Near-field resonances in diagnostics of multilayered media

K. P. Gaikovich, P. K. Gaikovich
Institute for Physics of Microstructures RAS, Nizhniy Novgorod, Russia

Abstract: A method of the coherent near-field sounding of multilayered dielectric structures is studied. It is based on field measurements with subwavelength probes (emitting and receiving) that are spaced in the near-field zone above the upper layer of the studied structure. It makes possible to achieve a subwavelength resolution at the control of the layers' depth. Especially high resolution can be achieved using the resonant response. The developed approach can be used, for instance, for the monitoring of epitaxy of multilayered heterostructures using SNOM techniques.

Various far-field interferometry methods of layers' depth sounding are widely applied for diagnostics of layered media. They mostly use measurements of parameters of reflected plane waves. New possibilities in the sounding of multilayered structures can be related to near-field measurements, such as the achievement of a higher lateral and depth resolution. A two-probe scheme of such near-field sounding is proposed here. One of them emits a coherent sounding field; the second probe receives the sum of emitted and reflected field components. Variances of the received field during the growth of the upper layer can be used to control its depth.

To calculate the received field, the lateral 2D plane waves' decomposition of fields is in use. The proper Green functions of the considered multilayered medium are obtained using the input impedance formalism and the summation of geometric series of multiple-reflected plane waves (see, for example, in [1-3]). Two-layer structures are studied in detail.

Let us consider the *n*-layered dielectric medium with the complex permittivity $\varepsilon_0 = \varepsilon_{0i}$ in i^{th} layer with the depth d_i. The field distribution $\mathbf{E}(\mathbf{r})$ is determined by the proper Green tensor (that includes near-field components):

$$\mathbf{E}(\mathbf{r}) = \int_V \mathbf{j}(\mathbf{r}')\overleftrightarrow{\mathbf{G}}(x-x', y-y', z, z')d\mathbf{r}', \qquad (1)$$

where $\mathbf{j}(\mathbf{r})$ is the current distribution in the source. It is an uneasy computational task for multilayered media. To solve this problem, the plane wave decomposition of (1) over lateral co-ordinates has been in use:

$$\mathbf{E}(\kappa_x, \kappa_y, z) = \frac{2\pi}{\varepsilon_1 \omega}\int_{z'} \mathbf{j}(\kappa_x, \kappa_y, z')\overleftrightarrow{\mathbf{G}}(\kappa_x, \kappa_y, z, z')dz'. \qquad (2)$$

In this way, the problem is reduced to the problem of plane wave propagation. The inverse Fourier transform of (2) gives the desired field distribution $\mathbf{E}(\mathbf{r})$. Necessary reflection coefficients of *n*-layered structures are obtained using the input impedance formalism [1]. The reflection coefficient of the considered *n*-layered structure is obtained using the input impedance formalism [1]:

$$R = \frac{z_{in}^{(2)} - z_1}{z_{in}^{(2)} + z_1}, \qquad (3)$$

$$z_{in}^{(j-1)} = \frac{z_{in}^{(j)} - iz_{j-1}tg(k_{(j-1)z}d_{j-1})}{z_{j-1} - iz_{in}^{(j)}tg(k_{(j-1)z}d_{j-1})} z_{j-1},$$

$$z_{in}^{(n)} = \frac{z_{n+1} - iz_n tg(k_{nz}d_n)}{z_n - iz_{n+1}tg(k_{nz}d_n)} z_n, \qquad z_{in}^{(n+1)} = z_{n+1},$$

$$z_j^{\parallel} = \frac{k_{zj}}{k_0\varepsilon_j}, \quad z_j^{\perp} = \frac{k_0}{k_{zj}}.$$

This approach takes into account both propagating and evanescent field components. The contribution of evanescent components (for $\kappa_\perp^2 > k^2$, $\kappa_\perp^2 = \kappa_x^2 + \kappa_y^2$) in the near-field distribution makes it possible to achieve a subwavelength resolution.

This field distribution depends on the depths and dielectric parameters of the studied multilayered structure. So, mentioned parameters can be obtained from measurements of properly chosen field parameters. In most cases the field intensity is measured, and it is reasonable to use the relative field intensity, measured as a function of co-ordinates as such informative parameter [2]:

$$\delta I = (I - I_0)/I_0 = (|E|^2 - |E_0|^2)/|E_0|^2, \qquad (4)$$

where E_0 is the field distribution in the free space. The number of measurements should be at least equal to the number of derived parameters. This problem is, in general, ill-posed. For the case of far-field (plane wave) sounding it was one of the first ill-posed problems studied by Tikhonov using his method of discrepancy minimizing. The same approach can also be used in the considered case of near-field measurements. But it is reasonable to begin this study for simple enough structures with few unknown parameters.

As it was shown in [2], a near-field source excites in the multilayer structure modes that produce the very sharp resonance response in the near-field zone above the stricture. Using measurements of these resonances, it is possible to determine dielectric and geometric parameters of structures.

In our modelling, the square source with homogeneously distributed in the x-y plane $\mathbf{j}(\mathbf{r}) = j_x\delta(z - z_0)\mathbf{x}_0$, $|x - x_0| < L_x/2, |y - y_0| < L_y/2$, L_x = 0.2λ, placed at z_0= 0.6λ in the free space (ε_1 = 1) above the sounded structure with complex permittivity parameters ε_2, ε_3, ε_4 = 1 has been in use. Two-dimensional distributions of δI in dependence on layers' depths have been calculated for various structures for the x-component of the field received at z = 0.2λ.

In Fig.1a the dependence δI on layers' depths d_2, d_3 is shown for the structure ε_2 = 16.0+i0.05 , ε_3 = 4.0+i0.05; in Fig.1b – for the structure with ε_2 = 4.0+i0.05 , ε_3 = 16.0+i0.05. Such multilayer structures (Mo-Si) are widely in use in X-ray optics.

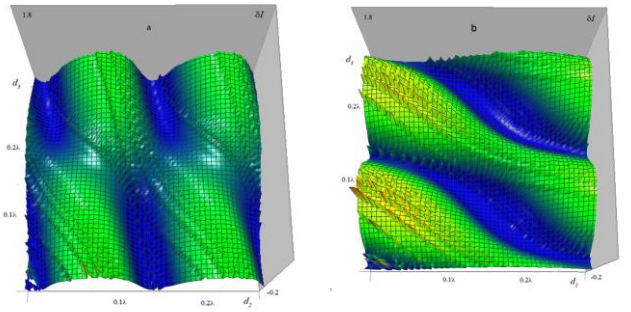

Fig.1. Distribution of the relative intensity $\delta I(d_2, d_3)$ in the region $0<d_1<0.25\lambda$, $0<d_2<0.25\lambda$.
Left (a), near-field zone, z = 0.2λ. Point source at z_0= 0.6; two-layer structure ε_2 = *16*+i*0.0*5 , ε_3 = *4*+i*0.05*; right (b) ε_2 = *4*+i*0.0*5 , ε_3 = *16*+i*0.05*.

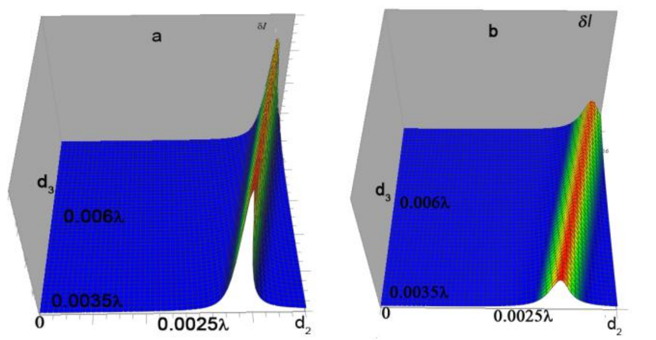

Fig.2. Distribution of the relative intensity $\delta I(d_2, d_3)$ in the region $0<d_2<0.005\lambda$, $0.0035<d_3<0.0085\lambda$.
Left (a), near-field zone, z = 0.2λ. Point source at z_0= 0.6; two-layer structure ε_2 = *16*+i*0.05* , ε_3 = *4*+i*0.05*; right (b) ε_2 = *16*+i*0.1* , ε_3 = *4*+i*0.05*.

In Fig.2a and Fig.2b results for $\delta I(d_2, d_3)$ are given on layers' depths d_2, d_3 in a subwavelength region.

It is easily seen in Fig.1a,b that measurements are sensitive to layers' depths. It is possible to see also lines of resonances, where the depth sensitivity is especially enhanced. These resonances are related to the near-field excitation of propagating modes in a structure, so they can be used for a very sensitive diagnostic of the layers' depth.

Results, shown in Fig.2, demonstrates this sensitivity of sharp resonance to the depth of layers in the distribution of $\delta I(d_2, d_3)$ in the region of 0.005λ. In the optical region it achieve values, smaller than 0.2 nm. Such a sensitivity is quite suitable to control the depth of layers for X-ray structures. The position of resonances in Fig.2a,b and field variations into these peaks are strongly dependent on the depths of layers and their dielectric parameters.

From the comparison of Fig.2a with Fig.2b one can see that the amplitude and the width of resonances are very sensitive to the level of absorption. The amplitude of resonances is sharply reduced for higher absorption, whereas the width of resonances is enhanced. So such measurements make it possible to determine the imaginary part of permittivity in the material of layers.

It should be mentioned that such resonances could make it more difficult to solve ill-posed problems with larger number of layers and unknown parameters. It is necessary to note that such resonances appear not in every structure, for example, there are no resonance peaks for two-layer structures in Fig.1a on the substrate with a higher permittivity, when there are no excited modes.

The obtained results demonstrate the feasibility of the high-sensitive method of the near-field control of multilayered structures that can be realized, for example, in the optical region using the SNOM techniques.

ACKNOWLEDGMENT

This work was supported by Russian Foundation for Basic Research (grant *No.* 08-02-00117) and by the Program of Physical Sciences Department of the Russian Academy of Sciences.

REFERENCES

[1] L.M. Brekhovskih, and O.A.Godin, *Acoustics of Layered Media*, Springer Verlag, Berlin, 1990.

[2] Gaikovich P. K. "Near-field sounding of multilayered media", Proceedings of ICTON 2009, Ponta Delgada, Portugal, June 28 – July 2, 2009, IEEE, pp. Th.A1.5 (1-4).

[3] Gaikovich K. P. , Gaikovich P. K. "Scanning coherent tomography of multilayered media with inhomogeneous region", Proceedings of ICTON 2008, Athens, Greece, June 22-26, 2008, IEEE, pp.246-249.