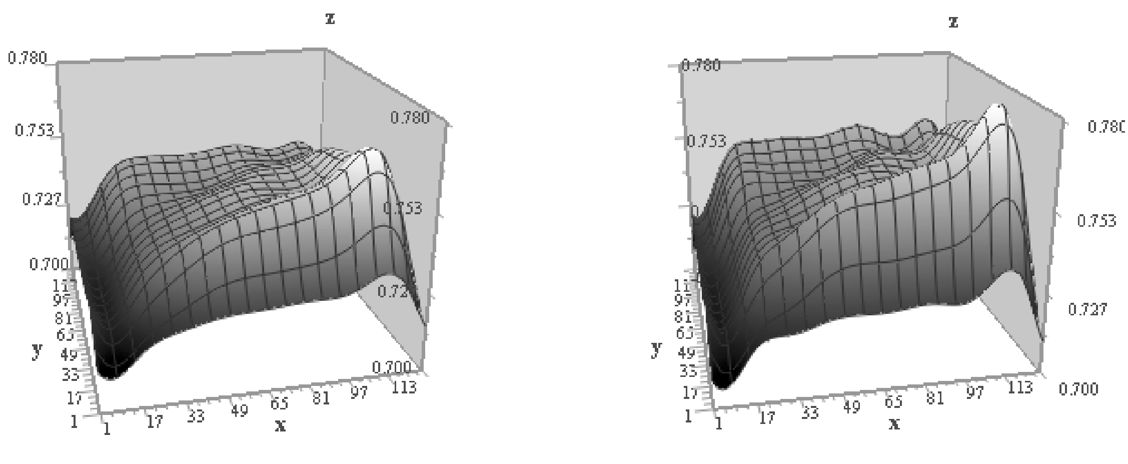

Fig. 2. Retrieval results by "measurement data" in Fig.1 at the assumed error level of 10% (left) and 5% (right) (in mV).

An important advantage of the considered method is the fact that it has a convergence in the space W_2^2, and, hence, in C with a maximum of modulus as a metric[7]. The only error parameter δz (estimated in L_2 metric) of the Tikhonov's method determines the achievable quality of retrieval. At $\delta z \to 0$ the retrieved distribution converges uniformly to the true solution. So, there is no need to study large statistical ensembles (like in statistical methods) to obtain some representative estimation of the retrieval accuracy – it is enough to make the numerical modeling for a typical, and, may be, for an extreme distribution. The results of numerical modeling at two values of δz are shown in Fig.2. The chosen parameters are close to those in real experiment. One can see that the convergence to the exact solution at the decrease of the assumed level of measurement errors, so at the 5% accuracy we have well enough retrieval of the initial distribution. So, numerical modeling shows that there is a real possibility to overcome the resolution limit related to the smoothing property of the probe transfer function.

3. NEAR-FIELD EMISSION OF SEMICONDUCTOR LASER

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 λ=961 nm. The working width of the active region of the laser consisted 100 μm. The laser scheme is shown in Fig.3.

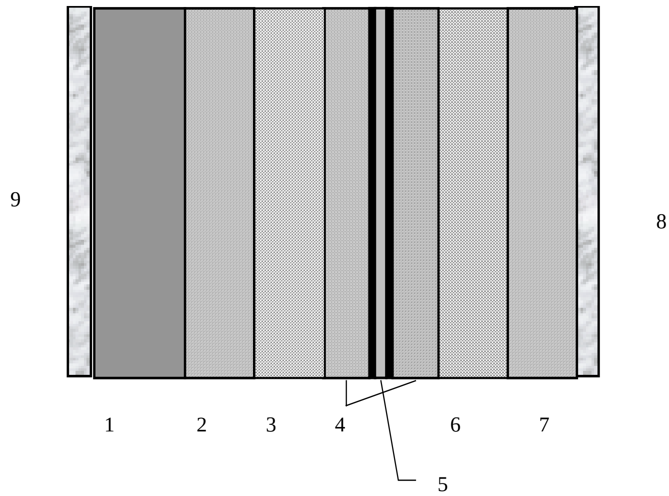

Fig.3. Structure of the laser. 1 – substrate n^+ - GaAs, 2 – buffer layer GaAs (550 nm), 3- bounding layer n - InGaP (500 nm), 4 – waveguide layers GaAs (300 nm), 5 – active region consisting of two quantum walls InAs (8 nm) and separating layer GaAs (80 nm), 6 – bounding layer p – InGaP (500 nm), 7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

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 (right). 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.

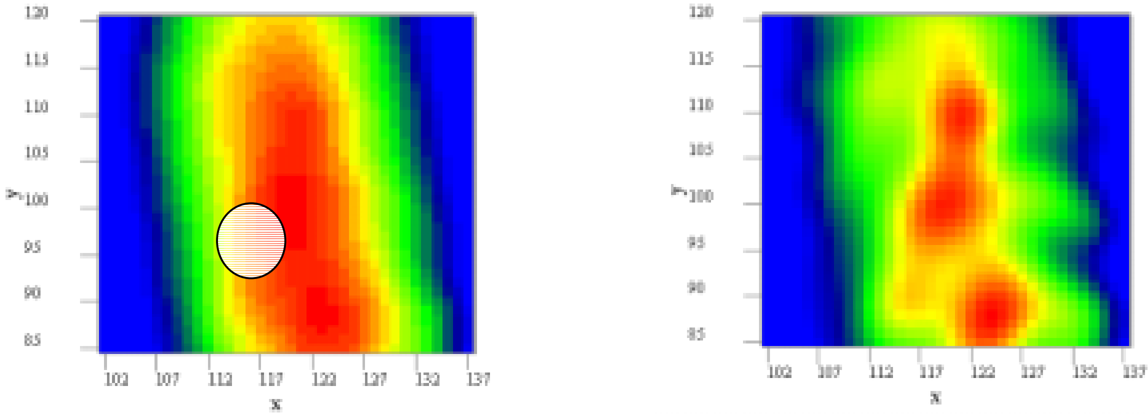

Figure 3. Mesured (left) and reconstructed (right) SNOM-images of near-field laser emission. Circle in the initial image marks the probe pattern footprint. The pixel size is 16 nm.

In Fig.4 it is clearly seen that the sharpness of the reconstructed image is much better than of the initial one. Image details which were smoothed in the measured image over the scale of the probe transfer function are revealed in the retrieved image. Taking into account the presented above results of the numerical modeling, it is possible to consider this retrieved image as the true structure of inhomogeneities of the near-field laser emission.

4. CONCLUSIONS

In the SNOM measurements of the near-field semiconductor laser emission small (3-4%) variations with a spatial size of about 50 nm have been discerned due to sub-aperture resolution obtained by Tikhonov's image deconvolution. These variations could be related to nano-scale inhomogeneities of the emitting surface, and this relationship will be a subject of the further research.

REFERENCES

[1] J.Kim, J.T.Boyd, H.E.Jackson, K.D.Choquette. Near-field spectroscopy of selectively oxidized vertical cavity surface emitting lasers. Applied Physics Letters, 2000, vol.76, *No*.5, pp.526-528.

[2] D.K.Young, M.P.Mack, A.C.Abare, and al. Near-field scanning optical microscopy of indium gallium nitride multiple-quantum-well laser diodes. Applied Physics Letters, 1999, vol.74, *No*.16, pp.2349-2351.

[3] J.Kim, D.E.Pride, J.T.Boyd, and H.E.Jackson. Spectrally-resolved near-field investigation of proton implanted vertical cavity surface emitting lasers. Applied Physics Letters, 1998, vol.72, *No*.24, pp.3112-2351.

[4] V.F.Dryakhlushin, A.Yu.Klimov, V.V.Rogov, and S.A.Gusev, A probe for a near-field scanning optical microscope. Instruments and experimental techniques, vol.41, No.2, pp.139-139, 1998.

[5] Gaikovich K.P., Dryakhlushin V.F., Nozdrin Yu.N., Reznik A.N., Vaks V.L., Zhilin A.V. Rectification of near-field images. Proceedings of 2002 4d International Conference on Transparent Optical Networks (ICTON 2002, Warsaw, Poland, April 21-25, 2002), National Institute of telecommunications, 2002, ISBN 0-7803-7357-8, pp.192-196.

[6] Gaikovich K.P., Dryakhlushin V.F., Kruglov A.V., and Zhilin A.V. Rectification of SNOM-images taking into account the probe transfer function. Physics of Low-Dimensional Structures, 2002, vol.5/6, pp.93-98.

[7] A.N.Tikhonov, Solution of ill-posed problems. New York, Winston, 1977.