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INFLUENCE OF LASER RADIATION ON THE ABSORPTION OF A WEAK ELECTROMAGNETIC WAVE BY CONFINED ELECTRONS IN DOPED SUPERLATTICES

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Abstract. *The absorption coefficient of a weak electromagnetic wave by confined electrons in the presence of laser radiation in doped superlattices (DSL) is calculated by using the quantum kinetic equation for electrons. The analytic expressions of the absorption coefficient of a weak electromagnetic wave (EMW) in the presence of laser radiation field for the case of electron optical phonon scattering are obtained. The dependence of the absorption coefficient on the intensity E_{01} and frequency Ω_1 of the external laser radiation, the intensity E_{02} and frequency Ω_2 of the weak electromagnetic wave, the temperature T of the system are analyzed. The results are numerically calculated, plotted, and discussed for n-GaAs/p-GaAs doped superlattices. The appearance of a laser radiation causes surprising changes in the absorption coefficient. All the results are compared with those for the normal bulk semiconductors.*

I. INTRODUCTION

In recent times, there has been more and more interest in studying and discovering the behavior of low-dimensional system, in particular, DSL. The confinement of electrons in these systems considerably enhances the electron mobility and leads to their unusual behaviors under external stimuli. As a result, the properties of low - dimensional systems, especially the optical properties, are very different in comparison with those of normal bulk semiconductors [1-5]. The linear absorption of a weak EMW by confined electron in low-dimensional systems has been investigated by using the Kubo-Mori method [6-9], the nonlinear absorption of a strong electromagnetic wave by confined electrons in low-dimensional systems has been studied by using the quantum kinetic equation method [10-15]. The problem of influence of laser radiation on the absorption of a weak electromagnetic wave by free electrons in normal bulk semiconductors has been investigated by using the quantum kinetic equation method [16]. However, the problem of influence of laser radiation on the absorption of a weak electromagnetic wave in DSL is still open for study. Research influence of laser radiation on the absorption of a weak electromagnetic wave have an important role in experimental. Because in experimental, it is difficult to directly measure the AC a strong EMW. Therefore, to solve this problem, one study influence of strong EMW on electrons in semiconductor which is located in the weak electromagnetic waves [16]. Therefore, in this paper, we study influence of laser radiation on the absorption of a weak electromagnetic wave by confined electrons in DSL. The electron-optical phonon scattering mechanism is considered. The absorption coefficient of a weak electromagnetic wave in the presence of laser radiation field are obtained by using the quantum kinetic equation for electrons in a DSL. Then, we estimate numerical values for the specific n-GaAs/p-GaAs DSL to clarify our results.

II. THE ABSORPTION COEFFICIENT OF A WEAK EMW IN THE PRESENCE OF LASER RADIATION FIELD IN A DSL

II.1. The electron distribution function in a doped superlattice

It is well known that the motion of an electron in a DSL is confined and that its energy spectrum is quantized into discrete levels. We assume that the quantization direction is the z direction. The Hamiltonian of the electron - optical phonon system in a DSL in the second quantization representation can be written as:

$$H = \sum_{n,\vec{p}_\perp} \varepsilon_{n,\vec{p}_\perp}(\vec{p}_\perp - \tfrac{e}{\hbar c}\vec{A}(t))a^+_{n,\vec{p}_\perp} a_{n,\vec{p}_\perp} + \sum_{\vec{q}} \hbar\omega_{\vec{q}} b^+_{\vec{q}} b_{\vec{q}} +$$

$$+ \sum_{n,n',\vec{p}_\perp,\vec{q}} C_{\vec{q}} I_{n,n'}(q_z) a^+_{n',\vec{p}_\perp+\vec{q}_\perp} a_{n,\vec{p}_\perp}(b_{\vec{q}} + b^+_{-\vec{q}}) \tag{1}$$

where n denotes the quantization of the energy spectrum in the z direction (n =1,2,...), $(n, \vec{p}_\perp)$ and $(n', \vec{p}_\perp + \vec{q}_\perp)$ are electron states before and after scattering, respectively. $\vec{p}_\perp(\vec{q}_\perp)$ is the in - plane (x,y) wave vector of the electron (phonon), $a^+_{n,\vec{p}_\perp}$ and $a_{n,\vec{p}_\perp}$ ($b^+_{\vec{q}}$ and $b_{\vec{q}}$) are the creation and the annihilation operators of electron (phonon), respectively. $\vec{q} = (\vec{q}_\perp, q_z)$, $\vec{A}(t)$ is the vector potential of EMW, and $\hbar\omega_0$ is the energy of an optical phonon, $C_{\vec{q}}$ is a constant in the case of electron - optical phonon interaction [17]:

$$\left|C_{\vec{q}}\right|^2 = \frac{2\pi e^2 \hbar\omega_0}{V\varepsilon_0 q^2}\left(\frac{1}{\chi_\infty} - \frac{1}{\chi_0}\right) \tag{2}$$

Here, V, e, ε_0 are the normalization volume, the electron charge and the electronic constant (often V=1), χ_0 and χ_∞ are the static and the high - frequency dielectric constants, respectively.

The electron form factor, $I_{n,n'}(q_z)$ is written as:

$$I_{n,n'}(q_z) = \sum_{l=1}^{N_d} \int_0^d e^{iq_z z}\psi_n(z - ld)\psi_{n'}(z - ld)dz \tag{3}$$

In DSL, the electron energy takes the simple form:

$$\varepsilon_n(\vec{p}_\perp) = \frac{\hbar^2 \vec{p}_\perp^2}{2m^*} + \hbar\omega_p\left(n + \frac{1}{2}\right) \tag{4}$$

Here, m^* is the effective mass of electron, $\psi_n(z)$ is the wave function of the n-th state for a single potential well which compose the DSL potential, d is the DSL period, N_d is the number of DSL period, $\omega_p = \left(\frac{4\pi e^2 n_D}{\chi_0 m^*}\right)^{1/2}$ is the frequency plasma caused by donor doping concentration, n_D is the doping concentration.

In order to establish the quantum kinetic equations for electrons in DSL, we use the general quantum equation for statistical average value of the electron particle number operator(or electron distribution function) $n_{n,\vec{p}_\perp}(t) = \left\langle a^+_{n,\vec{p}_\perp} a_{n,\vec{p}_\perp} \right\rangle_t$ [17]:

$$i\hbar \frac{\partial n_{n,\vec{p}_\perp}(t)}{\partial t} = \left\langle \left[a^+_{n,\vec{p}_\perp} a_{n,\vec{p}_\perp} \right], H \right\rangle_t \tag{5}$$

where $\langle \psi \rangle_t$ denotes a statistical average value at the moment t, and $\langle \psi \rangle_t = Tr(\hat{W}\hat{\psi})$ ($\hat{W}$ being the density matrix operator). Starting from the Hamiltonian in Eq. (1) and using the commutative relations of the creation and the annihilation operators, we obtain the quantum kinetic equation for electrons in DSL:

$$\begin{aligned}
&\frac{\partial n_{n,\vec{p}_\perp}(t)}{\partial t} = -\frac{1}{\hbar^2} \sum_{n',\vec{q}} \left|C_{\vec{q}}\right|^2 \left|I_{n,n'}(q_z)\right|^2 \sum_{l,s,m,f=-\infty}^{+\infty} J_l(\vec{a}_1\vec{q}_\perp) J_s(\vec{a}_1\vec{q}_\perp) J_m(\vec{a}_2\vec{q}_\perp) J_f(\vec{a}_2\vec{q}_\perp) \\
&\times e^{i\{[(s-l)\Omega_1+(m-f)\Omega_2-i\delta]t+(s-l)\varphi_1\}} \\
&\times \int_{-\infty}^{t} dt_2 \left\{ \left[n_{n,\vec{p}_\perp}(t_2) N_{\vec{q}} - n_{n',\vec{p}_\perp+\vec{q}_\perp}(t_2)(N_{\vec{q}}+1) \right] e^{\frac{i}{\hbar}\left[\varepsilon_{n'}(\vec{p}_\perp+\vec{q}_\perp)-\varepsilon_n(\vec{p}_\perp)-\hbar\omega_{\vec{q}}-s\hbar\Omega_1-m\hbar\Omega_2+i\hbar\delta\right](t-t_2)} \right. \\
&+ \left[n_{n,\vec{p}_\perp}(t_2)(N_{\vec{q}}+1) - n_{n',\vec{p}_\perp+\vec{q}_\perp}(t_2) N_{\vec{q}} \right] e^{\frac{i}{\hbar}\left[\varepsilon_{n'}(\vec{p}_\perp+\vec{q}_\perp)-\varepsilon_n(\vec{p}_\perp)+\hbar\omega_{\vec{q}}-s\hbar\Omega_1-m\hbar\Omega_2+i\hbar\delta\right](t-t_2)} \\
&- \left[n_{n',\vec{p}_\perp-\vec{q}_\perp}(t_2) N_{\vec{q}} - n_{n,\vec{p}_\perp}(t_2)(N_{\vec{q}}+1) \right] e^{\frac{i}{\hbar}\left[\varepsilon_n(\vec{p}_\perp)-\varepsilon_{n'}(\vec{p}_\perp-\vec{q}_\perp)-\hbar\omega_{\vec{q}}-s\hbar\Omega_1-m\hbar\Omega_2+i\hbar\delta\right](t-t_2)} \\
&\left. - \left[n_{n',\vec{p}_\perp-\vec{q}_\perp}(t_2)(N_{\vec{q}}+1) - n_{n,\vec{p}_\perp}(t_2) N_{\vec{q}} \right] e^{\frac{i}{\hbar}\left[\varepsilon_n(\vec{p}_\perp)-\varepsilon_{n'}(\vec{p}_\perp-\vec{q}_\perp)+\hbar\omega_{\vec{q}}-s\hbar\Omega_1-m\hbar\Omega_2+i\hbar\delta\right](t-t_2)} \right\}
\end{aligned} \tag{6}$$

If we consider similar problem but in the normal bulk semiconductors, that authors V. L. Malevich, E. M. Epstein published, we will see that equation (6) has similarity to the quantum kinetic equation for electrons in the bulk semiconductor [16].

It is well known that to obtain the explicit solutions from Eq. (6) is very difficult. In this paper, we use the first - order tautology approximation method to solve this equation [17-19]. In detail, in Eq. (6), we choose the initial approximation of $n_{n,\vec{p}_\perp}(t)$ as:

$n^0_{n,\vec{p}_\perp}(t_2) = \bar{n}_{n,\vec{p}_\perp}$, $n^0_{n,\vec{p}_\perp+\vec{q}_\perp}(t_2) = \bar{n}_{n,\vec{p}_\perp+\vec{q}_\perp}$, $n^0_{n,\vec{p}_\perp-\vec{q}_\perp}(t_2) = \bar{n}_{n,\vec{p}_\perp-\vec{q}_\perp}$

Where $\bar{n}_{n,\vec{p}_\perp}$ is the balanced distribution function of electrons. We perform the integral with respect to t_2; Next, we perform the integral with respect to t of Eq. (6). The expression for the unbalanced electron distribution function can be written as:

$$\begin{aligned}
&n_{n,\vec{p}_\perp}(t) = \bar{n}_{n,\vec{p}_\perp} - \frac{1}{\hbar} \sum_{n',\vec{q}} \left|C_{\vec{q}}\right|^2 \left|I_{n,n'}(q_z)\right|^2 \sum_{k,s,r,m=-\infty}^{+\infty} J_s(\vec{a}_1\vec{q}_\perp) J_{k+s}(\vec{a}_1\vec{q}_\perp) J_m(\vec{a}_2\vec{q}_\perp) J_{r+m}(\vec{a}_2\vec{q}_\perp) \\
&\times \frac{e^{-i\{[k\Omega_1+r\Omega_2+i\delta]t+k\varphi_1\}}}{k\Omega_1+r\Omega_2+i\delta} \\
&\times \left\{ \frac{\bar{n}_{n',\vec{p}_\perp-\vec{q}_\perp} N_{\vec{q}} - \bar{n}_{n,\vec{p}_\perp}(N_{\vec{q}}+1)}{\varepsilon_n(\vec{p}_\perp)-\varepsilon_{n'}(\vec{p}_\perp-\vec{q}_\perp)-\hbar\omega_{\vec{q}}-s\hbar\Omega_1-m\hbar\Omega_2+i\hbar\delta} + \frac{\bar{n}_{n',\vec{p}_\perp-\vec{q}_\perp}(N_{\vec{q}}+1) - \bar{n}_{n,\vec{p}_\perp} N_{\vec{q}}}{\varepsilon_n(\vec{p}_\perp)-\varepsilon_{n'}(\vec{p}_\perp-\vec{q}_\perp)+\hbar\omega_{\vec{q}}-s\hbar\Omega_1-m\hbar\Omega_2+i\hbar\delta} \right. \\
&\left. - \frac{\bar{n}_{n,\vec{p}_\perp} N_{\vec{q}} - \bar{n}_{n',\vec{p}_\perp+\vec{q}_\perp}(N_{\vec{q}}+1)}{\varepsilon_{n'}(\vec{p}_\perp+\vec{q}_\perp)-\varepsilon_n(\vec{p}_\perp)-\hbar\omega_{\vec{q}}-s\hbar\Omega_1-m\hbar\Omega_2+i\hbar\delta} - \frac{\bar{n}_{n,\vec{p}_\perp}(N_{\vec{q}}+1) - \bar{n}_{n',\vec{p}_\perp+\vec{q}_\perp} N_{\vec{q}}}{\varepsilon_{n'}(\vec{p}_\perp+\vec{q}_\perp)-\varepsilon_n(\vec{p}_\perp)+\hbar\omega_{\vec{q}}-s\hbar\Omega_1-m\hbar\Omega_2+i\hbar\delta} \right\}
\end{aligned} \tag{7}$$

where $\vec{a}_1 = \frac{e\vec{E}_{01}}{m^*\Omega_1^2}$, $\vec{a}_2 = \frac{e\vec{E}_{02}}{m^*\Omega_2^2}$, $N_{\vec{q}}$ is the balanced distribution function of phonons, $\vec{E}_{01}$ and Ω_1 are the intensity and frequency of a strong EMW (laser radiation), $\vec{E}_{02}$ and Ω_2

are the intensity and frequency of a weak EMW; φ_1 is the phase difference between two electromagnetic waves, $J_k(x)$ is the Bessel function.

II.2. Calculations of the absorption coefficient of a weak EMW in the presence of laser radiation in a DSL

The carrier current density formula in DSL takes the form:

$$\vec{j}_\perp(t) = \frac{e\hbar}{m^*}\sum_{n,\vec{p}_\perp}\Big(\vec{p}_\perp - \frac{e}{\hbar c}\vec{A}(t)\Big)n_{n,\vec{p}_\perp}(t) \tag{8}$$

Because the motion of electrons is confined along the z direction in a DSL, we only consider the in - plane (x,y) current density vector of electrons $\vec{j}_\perp(t)$.

The AC of a weak EMW by confined electrons in the DSL takes the simple form [17]:

$$\alpha = \frac{8\pi}{c\sqrt{\chi_\infty}E_{02}^2}\Big\langle \vec{j}_\perp(t)\vec{E}_{02}\sin\Omega_2 t\Big\rangle_t \tag{9}$$

From the expressions Eqs. (8), (9), we established the AC of a weak EMW in DSL:

$$\begin{aligned}\alpha = {} & \frac{n_0\omega_p e^4\hbar\omega_0}{\sqrt{2\pi\chi_\infty}(m^*k_bT)^{3/2}\varepsilon_0 c\Omega_2^3}\left(\frac{1}{\chi_\infty}-\frac{1}{\chi_0}\right)\sum_{n,n'=-\infty}^{+\infty} II_{n,n'} \\ & \times\Big[(D_{0,1}-D_{0,-1}) - \tfrac{1}{2}(H_{0,1}-H_{0,-1}) + \tfrac{3}{32}(G_{0,1}-G_{0,-1}) \\ & +\tfrac{1}{4}(H_{-1,1}-H_{-1,-1}+H_{1,1}-H_{1,-1}) - \tfrac{1}{16}(G_{-1,1}-G_{-1,-1}+G_{1,1}-G_{1,-1}) \\ & +\tfrac{1}{64}(G_{-2,1}-G_{-2,-1}+G_{2,1}-G_{2,-1})\Big\}\end{aligned} \tag{10}$$

Where:

$$D_{s,m} = \pi e^{-\frac{\xi_{s,m}}{2k_bT}}\left(\frac{4{m^*}^2\xi_{s,m}^2}{\hbar^4}\right)^{1/4} K_{1/2}\left(\frac{|\xi_{s,m}|}{2k_bT}\right)\left[e^{-\frac{\varepsilon_n}{k_bT}}(N_{\omega_0}+1) - e^{-\frac{\varepsilon_{n'}-\xi_{s,m}}{k_bT}}N_{\omega_0}\right]$$

$$H_{s,m} = a_1^2\left(\tfrac{\pi}{2}+\tfrac{\pi}{4}\cos 2\gamma\right)e^{-\frac{\xi_{s,m}}{2k_bT}}\left(\frac{4{m^*}^2\xi_{s,m}^2}{\hbar^4}\right)^{3/4} K_{3/2}\left(\frac{|\xi_{s,m}|}{2k_bT}\right)\left[e^{-\frac{\varepsilon_n}{k_bT}}(N_{\omega_0}+1) - e^{-\frac{\varepsilon_{n'}-\xi_{s,m}}{k_bT}}N_{\omega_0}\right]$$

$$G_{s,m} = a_1^4\left(\tfrac{3\pi}{8}+\tfrac{\pi}{4}\cos 2\gamma\right)e^{-\frac{\xi_{s,m}}{2k_bT}}\left(\frac{4{m^*}^2\xi_{s,m}^2}{\hbar^4}\right)^{5/4} K_{5/2}\left(\frac{|\xi_{s,m}|}{2k_bT}\right)\left[e^{-\frac{\varepsilon_n}{k_bT}}(N_{\omega_0}+1) - e^{-\frac{\varepsilon_{n'}-\xi_{s,m}}{k_bT}}N_{\omega_0}\right]$$

$II_{n,n'} = \int_{-\infty}^{+\infty}\left|I_{n,n'}(q_z)\right|^2 dq_z$; $N_{\omega_0} = \frac{1}{e^{\frac{\hbar\omega_0}{k_bT}}-1}$

$\xi_{s,m} = \hbar\omega_p(n'-n) + \hbar\omega_0 - s\hbar\Omega_1 - m\hbar\Omega_2$, with s = - 2, - 1,0,1,2; m= -1,1

γ is the angle between two vectors $\vec{E}_{01}$ and $\vec{E}_{02}$

III. NUMERICAL RESULTS AND DISCUSSION

In order to clarify the mechanism for the absorption of a weak EMW in a DSL in the presence of laser radiation, in this section, we will evaluate, plot, and discuss the expression of the AC for the case of a doped superlattice with equal thickness $d_n = d_p$ of the n- and p- doped layers, equal and constant doped concentration $n_D = n_A$: n-GaAs/p-GaAs [20]. The parameters used in the calculations are as follows [9,17]: $\chi_\infty = 10,9$, $\chi_0 = 12,9$, $m = 0,067m_0$, m_0 being the mass of free electron, $d = 80nm$, $n_0 = 10^{23}m^{-3}$, $n_D = 10^{23}m^{-3}$, $\hbar\omega_0 = 36,25meV$, $\gamma = \frac{\pi}{3}$

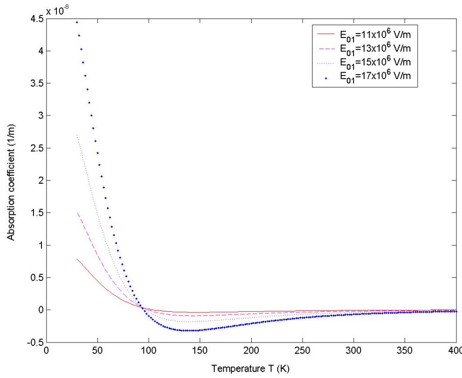

Fig. 1. The dependence of α on T ($\Omega_1 = 3 \times 10^{13} Hz$, $\Omega_2 = 10^{13} Hz$)

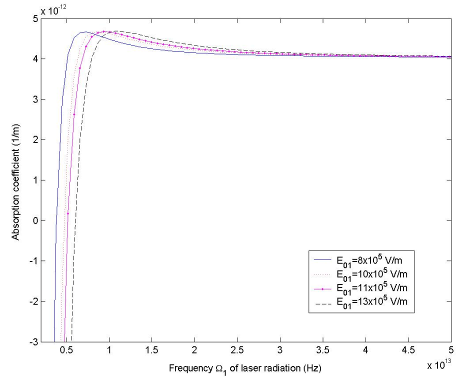

Fig. 2. The dependence of α on Ω_1 ($T = 30K$, $E_{01} = 10^6 V/m$)

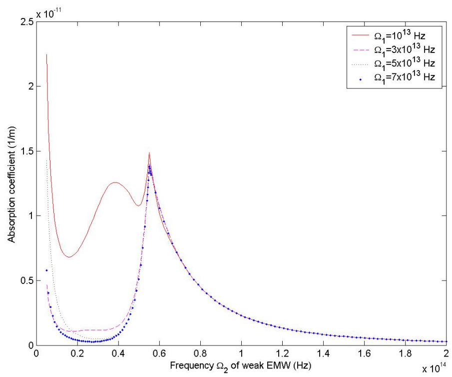

Fig. 3. The dependence of α on Ω_2 ($T = 90K$, $\Omega_2 = 5 \times 10^{13} Hz$)

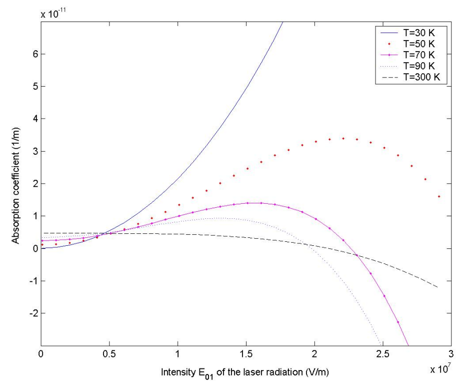

Fig. 4. The dependence of α on E_{01} ($\Omega_1 = 6 \times 10^{13} Hz$, $\Omega_2 = 3 \times 10^{13} Hz$)

Figure 1 show that when the temperature T of the system rises up from 30K to 400K, its absorption coefficient reduce, then gradually increase to 0.

Figure 2 show that when the frequency Ω_1 rises up, absorption coefficient speeds up too, then gradually reduce to a certain value, and curve has a maximum value.

Figure 3 show absorption coefficient as a function of the frequency Ω_2 of weak EMW. This figure shows that the curve has a maximum where $\Omega_2 = \omega_0$; with $\Omega_1 = 10^{13} Hz$, the curve has more than one maximum.

Figure 4 show absorption coefficient as a function of the intensity E_{01} of laser radiation. This figure shows that the curve can have maximum or no maximum in the surveyed interval.

These figures show that under influence of laser radiation, absorption coefficient of a weak EMW in a DSL can get negative values. So, by the presence of strong electromagnetic waves, in some conditions, the weak electromagnetic wave is increased. This is different from the case of the absence of laser radiation.

IV. CONCLUSION

In this paper, we analytically investigated influence of laser radiation on the absorption of a weak EMW by confined electrons in DSL. We obtained a quantum kinetic equations for electrons confined in DSL. By using the tautology approximation methods, we solved this equation to find the expression for the electron distribution function. Then, we found the formula of the AC in DSL. We numerically calculated and graphed the AC for n-GaAs/p-GaAs DSL to clarify.

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REFERENCES

[1] R. Tsu, L. Esaki, *Appl. Phys. Lett.* **22** (1973) 562.
[2] J. S. Harris Jr, *Int. J. Mod. Phys. B* **4** (1990) 1149.
[3] P. Zhao, *Phys. Rev. B* **49** (1994) 13589.
[4] N. Nishiguchi, *Phys. Rev. B* **52** (1995) 5279.
[5] R. Dingle, *Confined Carries Quantum states in ultra-thin Semiconductor Heterostructures,* in Festkorperprobleme XV, H. J. Queisser, Pergamon Vieweg, New York, 1975.
[6] Nguyen Quang Bau, Nguyen The Toan, Chhoumn Navy, Tran Cong Phong, *Comm. Phys.* **6** (1996) 30-40.
[7] N. Q. Bau, N. V. Nhan, T. C. Phong, *J. Kor. Phys. Soc.* **42** (2003) 647.
[8] N. Q. Bau, T. C. Phong, *J. Phys. Soc. Jpn* **67** (1998) 3875.
[9] N. Q. Bau, N. V. Nhan, T. C. Phong, *J. Korean. Phys. Soc.* **41** (2002) 149-154.
[10] N. Q. Bau, H. D. Trien, *Intech: Wave propagation* **22** (2011) 461-482.
[11] N. Q. Bau, L. T. Hung, N. D. Nam, *J. of Electromagn. Waves and Appl.* **24** (2010) 1751-1761.
[12] N. Q. Bau, M. D. Hung, L. T. Hung, *Pier Letters* **15** (2010) 175-185.
[13] N. Q. Bau, M. D. Hung, N. B. Ngoc, *J. Korean. Phys. Soc.* **42** (2009) 765-773.
[14] N. Q. Bau, L. T. Hung, H. D. Trien, *Intech: Behaviour of electromagnetic waves in different Media and Structures*, 2011 Ali Akdagli Ed., pp. 275-300.
[15] P. Vasilopoulos, M. Charbonneau, C. M. Van Vliet, *Phys. Rev. B* **35** (1987) 1334.
[16] V. L. Malevich, E. M. Epstein, *Izvestria BYZ, RadioPhysic T.* **18** (1975) 785-811.
[17] V. V. Pavlovich, E. M. Epstein, *Sov. Phys. Solid State.* **19** (1977) 1760.
[18] V. L. Malevich, E. M. Epstein, *Sov. Quantum Electronic* **1** (1974) 1468-1470.
[19] E. M. Epstein, *Sov. Communication of HEE of USSR, Ser. Radio* **18** (1975) 785.
[20] K. Ploog, G. H. Doller, *Adv. Phys.* **32** (1975) 285-359.

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