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A.I. Utkin, A.A. Yushkanov

# Interaction of Electromagnetic H-wave with the thin Metal Film is Located on the Dielectric Substrate

*Moscow State Regional University, 10a, Radio st., 105005, Moscow, Russia, e-mail: aiutkin@yandex.ru.*

Interaction of electromagnetic H-wave with thin metal film is located between two dielectric environments $\varepsilon_1$, $\varepsilon_2$ in the case of different incident angles of H-wave θ and in the case of different reflection coefficients $q_1$ и $q_2$ is calculated in this article. Behavior analysis of reflection coefficient $R$, transmission coefficient $T$ and absorption coefficient $A$ in the case of its frequency dependence $y$ and variation dielectric permeability of its environments is done.

**Keywords:** the thin metal film, electromagnetic H-wave, dielectric environments, reflection coefficient, transmission coefficient, absorption coefficient.

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## Introduction

Currently microelectronics, optoelectronics and thin-film technology are actively developing. In particular the greatest interest represents researching of interaction electromagnetic radiation with thin conductive films in the different frequency range [1-6]. This interest is related not only with extensive practical importance of thin conductive films, but with some unresolved theoretical tasks.

In our case thickness of the thin metal film $a$ is not more, than thickness of skin-layer δ and this thickness comparable with the average free path of electrons Λ. For this reason skin-effect is not considered. Skin-effect was researched in [8] in the case of the thin metal cylindrical wire. Quantum effects are not taken into account. This effects were researched in [9] in the case of quantum film in the dielectric environment.

## I. Problem Definition and Metods

Consider the thin metal layer thickness of $a$ is located between two dielectric (non-magnetic) environments, with dielectric permeability $\varepsilon_1$ (the first environment) and $\varepsilon_2$ (the second environment) with reflection coefficients $q_1$ and $q_2$ in the case of falling electromagnetic H-wave (from the first environment) at the θ angle. Reflection coefficients $q_1$ and $q_2$ are associated with reflection of electrons from top and lower surfaces layer. Clarify, if electric field vector is parallel the surface of the thin layer, then this wave is called H-wave. Electric field of electromagnetic wave is parallel the thin metal layer and directed along $Y$-axis, while $X$-axis is directed into the layer.

Then behavior of electromagnetic field inside the thin metal layer is described by the equation system [10]:

$$\begin{cases} \dfrac{dE_y}{dx} - ikH_z = 0, \\ \dfrac{dH_z}{dx} + ik(\sin^2\Theta - 1)E_y = -\dfrac{4p}{c} j_y. \end{cases} \tag{1}$$

$k = \omega/c$ – wave number, $c$ – speed of light, $j$ – electric current density.

We have reflections coefficient $R$, transmission coefficient $T$ and absorption coefficient $A$ of thin metal film, when H-wave falling on this film [11]:

$$T = \frac{1}{4}\left|P^{(1)} - P^{(2)}\right|^2,$$
$$R = \frac{1}{4}\left|P^{(1)} + P^{(2)}\right|^2, \tag{2}$$
$$A = 1 - T - R.$$

Expression (2) contains $P^{(1)}$ and $P^{(2)}$ [12] :

$$P^{(1)} = \frac{\sqrt{e_1}\cdot Z^{(1)}\cos\Theta - 1}{\sqrt{e_1}\cdot Z^{(1)}\cos\Theta + 1},$$
$$P^{(2)} = \frac{\sqrt{e_1}\cdot Z^{(2)}\cos\Theta - 1}{\sqrt{e_1}\cdot Z^{(2)}\cos\Theta + 1}. \tag{3}$$

$Z^{(1)}$ and $Z^{(2)}$ correspond to the impedance of lower surface the layer. In particular $Z^{(1)}$ corresponds antisymmetric, in electric field, configuration of the external field: $E_y(0) = -E_y(a)$, $H_z(0) = H_z(a)$, and $Z^{(2)}$ – corresponds symmetric configuration: $E_y(0) = E_y(a)$, $H_z(0) = -H_z(a)$ [11].

Expression for surface impedance in the case of interaction H-wave with the thin metal film, were obtained in [11] in the case when wavelength much more thickness of the thin layer:

$$Z^{(1)} = 0,$$
$$Z^{(2)} = \frac{c}{2pas_a} \tag{4}$$

For $\sigma_a$ expression (this is electrical conductivity of the thin metal layer, with average thickness of this layer) we used results [13]. In this article we compared our results with experiment data [14]. Our $\sigma_a$ expression have look:

$$s_a = s_0 l \int_0^1 \left(1-t^2\right)\left[2a + \frac{at}{x-iy}\left[\frac{q_1\left[q_2 \exp\left(-(x-iy)/t\right) - \exp\left(-(x-iy)/t\right)+1\right]-1}{q_1 q_2 \exp\left(-2(x-iy)/t\right)-1} + \right.\right.$$
$$\left.\left. + \frac{q_2\left[q_1 \exp\left(-(x-iy)/t\right) - \exp\left(-(x-iy)/t\right)+1\right]-1}{q_1 q_2 \exp\left(-2(x-iy)/t\right)-1}\right]\left[\exp\left(-(x-iy)/t\right)-1\right]\right]dt \tag{5}$$

$x = a/(v_F\tau)$ – the dimensionless frequency of bulk electron collision, $y = a\omega/v_F$ – the dimensionless frequency of the electric field, $\lambda = x/(x-iy)$, $\sigma_0 = \omega^2_p\tau/4\pi$ – the static electrical conductivity, $v_F$ – Fermi speed, $\tau$ – electron relaxation time, $\omega_p$ – plasma frequency, $q_1$ и $q_2$ – reflection coefficients.

Finally, reflection coefficient $R$, transmission coefficient $T$ and absorption coefficient $A$ (expression (2)) will have look [12]:

$$R = \left|\frac{\sqrt{e_{1,2} - \sin^2\Theta}\,(\overline{P} + P^{(1)}P^{(2)}) + \cos\Theta(\overline{P} - P^{(1)}P^{(2)})}{\sqrt{e_{1,2} - \sin^2\Theta}\,(1+\overline{P}) + \cos\Theta(1-\overline{P})}\right|^2$$
$$T = \cos\Theta\,\mathrm{Re}\sqrt{e_{1,2} - \sin^2\Theta}\left|\frac{P^{(2)} - P^{(1)}}{\sqrt{e_{1,2} - \sin^2\Theta}\,(1+\overline{P}) + \cos\Theta(1-\overline{P})}\right|^2 \tag{6}$$
$$A = 1 - T - R. \quad \varepsilon_{1,2} = \varepsilon_2/\varepsilon_1, \qquad \overline{P} = \frac{1}{2}(P^{(1)} + P^{(2)}).$$

Now we will begin to analyze behavior of this coefficients (expression (6)).

## II. Results and Discussion

Let us consider behavior of coefficients $R$, $T$ and $A$ in the case of their frequency dependence with variation dielectric permeability value of the second environment $\varepsilon_2$ and in the case of different reflection coefficients $q_1$ and $q_2$. Clarify some parameters of potassium for further calculations: $\omega_p = 6.5 \cdot 10^{15}$ 1/s, $v_F = 8.52 \cdot 10^5$ m/s, $\tau = 1.54 \cdot 10^{-13}$ s, $a = 10$ nm.

## Conclusions

In figure 1 we can see that the descending velocity of the curve increases with increasing values of the dielectric permittivity of the second environment $\varepsilon_2$.

In figure 2 we can see that the increase velocity of the curve increases with increasing values of the dielectric permittivity of the second environment $\varepsilon_2$.

In figure 3, in the case of not large value of the dielectric permittivity ($\varepsilon_2 < 30$) we can see, that coefficient $A$ increases, reaches maximum and descents. Cleary visible absorption maxima. In the case of large value of the dielectric permittivity ($\varepsilon_2 > 30$) coefficient $A$ begin immediately descents.

In figure 4, 5, 6 we can see, that variation of the thin

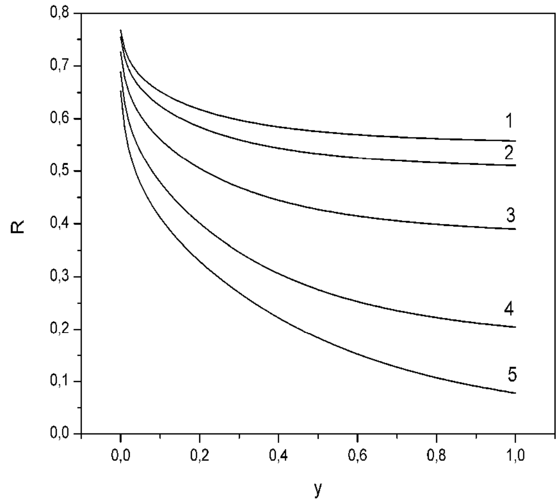


**Fig. 1.** The dependence of reflection coefficients *R* on the dimensionless frequency of the electric field *y*. Curve 1: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 40$, $q_1 = 0.5$, $q_2 = 0.6$; curve 2: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 30$, $q_1 = 0.5$, $q_2 = 0.6$; curve 3: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 15$, $q_1 = 0.5$, $q_2 = 0.6$; curve 4: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 5$, $q_1 = 0.5$, $q_2 = 0.6$; curve 5: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 1$, $q_1 = 0.5$, $q_2 = 0.6$.

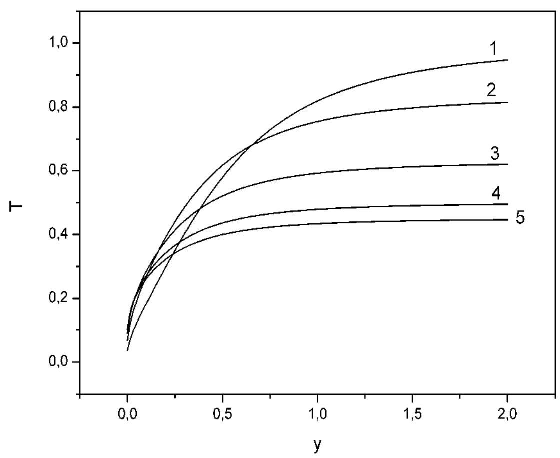


**Fig. 2.** The dependence of transmission coefficients *T* on the dimensionless frequency of the electric field *y*. Curve 1: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 1$, $q_1 = 0.5$, $q_2 = 0.6$; curve 2: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 5$, $q_1 = 0.5$, $q_2 = 0.6$; curve 3: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 15$, $q_1 = 0.5$, $q_2 = 0.6$; curve 4: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 30$, $q_1 = 0.5$, $q_2 = 0.6$; curve 5: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 40$, $q_1 = 0.5$, $q_2 = 0.6$.

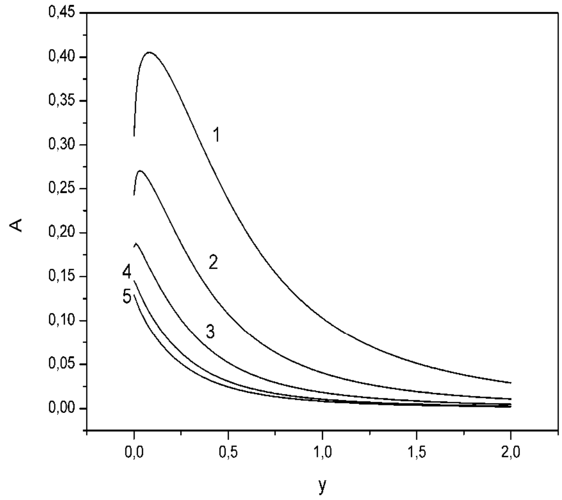


**Fig. 3.** The dependence of absorption coefficients *A* on the dimensionless frequency of the electric field *y*. Curve 1: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 1$, $q_1 = 0.5$, $q_2 = 0.6$; curve 2: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 5$, $q_1 = 0.5$, $q_2 = 0.6$; curve 3: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 15$, $q_1 = 0.5$, $q_2 = 0.6$; curve 4: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 30$, $q_1 = 0.5$, $q_2 = 0.6$; curve 5: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 40$, $q_1 = 0.5$, $q_2 = 0.6$.

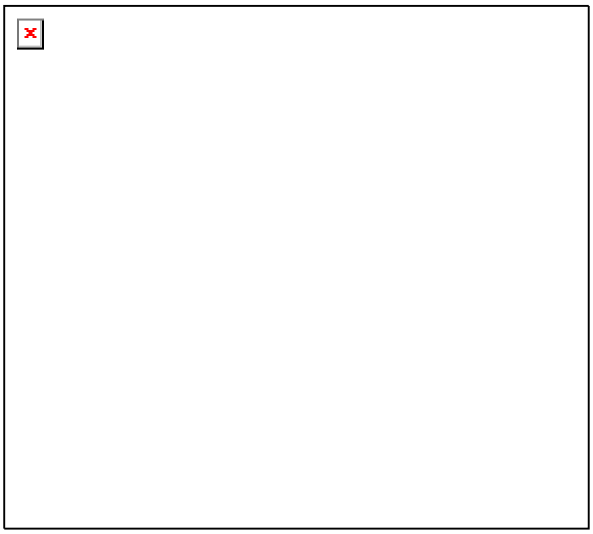

**Fig. 4.** The dependence of reflection coefficients *R* on the dimensionless frequency of the electric field *y*. Curve 1: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 1$, $q_2 = 1$; curve 2: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 0.8$, $q_2 = 0.9$; curve 3: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 0.5$, $q_2 = 0.6$; curve 4: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 0.2$, $q_2 = 0.3$; curve 5: $x = 0.002$, $\theta = 20^0$, $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 0$, $q_2 = 0$.

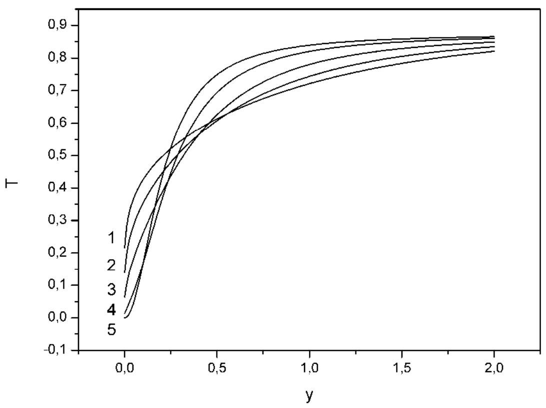


**Fig. 5.** The dependence of transmission coefficients *T* on the dimensionless frequency of the electric field *y*. Curve 1: x = 0.002, $\theta = 20^0$ , $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 0$, $q_2 = 0$; curve 2: x = 0.002, $\theta = 20^0$ , $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 0.2$, $q_2 = 0.3$; curve 3: x = 0.002, $\theta = 20^0$ , $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 0.5$, $q_2 = 0.6$; curve 4: x = 0.002, $\theta = 20^0$ , $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 0.8$, $q_2 = 0.9$; curve 5: x = 0.002, $\theta = 20^0$ , $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 1$, $q_2 = 1$.

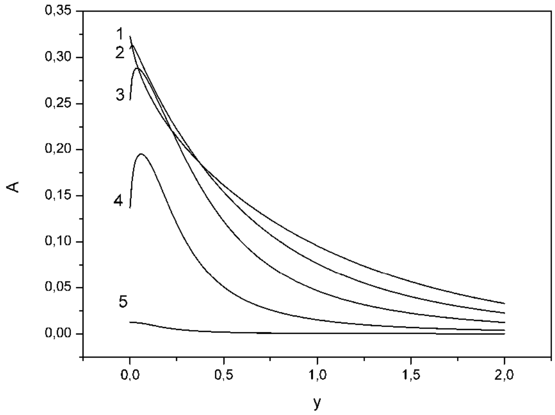


**Fig. 6.** The dependence of absorption coefficients *A* on the dimensionless frequency of the electric field *y*. Curve1: x = 0.002, $\theta = 20^0$ , $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 0$, $q_2 = 0$; curve 2: x = 0.002, $\theta = 20^0$ , $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 0.2$, $q_2 = 0.3$; curve 3: x = 0.002, $\theta = 20^0$ , $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 0.5$, $q_2 = 0.6$; curve 4: x = 0.002, $\theta = 20^0$ , $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 0.8$, $q_2 = 0.9$; curve 5: x = 0.002, $\theta = 20^0$ , $\varepsilon_1 = 1$, $\varepsilon_2 = 4$, $q_1 = 1$, $q_2 = 1$.

metal layer reflection coefficients $q_1$ and $q_2$ (from diffuse $q_1 = q_2 = 0$ to reflection $q_1 = q_2 = 1$ cases) affects to *R*, *T*, *A* coefficients. It is obvious that reflection coefficients will change, when the thin metal film borders with different environments. In particular, in figure 6, in the reflection case, coefficient *A* immediately descent. In all other cases coefficient *A* increases reaches its maximum and descents.

***Utkin A.I.*** **-** postgraduate student of Theoretical Physics department;
***Yushkanov A.A.*** **-** doctor of Science, professor of Theoretical Physics department.

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