A method for measuring electromagnetic and geometric parameters of thin films

B V Skvortsov and D M Zhivonosnovskaya
Samara University, Samara, Russia

1 E-mail: Jivonosnovsky@mail.ru

Abstract. We propose for a method of non-contact real-time measuring of electrical conductivity, permittivity and permeability of materials by probing the surface being measured with a pulsed or continuous signal, as well as theoretical foundation of the above method. An example of the engineering implementation of a device providing for measuring using both types of probing signals is described. We consider the errors of the developed methods emerging in the process of solving the system of nonlinear equations, as well as the ways to improve measuring accuracy. A comparative study of the types of probing signals demonstrated that a pulse signal type is the most versatile, as it is possible to optimize the measuring process by adjusting the pulse's shape and duration. However, processing of a reflected pulse signal requires more computational power when compared a continuous probe signal.

1. Introduction
The use of thin films in various fields, such as instrumentation (sensors), energy industry (optically transparent films of solar cells) and aerospace engineering (radio-absorbing thin films) has become one of the most promising trends in the development of modern instrumentation. Radiation-absorbing properties of thin films largely depend on their electromagnetic parameters (EMP), such as conductivity, permittivity and permeability, resulting in the need to measure the EMP both at the production stage and during operation. Most known contact and non-contact methods [1-6] do not provide for measuring conductivity, permittivity and permeability at the same time and cannot be implemented within a single integrated device. The paper includes a comparison of the measuring methods described in [7-8], each providing a way to measure all three parameters at the same time by the method of electromagnetic probing.

2. Engineering implementation
The device operates as follows. Generator 1 with the transmitting antenna 2 generates an electromagnetic signal Φ₁, which, upon the reflection from the measured sample 3, changes according to the electromagnetic properties of the measured film and the base plate (Φ₂) and is received by the receiving antenna 4. The received signal Φ₂ is processed by the amplitude and phase analysis unit 5. The information about their amplitude and phase, which are the initial data for determining the conductivity σₓ, permittivity εₓ and permeability μₓ of the measured film, passes through the control unit 6 is fed to the processing device 7. In addition to communication between the vector analyzer and the PC, the control unit also controls the generator 1.
Figure 1. Functional block diagram of the non-contact measuring device. 1 - generator, 2 - transmitting antenna, 3 - measured sample containing the film placed on a base plate, 4 - receiving antenna, 5 - amplitude and phase analysis unit, 6 - control unit, 7 - processing device, \( F_1 \) - probing signal, \( F_2 \) - reflected signal.

Prior to the measuring, the device is calibrated by determining the amplitude and phase of the signal reflected from an uncovered base plate. This makes it possible to rule out the influence of the electromagnetic parameters of the base plate and the propagation medium in order to increase the accuracy of the measuring procedure. The phase of the reflected signal is understood as the difference between the phases of the probing and the reflected signal (the process of determining this parameter is predefined in the algorithms of the vector analyzer).

3. Summary of the method

The measuring objective is to determine the current values of conductivity, permittivity and permeability, which can be found by solving the system of equations (1) connecting the amplitude \( A(\omega_i) \) and phase \( \phi(\omega_i) \) of the signal received by the receiver by the corresponding transformation functions \( F_A(\omega_i, \mu_s, \sigma_s, \varepsilon_s) \) and \( F_\phi \), for a specific frequency \( \omega_i, i=1, \ldots, n \).

\[
\begin{align*}
F_A(\omega_i, \mu_s, \sigma_s, \varepsilon_s) &= A(\omega_i) \\
F_\phi(\omega_i, \mu_s, \sigma_s, \varepsilon_s) &= \phi(\omega_i) \\
F_A(\omega_{i+1}, \mu_s, \sigma_s, \varepsilon_s) &= A(\omega_{i+1}) \\
F_\phi(\omega_{i+1}, \mu_s, \sigma_s, \varepsilon_s) &= \phi(\omega_{i+1})
\end{align*}
\]  

(1)

When a continuous electromagnetic wave is used as the probing signal, the amplitude and phase of the reflected signal are determined by formulas (2), (3).

\[
A(\omega) = G\Phi_0 e^{-2\alpha(R_1+R_2)} = G\Phi_0 e^{\frac{2\alpha(Z_{4h}+Z_{4h}-2H)}{\cos \theta_4}}
\]  

(2)

\[
\phi(\omega) = -4\omega \frac{R_1+R_2}{V_{\phi_1}} + 2\theta_3 = -4\omega \frac{Z_{4h}+Z_{4h}-2H}{V_{\phi_1} \cos \theta_4} + 2\theta_3
\]  

(3)

where \( F_0 \) is the Poynting vector, \( H \) is the film thickness, \( \theta_4 \) is the phase shift, \( R_1 \) is the signal path from the emitter to the measured sample, \( R_2 \) is the signal path from the measured sample to the receiver, \( Z_{4h}, Z_{4h} \) are the heights of the emitter and the signal receiver, \( \alpha \) is the medium absorbance determined by the formula (4).
\[
\alpha = \sqrt{\frac{\mu \omega (\sqrt{\sigma^2 + \varepsilon^2 \omega^2} - \varepsilon \omega)}{2}}
\]

\(V_{ph}\) is the phase velocity of the propagation medium depending on the frequency of the probing signal and the electromagnetic parameters of the propagation medium (usually air)

\[
V_{ph} = \sqrt{\frac{2\omega}{\mu (\varepsilon \omega + \sqrt{\sigma^2 + \varepsilon^2 \omega^2})}}.
\]

\(\theta_i\) is the angle of incidence, \(G\) is the reflectivity determined by the formula (6) [9]:

\[
G(j\omega) = \frac{1}{2} \left[ \frac{Z_2 \cos \theta_1 - Z_1 \cos \theta_2}{Z_2 \cos \theta_1 + Z_1 \cos \theta_2} + \frac{Z_2 \cos \theta_2 - Z_1 \cos \theta_1}{Z_2 \cos \theta_2 + Z_1 \cos \theta_1} \right],
\]

where \(\theta_{ref} = \arcsin\left[ \frac{\mu (\varepsilon \omega + \sqrt{\sigma^2 + \varepsilon^2 \omega^2})}{\mu (\varepsilon \omega + \sqrt{\sigma^2 + \varepsilon^2 \omega^2}) \sin \theta} \right]\) is the angle of reflection.

As can be seen from formula (6), the reflectivity depends on the electromagnetic parameters of the propagation medium and the measured film through the wave impedances of the media (7):

\[
Z_i = \frac{j \omega \mu}{\sigma + j \omega \varepsilon}; \quad Z_r = \frac{j \omega \mu_r}{\sigma_r + j \omega \varepsilon_r}.
\]

From the results of solving system 1 using a continuous probing signal given in [7], it can be seen that for different combinations of frequencies \(\omega_1, \omega_2\), the calculation results well match the reference values with measurement error not exceeding 5%.

When used a pulse signal for probing, the amplitude and phase of the reflected signal are determined by the formulas (8), (9):

\[
A(\omega) = |G(j\omega)||S(0, j\omega)| e^{-\sigma(\omega)(R_1 + R_2)} = F_A(\omega, \mu_x, \sigma_x, \varepsilon_x),
\]

\[
\varphi(\omega) = \varphi_G(\omega) + \varphi_A(\omega) + \frac{\omega (R_1 + R_2)}{V_{ph}(\omega)} = F_\varphi(\omega, \mu_x, \sigma_x, \varepsilon_x),
\]

where \(|G(j\omega)|, \varphi_G(\omega)\) are the modulus and phase of the complex reflectivity factor, \(|S(\theta, j\omega)|\), \(\varphi_A(\omega)\) are the modulus and phase of the spectrum of the probing pulse.

We set the initial conditions as follows: a rectangular-shaped probing pulse with a duration of \(10^{-8}\) sec with an amplitude of 1.0, \(R_1 = R_2 = 0.1\) m, \(\theta_1 = 10^\circ\). The medium of propagation of the probing pulse is air: \(\mu_{rel} = 1.00053, \varepsilon_{rel} = 1.00027, \sigma = 10^{-18} [1/\Omega \cdot m]\), EMP of the measured material: \(\mu_{rel} = 0.9998, \varepsilon_{rel} = 4, \sigma = 10^{-5} [1/\Omega \cdot m], \delta\varphi = 0\), range \(\delta A = \delta A_{min} + \delta A_{max}\). Then the relative error in determining the electromagnetic parameters is determined by the formulas:

\[
\delta \mu_x = \left[ \frac{\mu_x - \mu_x^{mea}}{\mu_x} \right] \cdot 100\% \quad \delta \sigma_x = \left[ \frac{\sigma_x - \sigma_x^{mea}}{\sigma_x} \right] \cdot 100\% \quad \delta \varepsilon_x = \left[ \frac{\varepsilon_x - \varepsilon_x^{mea}}{\varepsilon_x} \right] \cdot 100\%.
\]

We draw graphs of the dependence of the EMP measurement errors on the error in measuring the amplitude of the reflected signal \(\delta A = f(\delta A), \delta \sigma_x = f(\delta A), \delta \varepsilon_x = f(\delta A)\) for \(\delta\omega = 0, \delta\varphi = 0\) (figure 2).
Figure 2. Graphs of the dependence of the measurement errors of electromagnetic parameters on the error in measuring the amplitude of the reflected signal.

The error in measuring the amplitude of the spectrum of the reflected signal in the range of 10-15% has the greatest influence on the accuracy of determining the permeability (up to 4.5% in the selected range).

4. Conclusions
When comparing the methods, it can be concluded that the method error is the same for continuous and pulsed signals. This is due to the fact that this error is caused by the inaccuracy of the solution of the system of nonlinear equations, which was solved by the method of successive approximations. This error can be reduced by decreasing the iteration increments. At the same time, the pulse probing signal is more versatile, since the capability to adjust its shape and duration provides optimization options for the process of measuring. However, the pulse method does not imply a reconfiguration of the generator during the measuring procedure. The processing of a reflected pulse signal requires more computing power in comparison with a continuous probe signal.

References
[1] Chen L F, Ong C K, Neo C P, Varadan V V and Varadan V K 2004 Microwave Electronics Measurement and Materials Characterization (John Wiley & Sons Ltd) p 537
[2] Glebovich G V 1984 Objectprobingusingpicosecondpulses (Moscow: RadioiSvyaz) p 256
[3] Afonskiy A A and Dyakonov V P 2011 Electronic Measurementsin Nanotechnology and Microelectronics ed V P Dyakonov (Moscow: DMKPress) p 688
[4] Korneev A V, Selin D N, Spiridonov K A, Khitrov Yu A and Chernoles V P 1998 Pat. of the Russian Federation No 2103673 app. 21.11.95, publ. 20.02.98
[5] Ignatiev A A, Kulikov M N, Lyashenko A V, Vasiliev A V and Maslov A A 2012 Pat. of the Russian Federation No 2449303 app. 13.09.10, publ. 27.04.1212
[6] Zhuravlev V A, Zhuravlev A V and Khatskevich Yu A 2013 Izvestiya Vysshikh Uchebnykh Zavedenii Fizika 56 312-4
[7] Skvortsov B V and Zhivonosovskaya D M 2016 Avtometriya 52(4) 98–106
[8] Skvortsov B V, Borminsky S A and Zhivonosovskaya D M 2018 Avtometriya 54(4) 58–66
[9] Brekhovskikh L M 1973 Waves in Layered Media (Moscow: Nauka) p 344