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# Characteristics of anisotropic media over hydrocarbons in the mode of frequency-modulated signals

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**Abstract.** The article considers the impact of frequency-modulated signals on an anisotropic medium over oil and gas deposits. Modeling of the components of the tensors of the dielectric constant of the medium over hydrocarbon deposits was carried out. The characteristics of the medium over accumulations of hydrocarbons for frequency-modulated signals from the frequency of the carrier oscillation, the frequency modulation index for the right and left polarizations of electromagnetic waves are studied. Methods of searching for hydrocarbons based on the variation in the characteristics of the applied signals are recommended. It is proposed to introduce new search modes to improve the accuracy of determining the boundaries of hydrocarbon deposits. The influence pattern of the dielectric constant of an anisotropic medium on the real and phase components of the tensor components are established. The research results can be applied in the electrical exploration of minerals.

## 1. Introduction

The relevance of this work is determined by the establishment of new patterns of interaction of electromagnetic waves (EMW) with anisotropic media over hydrocarbon deposits to improve the accuracy of determining their boundaries [1]. These requirements, as well as the prospects for their application, are most consistent with electromagnetic methods (EMM) [2]. The requirements of modern economics and prospecting geophysics require the improvement of field testing technics [3] and their efficiency, especially in complex geological conditions. Improvement of EMM search for hydrocarbons (oil and gas) shows their high practical significance [4]. Varieties of complex application of magnetotelluric, seismic and gravimetric methods for geological exploration work show their high accuracy and reliability [5].

The result set of active research in the field of traditional seismic methods in mineral exploration can be used to develop promising EMMs [6] along with the additional use of magnetotelluric and gravimetric data [7]. The modes of sounding and studies of the characteristics of host rocks over hydrocarbon deposits based on the propagation of EMW over a geoprofile object provide additional information and improve the accuracy of determining the boundaries of the hydrocarbon deposits [8].

The experience of marine electrical exploration [9] shows that the most complex problems of hydrocarbon prospecting can be successfully solved with a qualitative increase in the level of reliability of hydrocarbon identification. Methods of 3D electrical exploration by the formation of the field over the object of research [10] show their high practical orientation. When developing hydrocarbon resources and evaluating the use of remote technologies, a new Russian satellite technology is used to search for the locations of minerals [11]. The active introduction of various methods with sufficiently good characteristics leads to the achievement of high indicators of accuracy and identification of hydrocarbon deposits [12].

## 2. The use of frequency-modulated signals for the search for hydrocarbons

The propagation of frequency-modulated (FM) signals in an anisotropic medium over hydrocarbon deposits was considered in articles [13, 14]. It is of interest to study additional modes for the implementation of new methods of electrical exploration based on the interaction of FM signals with a geoprofile object.

We will analyze the effect of FM oscillations of the following type on an anisotropic medium

$$e(t) = E_2 \cos(\,\omega_2 t + \beta \sin \omega_1\, t), \tag{1}$$

where $E_2$ and $\omega_2 = 2 \cdot \pi \cdot f_2$ - the amplitude and frequency of the carrier signal, respectively; $\omega_1 = 2 \cdot \pi \cdot f_1$ - modulating frequency; $\beta = \frac{\Delta\omega}{\omega_1}$ - modulation index; $\Delta\omega$ - frequency deviation.

The dielectric permittivity tensor of the medium over the hydrocarbon deposits for such a mode has the form [14]:

$$\begin{cases} \dot{\varepsilon}_1 = \varepsilon_r \left(1 + \beta \cdot k_\omega \cos \omega_1 t\right) \\ + \sum_{i=1}^{2} \left\{ \dfrac{\omega_{\Pi i}^2 \tilde{\omega}_3}{\omega_2} \dfrac{\omega_{\Gamma i}^2 - \tilde{\omega}_3^2 - \nu_i^2}{(\nu_i^2 + \omega_{\Gamma i}^2 - \tilde{\omega}_3^2)^2 + 4\tilde{\omega}_3^2 \nu_i^2} - j\left[ \dfrac{\sigma_r}{\omega_2 \varepsilon_0} + \dfrac{\omega_{\Pi i}^2 \nu_i}{\omega_2} \dfrac{\tilde{\omega}_3^2 + \nu_i^2 + \omega_{\Gamma i}^2}{(\nu_i^2 + \omega_{\Gamma i}^2 - \tilde{\omega}_3^2)^2 + 4\tilde{\omega}_3^2 \nu_i^2} \right] \right\} \\ \dot{\varepsilon}_2 = \sum_{i=1}^{2} \left\{ \dfrac{\omega_{\Pi i}^2 \omega_{\Gamma i}}{\omega_2} \dfrac{\omega_{\Gamma i}^2 - \tilde{\omega}_3^2 + \nu_i^2}{(\nu_i^2 + \omega_{\Gamma i}^2 - \tilde{\omega}_3^2)^2 + 4\tilde{\omega}_3^2 \nu_i^2} - \dfrac{2 j \tilde{\omega}_3 \nu_i \omega_{\Pi i}^2 \omega_{\Gamma i}}{\left[ (\nu_i^2 + \omega_{\Gamma i}^2 - \tilde{\omega}_3^2)^2 + 4\tilde{\omega}_3^2 \nu_i^2 \right] \omega_2} \right\} \\ \dot{\varepsilon}_3 = \varepsilon_r \left(1 + \beta \cdot k_\omega \cos \omega_1 t\right) + \sum_{i=1}^{2} \left\{ \dfrac{\omega_{\Pi i}^2 \tilde{\omega}_3}{\omega_2} \dfrac{1}{\nu_i^2 + \tilde{\omega}_3^2} - j\left[ \dfrac{\sigma_r}{\omega_2 \varepsilon_0} + \dfrac{\omega_{\Pi i}^2 \nu_i}{\omega_2} \dfrac{1}{\tilde{\omega}_3^2 + \nu_i^2} \right] \right\} \end{cases} \tag{2}$$

Expressions (2) contain the components of the dielectric permittivity tensor of the medium above the hydrocarbon deposits $\dot{\varepsilon}_1$, $\dot{\varepsilon}_2$, $\dot{\varepsilon}_3$; plasma frequency $\omega_{\Pi i}$; gyrotropic frequency $\omega_{\Gamma i}$; frequency ratio factor $k_{\omega,}$; particle collision frequency$\nu_i$; relative permittivity of the medium $\varepsilon_r$; medium conductivity $\sigma_r$; dielectric constant $\varepsilon_0$. At the same time:

$$\tilde{\omega}_3 = \omega_2\ [1 + \beta \cdot k_\omega \cos \omega_1\, t] \tag{3}$$

It is of interest to analyze the frequency characteristics of the combinational components

$$\begin{aligned} \dot{\varepsilon}_R &= \dot{\varepsilon}_1 + \dot{\varepsilon}_2 = R\dot{e}\, \varepsilon_R + j\, I\dot{m}\, \varepsilon_R \\ \dot{\varepsilon}_L &= \dot{\varepsilon}_1 - \dot{\varepsilon}_2 = R\dot{e}\, \varepsilon_L + j\, I\dot{m}\, \varepsilon_L \end{aligned} \tag{4}$$

The first formula of expressions (4) corresponds to EMW with right polarization, the second formula of expressions (4) corresponds to EMW with left polarization.

The analysis of the components (4) of the dielectric constant of the medium above the hydrocarbon zone for the parameters of the medium above the hydrocarbon deposits [1] was carried out: the values of the dielectric constant of the host rocks $\varepsilon_r = 1 - 30$ and electrical conductivity $\sigma_r = 1 \cdot 10^{-5} - 1$ cm/m; particle concentration $N_e = N_и = (10^{16} - 10^{18})\,m^{-3}$, particle collision frequency $\nu = 2 \cdot \pi \cdot 10^9$ rad/s.

Plasma frequency

$$\omega_{\Pi i} = q_i \left(\frac{N_i}{m_i \varepsilon_0}\right)^{\frac{1}{2}} \quad (5)$$

Expressions (5) contain $q_i$, $N_i$, $m_i$ – charge, concentration and mass of particles.

## 3. Research results

The analysis of expressions (4) for the component of the real component of the permittivity for the right polarization of the EMW on the modulation index at $f_2 = 10^4$ Hz (figure 1), at $f_2 = 10^7$ Hz (figure 2) for electron-ionic conductivity. It has been established that at low modulation indices (β=1–10) the real component of the tensor component takes almost constant values.

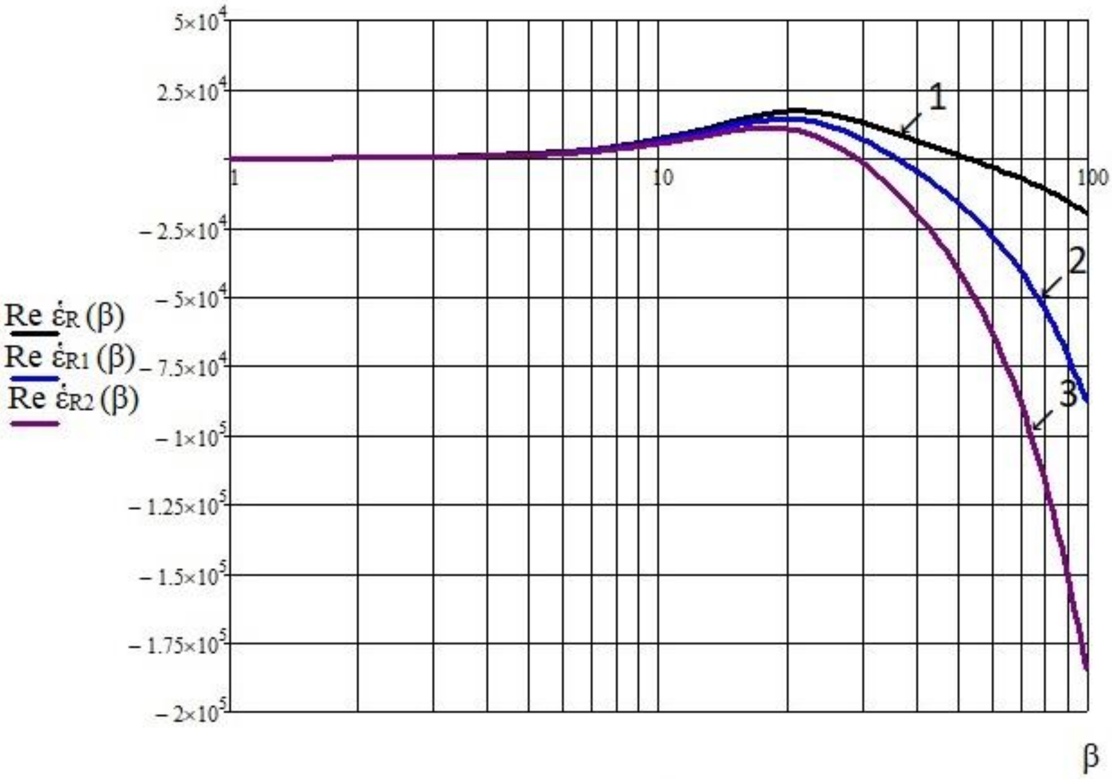


**Figure 1.** Dependences of the real component of the permittivity on the modulation index for the right polarization of the EMW at $f_2 = 10^4$ Hz: 1 – Re $\dot{\varepsilon}_R$ (β), $\varepsilon_r = 3$; 2– Re $\dot{\varepsilon}_{R1}$ (β), $\varepsilon_r = 10$; 3 – Re $\dot{\varepsilon}_{R2}$ (β), $\varepsilon_r = 20$.

The range β =10 - 100, characterized by a sharp change in the considered component of the dielectric permittivity tensor of the medium over hydrocarbons, is of interest. At β = 20 the maximum of this characteristic is observed. In the range of modulation indices (β =10 - 100) there is a sharp decrease in the considered component of the dielectric permittivity tensor of the medium over the hydrocarbon deposits.

The transition point through zero corresponds to the modulation indices β = 30 - 50. Large values of the dielectric permittivity of an anisotropic medium correspond to smaller values of the real components of the dielectric constant tensor of an anisotropic medium above the hydrocarbon deposits. It has been established that at $f_2 = 10^7$ Hz, the range β = 10 – 100 is of interest, which is characterized by a sharp change in the considered component of the permittivity tensor of the medium over hydrocarbons; there are no maxima of this characteristic. The regularities of the influence of the dielectric constant of an anisotropic medium on the values of the real components of the tensor component of an anisotropic medium over the hydrocarbon deposits are the same as in the previous case.

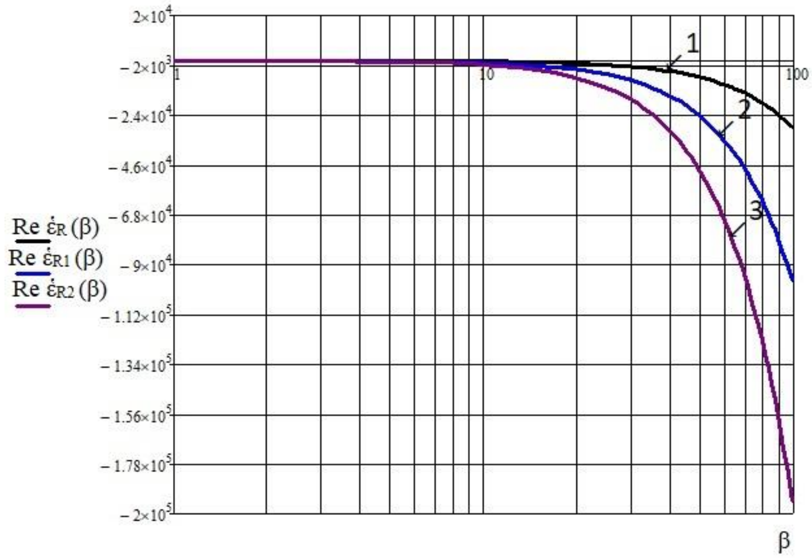


**Figure 2.** Dependences of the real component of the permittivity on the modulation index for the right polarization of EMW at $f_2 = 10^7$ Hz: 1 – Re $\dot{\varepsilon}_R$ (β), $\varepsilon_r = 3$; 2 – Re $\dot{\varepsilon}_{R1}$ (β),$\varepsilon_r = 10$; 3 – Re $\dot{\varepsilon}_{R2}$ (β), $\varepsilon_r = 20$.

Expressions (4) were analyzed for the real component of the permittivity for the left polarization of the EMW on the modulation index at $f_2 = 10^4$Hz (figure 3) and for the phase component of the permittivity for the right polarization of the EMW on the modulation index at $f_2 = 10^4$ Hz (figure 4 ) for electron-ionic conductivity.

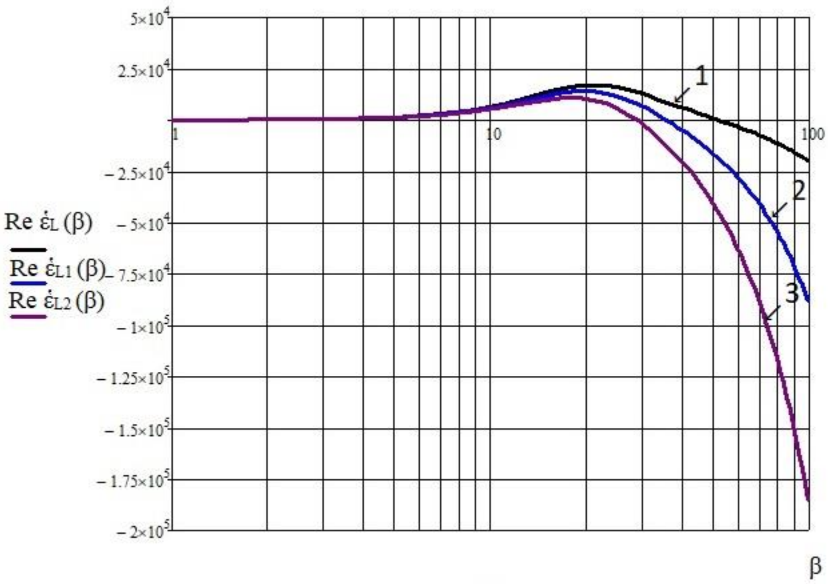


**Figure 3.** Dependences of the real component of the permittivity on the modulation index for the left polarization of EMW at $f_2 = 10^4$ Hz: 1 – Re $\dot{\varepsilon}_L$ (β), $\varepsilon_r = 3$; 2 – Re $\dot{\varepsilon}_{L1}$ (β),$\varepsilon_r = 10$; 3 – Re $\dot{\varepsilon}_{L2}$ (β), $\varepsilon_r = 20$.

It was found that the patterns of change in the component of the dielectric permittivity tensor of the medium over hydrocarbons for the left polarization of EMW are the same as for the component of the dielectric permittivity tensor of the medium above the hydrocarbons for the right polarization of EMW. At low modulation indices (β = 1 – 10), the phase component of the tensor component takes almost constant values. The range β = 10-100 with a sharp change in the component under consideration is of interest. At β = 20-25, the maximum of this characteristic is observed with a transition point through zero at β = 25-50. With an increase in the dielectric permittivity of an anisotropic medium, a decrease in the values of the phase components of the dielectric permittivity tensor of an anisotropic medium above the hydrocarbon deposits is observed.

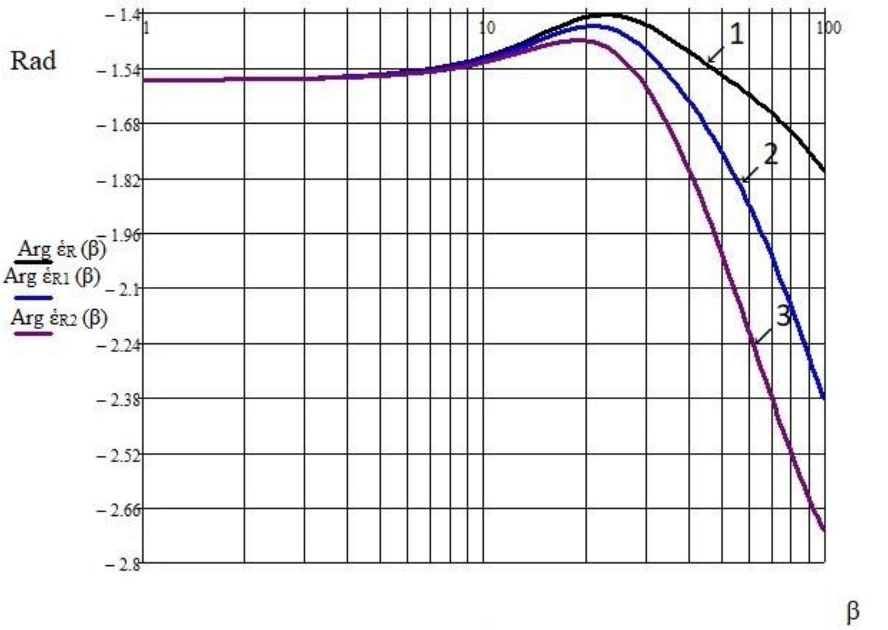


**Figure 4.** Dependences of the phase component of the permittivity on the modulation index for the right polarization of EMW at $f_2 = 10^4$ Hz: 1 – Arg $\acute{\varepsilon}_R$ (β), $\varepsilon_r$ = 3; 2 – Arg $\acute{\varepsilon}_{R1}$ (β),$\varepsilon_r$ = 10; 3 – Arg $\acute{\varepsilon}_{R2}$ (β), $\varepsilon_r$ = 20.

## 4. Conclusion

The analysis of the interaction of FM signals with anisotropic media above hydrocarbons deposits showed:

- the range of modulation indices β = 10 - 100 is characterized by a sharp change in the material components of the permittivity for the right and left polarizations of the EMV with a transition point through zero at β = 30 - 50;
- the patterns of change in the phase components of the dielectric permittivity tensor of the medium over hydrocarbons are the same as for real components.

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