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FORCED FREQUENCY SYNCHRONIZATION EFFECT IN THE MICROWAVE MICROSCOPE WITH THE ACTIVE PROBE

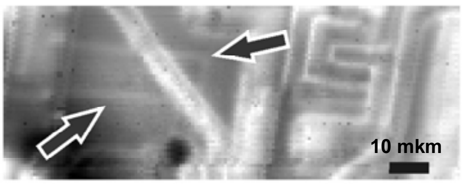
Forced frequency synchronization of the active probe of the microwave microscope is considered. A method of probe's sensitivity increasing based on the quasiperiodic regime with high curvature of the frequency characteristic was proposed.
Keywords: near-field microwave microscope, forced frequency synchronization

Scanning near-field microwave microscopy (SNMM) [1] is a modern method of dielectrics and semiconductors properties examination. It provides local measurements with high sensitivity to dielectric permittivity and losses and can be combined with other types of scanning probe microscopy.

Microwave microscopy is based on measuring of the resonant frequency and quality factor of the microwave probe while scanning the sample under study. One of the most widespread types of resonator is λ/4 coaxial resonator with the needle on the central line. To measure f_{res} and Q with the maximal accuracy different modulation and compensation schemes are applied. We proposed a microwave probe scheme of active type [5], which is simpler and provides sensitivity $\Delta\varepsilon/\varepsilon \sim 10^{-3}$ with spatial resolution $\Delta x \sim 10$ mkm. In a proposed scheme a resonator is a frequency driving element of a microwave generator. Thus the output signal frequency is measured directly by the counter with high accuracy.

Microwave microscopy is widely used for low-contrast and subsurface inhomogeneities visualization. Fig.1 shows a result of scanning of a TM5 microscheme fragment. One can see a hidden layer on the SNMM image.

Optical image



SNMM image

Fig. 1. Obtained image of the TM 5 microscheme with a hidden layer

Except inhomogeneities visualization and dielectric properties measurement SNMM can be used for local field imaging [3]. In a standard microscope scheme a detector is connected to the resonator and its output is proportional to external field amplitude. Such system is sensitive to vertical component of electric field of resonant (or close enough) frequency.

In [2] an electric-field probe design was proposed, sensitive to both normal and tangential spatial-field components.

The purpose of this work is to study the particular qualities of filed visualization using microwave microscope with an active probe.

In contrast to described devices, which are simply passive resonant receivers with subsequent signal amplification, our microscope is actually a generator. Thus, we observed forced frequency synchronization effect, when external field is applied to the resonator. Fig.2 shows the dependence of the measured signal frequency (from the probe's output) from the external field frequency. This dependence is often plotted as a dependence of beat frequency from the mistuning. Area 1 is a quasiperiodic regime. Generation frequency is not changed here, but the "effective" of "observed" frequency, which is measured by the frequency counter, is changed. Segment 2 is a bifurcation area. Frequency cannot be measured here; its width is defined by the noise level of external source and resonant frequency stability. Finally, area 3 is forced synchronization regime.

The output signal of active probe was observed also on C4-27 spectrum analyzer. Two distinct spectrum components were observed in area 1, which merged in one in area 2 and only one frequency signal was observed in synchronization area 3. These results correlate with the classic theory of forced frequency synchronization [4].

According to geometry of microwave resonator (inset in Fig.3) such probe is sensitive to vertical component of electrical field only. Nevertheless by modifying probes' tip geometry we can achieve sensitivity to required component of electric or magnetic field.

We measured the dependence of the width of the forced frequency synchronization area from the power of external source. This series of measurements allowed us to plot a so called Arnold tongue – parametric plot of synchronization area.

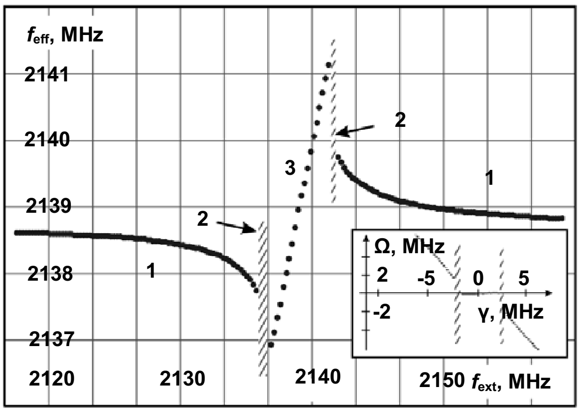


Fig. 2. Dependence of the measured frequency of the active probe signal from the external source frequency

It is known, that for the frequencies close to resonance, even an external signal with small amplitude can cause forced frequency synchronization effect. Thus, the described method can be used for detecting electromagnetic fields with low intensity.

Unfortunately, for the power level less than 1 mW, we could not measure synchronization area width because of external source's low stability and low accuracy of frequency setup. Generator Г4-122 did not provide sufficient values of the parameters stated above.

We also should note that the dependence in Fig.3 has unusual form because we plotted the dependence from the power of the external signal, not from its amplitude.

As we stated above, one of the widespread SNMM application is hidden inhomogeneities visualization. This however requires high sensitivity and corresponding signal-to-noise ratio.

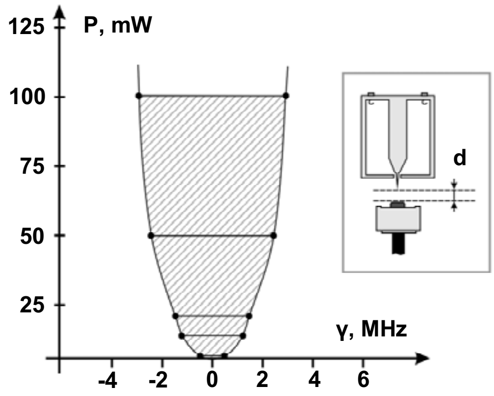


Fig. 3. Parametric plot of forced frequency synchronization area

We proposed to use a quasiperiodic regime with high curvature to increase sensitivity of our scheme. As it shown in Fig.4 when close to the bifurcation point, the effective frequency shift Δf_{eff} can significantly exceed resonant frequency shift Δf_r .

When close to bifurcation point, beat frequency dependence from mistuning can be approximated as $\Omega \sim \sqrt{\gamma - \gamma_{max}}$.

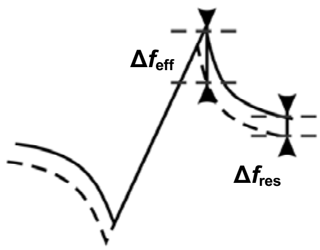


Fig. 4. Shift of resonant Δf_r and effective Δf_{eff} frequency of the loaded probe with external field "highlight"

According to this, signal amplification coefficient will be nonlinear. But as we consider this method only for small signals linear approximation can be used. In linear approximation effective frequency shift is determined by Δf_r and external generator stability Δf_s

$$\Delta f_{eff} \approx \beta\ (\ \Delta f_s + \Delta f_r\ ),$$

where β is frequency characteristic curvature.

This effect was demonstrated by scanning defects in ceramic sample with/without external "highlight" (Fig.5). External signal was filed to the probe's tip by means of microstrip line. Informal signal increment in this experiment was only ~1.5 times because of low stability and frequency setup accuracy of the Г4-122 generator that was used in this experiment as external signal source. At the same time by interpolating curve in area 2 (Fig.2) we can calculate amplification coefficient β~6 for Δf_r < 200 kHz.

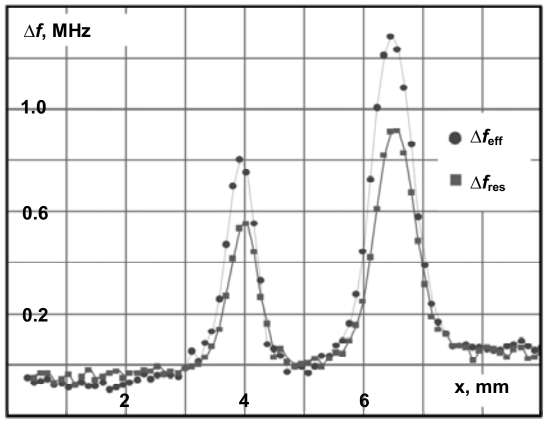


Fig. 5. Shift of resonant Δf_r and effective Δf_{eff} frequency when scanning test sample

We also found that amplification can be considered linear for such small frequency shifts. By using low-noise frequency synthesizer signal amplification β~10 and more can be achieved. Furthermore, this element can be built in the active probe scheme directly and described regime can be used optionally for studding samples with low dielectric contrast.

Conclusion. Particular qualities of field visualization regime using microwave microscope with active probe were described. Synchronization area for different power value of external field was measured. We also proposed a method of active probe sensitivity increasing, which is based on frequency shift signal measuring while using external field source to put the generator (active probe) in quasiperiodic regime. This method is suitable for resonant meters of generator type.

Reference

1. B.T. Rosner, D.W. Van Der Weide // Review of scientific instruments. – 2002. – Vol. 73, № 7. – P. 2505–2522. 2. R. Kantor, I.V. Shvets // IEEE Transactions on Microwave Theory and Techniques. – 2003. – Vol. 51, № 11. – P. 2228–2234. 3. S.K. Dutta, C.P. Vlahacos, D.E. Steinhauer, A.S. Thanawalla, B.J. Feenstra, F.C. Wellstood, S.M. Anlage, H.S. Newman // Applied physics letters. – 1999. – Vol. 74, № 1. – P. 156–158. 4. А. Пиковский, М. Розенблюм, Ю. Куртс // Синхронизация. Фундаментальное нелинейное явление. – М.: Техносфера, 2003. – 496 с. 5. В.С. Сидоренко, Ю.О. Гайдай, О.В. Сінькевич, С.В. Жила. // Пат. № 60519 Україна, МПК7 G 01 B 7/34. – № 2002119038; заявл. 13.11.2002; опубл. 15.10.2003, Бюл. № 10.

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ЕФЕКТ ВИМУШЕНОЇ СИНХРОНІЗАЦІЇ ЧАСТОТИ У МІКРОХВИЛЬОВОМУ МІКРОСКОПІ З АКТИВНИМ ЗОНДОМ

Розглянуто ефект вимушеної синхронізації частоти активного зонда мікрохвильового мікроскопа при дії зовнішнього поля з частотою близькою до резонансної. Запропоновано використати квазіперіодичний режим для підвищення чутливості зонда до малих змін діелектричної проникності.

Ключові слова: ближньопольовий мікрохвильовий мікроскоп, вимушена синхронізація частоти.

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ЭФФЕКТ ВЫНУЖДЕННОЙ СИНХРОНИЗАЦИИ ЧАСТОТЫ В МИКРОВОЛНОВОМ МИКРОСКОПЕ С АКТИВНЫМ ЗОНДОМ

Рассмотрен эффект вынужденной синхронизации частоты активного зонда микроволнового микроскопа под действием внешнего поля с частотой близкой к резонансной. Предложено использовать квазипериодический режим для повышения чувствительности зонда к малым изменениям диэлектрической проницаемости.
Ключевые слова: ближнеполевой микроволновый микроскоп, вынужденная синхронизация частоты

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COHERENT LIGHT PROPAGATION IN OPTICALLY INHOMOGENEOUS MEDIA

Phenomenon of a depolarization for an optical signals which were propagated in media with the statistically distributed parameters has been investigated theoretically. Polarization characteristics were calculated by using a coherent matrix method. The dependence of polarization degree of wave on parameters of scattering medium has been calculated for the Fraunhofer diffraction zone.
Key words: degree of polarization, statistically inhomogeneuos medium.

Introduction. The coherent light propagation through optically inhomogeneous medium is one of the most important problem of the statistical optics [2]. Description of such propagation we could consider using of Maxwell formalism as a detailed analyze of an electromagnetic waves scattering under every fluctuation [7]. This problem takes on special significance for multiple scattering because of corresponding coefficients of stochastic equations are random field [5, 6]. Usually, such equations have not analytical solutions and are difficult for numerical analyze. Therefore, it is interesting to construct more simple models for description of the propagation process of waves through inhomogeneous medium with multiple scattering.

The model of phase screen could be considered as possible approximation for this case. Method of phase screen is familiar for scalar approximation of a diffraction problems, including, for example, wave propagation through turbulent atmosphere [4]. It can be proper for multiple scattering at some restriction. Then the propagation process of waves is considered as propagation through set of the phase screen with corresponding statistical properties.

In this work the theoretical method of the description of coherent light propagation through statistically inhomogeneous anisotropic medium by the phase screen method was proposed. Also we considered systems with multiple scattering using offered method.

Correlation matrix transformation. Correlation matrix method is the most convenient for investigation of polarization properties of the scattered light. In this case light propagation by the statistically stratified medium could be obtained as linear integral transform. The parameters of kernel of this transform are determined by the statistics of the medium. The advantage of this method consist in indifference between the statistically stratified mediums, where inhomogeneous could be produced by the inhomogeneous of relief fluctuation or refraction index fluctuations.

Let us consider general principles that were underlay our scattering model. The scattering geometry is depicted on the Fig. 1. Gaussian beam of wavelength λ normally irradiates the statistically stratified medium, which could be represented as phase screen with local inhomogeneties of refraction index ($n_x=n_x(\rho)$, $n_y=n_y(\rho)$, where $\rho=\{\xi, \eta\}$ is the coordinate in the plane of phase screen) and set of local heights $h=h(\rho)$.

Complex amplitude of the electromagnetic wave in the registering plane arbitrary point $r=\{x, y\}$ could be given by Jones vector [3]:

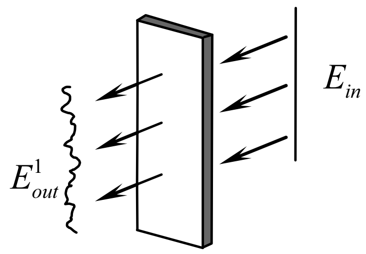

Fig. 1. Geometry of light scattering by phase screen

$$E(\mathbf{r}) = \begin{pmatrix} E_x(\mathbf{r}) \\ E_y(\mathbf{r}) \end{pmatrix}. \qquad (1)$$

The relation between the vectors of scattered wave $E(\mathbf{r})$ in arbitrary point $\mathbf{r}$ with the vector $E_0(\rho)$ in general case can be expressed by the linear integral [1]:

$$E(\mathbf{r}) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} H(\mathbf{r},\rho)E_0(\rho)d^2\rho , \qquad (2)$$

where $H(\mathbf{r},\rho)$ is random coherent point spread function (PSF) of linear optical channel. This PSF could be expressed by the Green function, which in approaching of the anisotropic phase screen could be given as:

$$H(\mathbf{r},\rho) = \frac{1}{i\lambda z}\exp\left(i\left(\tfrac{2\pi}{\lambda}\left|\mathbf{r}-\rho\right| + \phi_j(\rho)\right)\right)\cos(\mathbf{n},\mathbf{r}-\rho) . \qquad (3)$$

here φ_x and φ_y is the random phases, which formed by the casual relief or refraction index fluctuation, and could be expressed as:

$$\phi_j(\rho) = \frac{2\pi}{\lambda} n_j(\rho)h(\rho);\ j = x, y , \qquad (4)$$

where $n_x(\rho)$ and $n_y(\rho)$ is the fluctuations of anisotropic index of refraction, $h(\rho)$ is the random distribution of relief inhomogeneous. So the formula (2) for the Fraunhofer diffraction zone is transforming in:

$$E^1_{out}(\mathbf{r}) = \frac{\exp\left(i\frac{\pi}{z\lambda}\left(x^2+y^2\right)\right)}{i\lambda z}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\exp\left(i\frac{2\pi}{z\lambda}\left(x\xi+\eta y\right)\right)\times$$
$$\times E_0\exp\left(i\frac{\pi}{z\lambda}\left(\xi^2+\eta^2+zn(\rho)h(\rho)\right)\right)d\xi d\eta , \qquad (5)$$

where x, y are coordinates in registering plane; ξ, η are coordinates in the scattering plane; z is the distance between the scattering and registering planes. Let us make denotation: