Rectification of Near-Field Images

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ABSTRACT

Significant enhancement of resolution in the scanning near-field optical microscopy (SNOM) and in the microwave subsurface imaging is achieved by deconvolution of measured 2-D distributions using Tikhonov's method. This method makes it possible to obtain much better sharpness of images.

Keywords: scanning near-field optical microscopy, microwaves, deconvolution.

1. INTRODUCTION

Image deconvolution method based on the Tikhonov's theory of ill-posed problems is applied to retrieval of images distorted by the instrument transfer function influence. An actual problem in various fields of physics (various kinds of microscopy, radio astronomy, radar and radiometer imaging) is the correction of the instrument transfer function influence on measured 2-D images. Under this influence the smoothing of the real picture takes place, and even its distortion in cases when the transfer function has a complicated structure. 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 2-D convolution type, which is known as ill-posed problem. In this paper the possibility of Tikhonov's method of generalized discrepancy [1] is considered. The same approach has been used successfully in the problem of 2-D currents distribution on the superconductor film by measurements of magnetic field above its surface [2]. In the present paper this method is applied to rectification of the scanning near-field optical microscopy (SNOM) images and of the microwave 2-D imaging of the subsurface dielectrical structures.

2. RECTIFICATION OF SNOM IMAGES

If a 2-D distribution of some physical quantity is measured, which is related to image, then the relation between the measured and the true distribution in most cases could be (at least, approximately) expressed as 2-D convolution:

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

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. It is known that the accuracy of retrieval for ill-posed equations can be determined on the basis of numerical simulation only, and these results for Tikhonov's method are presented in [3].

In the present paper this method is applied to the retrieval of scanning near-field optical microscopy (SNOM) images. The key element of a SNOM is its probe [4]. The size of the probe

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The work reported in this paper was supported by the RFBR, Grants *No*. 00-02-16487, 01-02-16432, 01-02-16444.

aperture determines the microscope resolution and the optical radiation power emerging from the probe and this size (~50 nm) is much smaller than the wavelength of light. It determines the effective width of the transfer function (kernel K) in (1), which we have to know to solve this equation. It is possible to determine this function by measurements of a small (much less than the size of aperture) test structure *z(s,t)*. This structure can be considered as δ-function, so one has from (1) $z_m(x,y) = K(x,y)$. In real measurements there are almost always suitable small structures, which can be considered as δ-functions. In such cases the smallest image inhomogeneities are similar and they repeat actually the form of *K(x,y)*. In Fig.1 one can see examples of such smallest details of the SNOM image shown in Fig.2 (left), and the corresponding kernel can be well approximated by the 2-D Gauss distribution

$$K(x,y) = \frac{4}{p s_x s_y} \exp[-4(\frac{x^2}{s_x^y} + \frac{y^2}{s_y^2})]\,, \qquad (2)$$

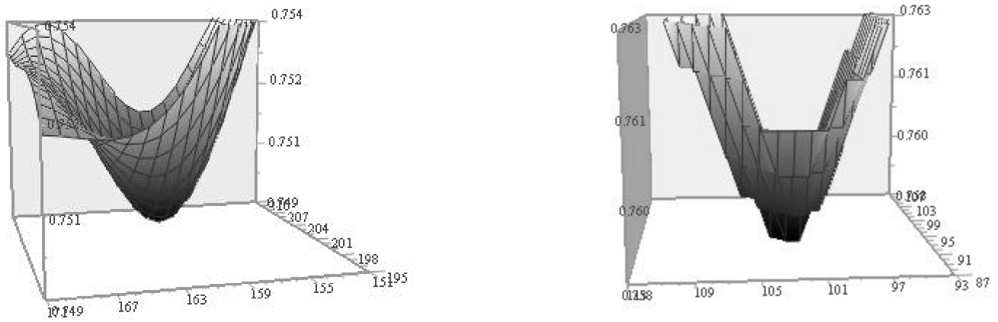

Figure 1. Two examples of smallest SNOM image details (in mV), which determine the transfer function K(x,y). The pixel size is 3.3 nm.

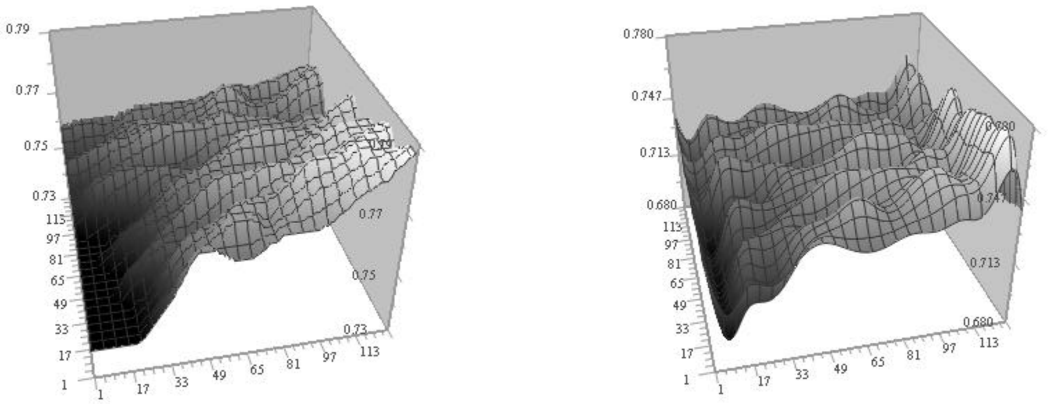

Figure 2. Initial (left) and retrieved (right) SNOM-images (in mV). The pixel size is 3.3 nm.

where parameters $\sigma_x = \sigma_y = \sigma \cong 20$ pixels = 66 nm were evaluated from measurements given in Fig.1 (left). This value can be considered as the resolution of the measured image and, also, as the upper limit of the size of the probe aperture $D \leq 66$ nm that seems as a reasonable value.

In Fig. 2 the results of retrieval of SNOM-images are shown. It is obvious that the resolution of retrieved image is much better and the edge of the test sample is more clearly seen. The test sample was a very thin vanadium film (<10 nm) on the quartz partially etched to the substrate. The initial image was obtained with the help of the scanning near-field optical microscope “Aurora” by “Topometrix” firm, operating at wavelength of optical radiation of 488 nm; the transmission coefficient of the probe was $4{\cdot}10^{-3}$. The noise level (parameter of Tikhonov’s method that determines the value of regularization parameter) was 0.03 mV.

At this level of measurements accuracy the achieved resolution σ_r in retrieved images is at least 3 times better than the resolution in initially measured images. The achieved resolution σ_r can be determined by the smallest details of the retrieved image in the same way as the resolution of the initial image σ in (2). So, we obtain $\sigma_r \cong 22$ nm, or about 0.045 of the SNOM wavelength.

3. MICROWAVE SUBSURFACE IMAGING

Surfaces imaging by near-field microscopy at microwave (MW) frequencies is enough developed by now. Corresponding devises have the resolution scale $\sigma \ll \lambda$ approximately equal to aperture size $D \approx \sigma = \lambda/n$, where λ is the operating wavelength, $n \gg 1$. Only the obvious property of near-field measurements to make resolution higher by decreasing D has been considered earlier. For MW near-field microscopes the value of n is typically of about 10^2 - 10^3; with the maximum reported value of $n \approx 10^5$. It is necessary to note that increasing of n leads to decreasing of the sounding depth h because the condition $h \sim \sigma$. Thus, a large penetration depth as an important advantage of MW can be lost. In this work we have built a MW near-field system with a low enough space resolution ($n \sim 10^2$) especially for the subsurface sounding of samples. But for all that, a special mathematical procedure of super- aperture resolution has been developed to compensate for losses of resolution.

We have used a 2-D scanning near-field system, and shows a small-aperture antenna used as a probe. Sensitive element of antenna with the size of 5×6 mm^2 have the meander form and is made in contact with a microstrip resonator (resonant frequency $f_0 \approx 640$ MHz, bandwidth Δf » 15 MHz). The test samples were Al_2O_3 substrates with the deposited Cu films (~ 100 nm) from which the metal-dielectric structures have been formed. Optically opaque dielectric plates with various depths covered the samples. As the probe approaches the sample, the equivalent impedance of sensitive element changes and the resonant frequency f_0 shifts. Inhomogeneities of the sample dielectric constant lead to variances of f_0. In normal operation, we apply the microwave power at a frequency that is somewhat off the resonant frequency. So, we measure changes of antenna reflection coefficient induced by the sample structure inhomogeneities. To make the sensitivity higher we used the 1 KHz meander modulation of MW radiation on the antenna input and the selective amplification of the reflected signal at the modulation frequency. The 2-D scanning of antenna by stepper motors with the step in x and y-directions of 0.125 mm makes images with the maximal size of observed area $4{\times}4$ cm^2. Coordinates of each pixel and corresponding measurement results are stored in a computer.

The sample image is 2-D distribution of the measured antenna reflection coefficient R_m, and it can be expressed (at least, approximately) as a function of probe coordinates:

$$R_m(x,y) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} K(x-x', y-y')R(x',y')dx'dy' \quad , \tag{3}$$

where $R(x,y)$ is the true image of a sample, $K(x,y)$ is the transfer function of antenna. Thus, the initial measured image is the 2-D convolution of the real image and the antenna transfer function. The influence of the antenna transfer function leads to the smoothing of observed image contrasts. For our system $K(x,y)$ have been determined by scanning of simple one-dimensional metal – dielectric interface. It was obtained that a good approximation for $K(x,y)$ is (2) where parameters $\sigma_x = 2.3$

mm, σ_y = 3.6 mm were determined from measurements. These parameters can be considered as the resolution in x and y-direction.

The reconstruction of images has been done by deconvolution of (3) using the measured image as the left part of (3) and the obtained transfer function (2). It is well known that the solution of integral Fredholm equation of the 1-st kind (3) is an ill-posed inverse problem. Special mathematical technique based on Tikhonov's method of generalized discrepancy has been developed for this purpose. An efficiency of developed technique have been examined by the retrieval of images of samples produced as two parallel dielectric strips carried through metal cower under the dielectric layer. The width of strips w and metal covered distance between them d were equal ($w = d$).

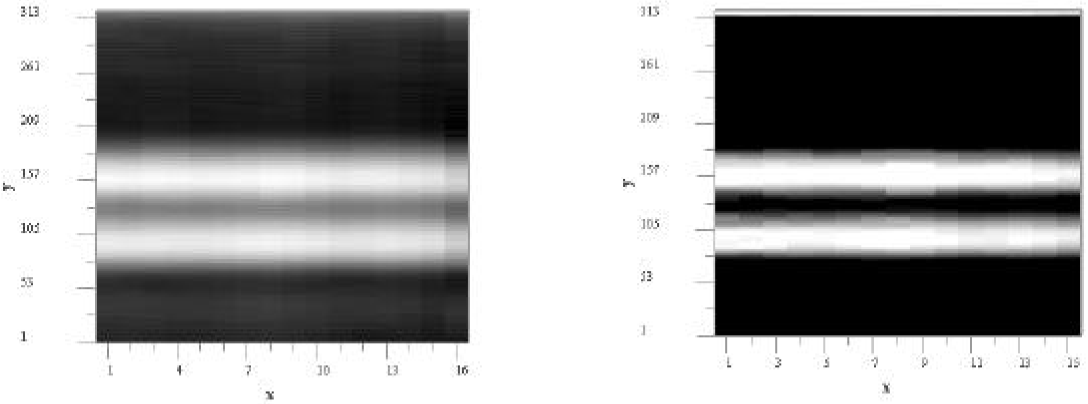

Figure 3. Initial (left) and reconstructed (right) image of dielectric strips under optically non-transparent layer with the depth h = 1.3 mm . Pixel size is 0.125 mm; w = d = 4 mm.

In Fig.3 it is clearly seen that the sharpness of the reconstructed image is much better than of the initial one. It is because the space resolution after deconvolution became higher than the initial resolution of antenna. Our calculations gives that new resolution became about 3 times better than the measured resolution $\sigma_{x,y}$ in (2).

4. CONCLUSIONS

Thus, we can conclude that the developed method of image rectification permits one to obtain much better image sharpness on the basis of numerical processing of measured SNOM-images. The super-aperture resolution for subsurface MW near-field microscope have also been achieved. In both cases the resolution of retrieved images appears about 3 times better than for initially measured images.

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