Simulation of Optical Properties of Terahertz Hyperbolic Metamaterials Based on Multiple Quantum Wells

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One of types of hyperbolic metamaterials is a stack of alternating dielectric and metallic layers (thickness d_d, dielectric function $\epsilon_d(\omega)$ and d_m, $\epsilon_m(\omega)$, respectively), where $\omega \sim 1/\lambda$ is the frequency of the electromagnetic wave. Within an effective medium approach, i.e., when the wavelenght $\lambda \gg (d_d + d_m)$ the material behaves as an optically uniaxial medium with the effective dielectric constants $\epsilon_{\|} = p\epsilon_m + (1-p)\epsilon_d$ and $\epsilon_{\perp} = \epsilon_m\epsilon_d/[p\epsilon_d + (1-p)\epsilon_m]$, where $\epsilon_{\|}$ and $\epsilon_{\perp}$ describe the dielectric polarization of the effective medium material for the electric field with zero and non-zero component along the optical axis (which is perpendicular to the surface of the layers) and $p = d_m/(d_m+d_d)$.

Considering the electric field of the wave propagating in this medium, one gets from the Maxwell's equations

$$\left(k_{\perp}^2 + k_{\|}^2 - \epsilon_{\|}\frac{\omega^2}{c^2}\right)\left(k_{\perp}^2\epsilon_{\perp} + k_{\|}^2\epsilon_{\|} - \epsilon_{\perp}\epsilon_{\|}\frac{\omega^2}{c^2}\right) = 0 \tag{1}$$

where c is the speed of light, and $k_{\perp}$ and $k_{\|}$ are components of the wave vector perpendicular and parallel to the layers, respectively.

By equating to zero the first and second term in Eq. 1 one gets equations describing a spherical and ellipsoidal isofrequency surfaces, if $\epsilon_{\perp}\epsilon_{\|} > 0$. These solutions correspond to the Transverse Electric (TE) and Transverse Magnetic (TM) modes, respectively. However, if $\epsilon_{\perp}\epsilon_{\|} < 0$, TM waves (these with a non-zero component of the electric field of the wave in the direction of the optical axis) are supported by a hyperboloidal isofrequency surface with allowing k-vectors to stretch to infinity (in fact, to $2\pi/a$, where a is the period of the lattice).

The aim of the present paper is to numerically simulate THz optical properties of structures in which conductive and dielectric layers are CdTe quantum wells containing electrons and $Cd_{1-x}Mg_xTe$ barriers, respectively, situated on a SI-GaAs substrate (thickness d_s). The essential difference between our study and the work of other groups is introduction of magnetic field which leads to an anisotropy of the conductive layers and introduces a cyclotron resonance. Numerical simulations are carried out according to a transfer matrix method for anisotropic system. The results are coeffcients of energy transfer for both TE and TM modes and allow to determine the state of polarization of transmitted and reflected waves. Simulations are carried out as a function of geometrical parameters of structures (the number of quantum wells N, d_d, d_m, d_s), the electron concentration in the wells, the magnetic field, the frequency of the wave and the angle of incidence.

We applied the numerical procedure treating the system as composed of N periods of layers characterized by ϵ_m, ϵ_d on a substrate or as a system of the thickness $N(d_d + d_m)$ characterized by effective parameters $\epsilon_{\perp}$, $\epsilon_{\|}$. This allows us to establish the validity of the effective medium approach in the presence of magnetic field, which is a new result.

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