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Optical Absorption in an Array of Quantum Wires: Effects of Structural Parameters and External Fields

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Abstract:

In this present paper, the linear optical absorption coefficient in an array of quantum wires under the external electric and magnetic fields is studied. The effects of the external fields and structural parameters such as wires' radius, the number of wires, the distance between wires, and the Al composition on the optical absorption are investigated. Results indicate that the resonant peak of the absorption coefficient shifts toward the lower photon energies with increasing structural parameters. Also, results reveal that the absorption frequency is in the terahertz range and shifts to the higher (lower) energies by increasing the electric (magnetic) field. The resonant peak value of the linear optical absorption decreases by increasing the wires' radius, the distance between wires, and the Al composition. However, it changes non-monotonically with the number of wires. Also, the optical absorption reduces with the increase of the electric field and changes non-monotonically with the magnetic field.

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1. INTRODUCTION

The low-dimensional semiconductor structures namely quantum wells, quantum wires, and quantum dots have gained considerable interest due to their extraordinary physical and electrical properties [1,2]. With the recent developments, the low-dimensional nanostructures have come up with the potential technological applications in optoelectronic and electronic devices, such as infrared photo-detectors, light-emitting quantum dot lasers, single-electron transistors and ultra-fast systems like quantum computers [1, 2, 3, 4].

Among all these low-dimensional structures, the quantum wires due to the motion confinement of charge carriers in two directions have remarkable physical properties. Consequently, this limitation causes a discrete energy spectrum [5] which leads to changes in the optical and physical aspects of the system [6, 7, 8, 9, 10, 11, 12, 13, 14]. The investigation of quantum wires plays an important role in fundamental sciences to explore the technology to fabricate the electronic, optoelectronic and quantum-computing devices [15, 16]. Also, the quantum wires can be grown into the desired radius even in nanometer size with the development of the epitaxial crystal growth techniques namely metal-organic chemical vapor deposition and molecular-beam epitaxy [17].

On the other hand, the microscopic physics of nanostructure systems can be disposable by means of the optical properties of these systems to apply in optoelectronic devices [18]. By comparison, the analysis of the optical absorption spectrum outstrips other methods to investigate the low-dimensional structures [19]. So, both linear and nonlinear optical absorption coefficients (ACs) in nanostructures have been studied theoretically and experimentally by various researchers [20, 21, 22, 23, 24, 25, 26, 27]. For instance, in the case of quantum wires, the optical ACs in an asymmetric ridge quantum wire were studied by Sadeghi and showed that the incident optical intensity also affects the total absorption [28]. Arunachalam et al. investigated the exciton optical ACs and refractive index changes in a strained $InAs/GaAs$ quantum wire under the magnetic field. They found that the variation of these two optical properties is dependent on the incident optical intensity and the magnetic field [29]. Phuc and Phong calculated the nonlinear AC of a strong electromagnetic wave in quantum wires [30]. Santander and Adame analyzed the exciton states and ACs in quantum wires under laser radiation [31]. The magneto-optical absorption of nanowires in the presence of Rashba spin-orbit interaction was studied by Sakr [32]. The effects of electron-phonon interaction and impurity on the optical properties of hexagonal-shaped quantum wires were investigated by Khordad and Bahramiyan. They found that in the presence of a central impurity, the AC increases and shifts toward higher energies when electron-phonon interaction is considered [33].

So far, few studies have devoted to the optical properties of quantum wire arrays due to the difficulty in obtaining their quantum states. In this work, we intend to study the linear absorption coefficient (LAC) of an array of quantum wires affected by external magnetic and electric fields.

2. THEORY

We consider an $N \times N$ array of $GaAs/Al_X Ga_{1-X} As$ coupled quantum wires, as shown in Fig. 1, where a and b are the wires' radius and the distance between the wires, respectively. An external magnetic field B with vector potential $A = \frac{B}{2}(-y, x, 0)$ along z-direction and an electric field F along the positive $x-$direction are applied on the structure. Therefore, the Hamiltonian of the system in the effective-mass approximation is written as below [34]:

$$H = -\frac{\hbar^2}{2m^*}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right) + \frac{ieB\hbar}{2m^*}\left(y\frac{\partial}{\partial x} - x\frac{\partial}{\partial y}\right) + \frac{e^2 B^2}{8m^*}\left(x^2 + y^2\right) + V_C(x, y) - eFx \qquad (1)$$

where $\hbar$ is the reduced Planck constant and e is the elementary charge. The electron effective mass m^* and the confinement potential $V_C(x, y)$, are as follows:

$$m^*, V_C(x, y) = \begin{cases} 0.067\, m_0, 0 & GaAS \\ (0.067 + .083X)\, m_0, V_0 & Al_X Ga_{1-X} As \end{cases} \qquad (2)$$

where m^* and X are the free electron mass and the Al concentration, respectively. Additionally, V_0 defining the barrier height which is expressed as $V_0 = 0.67\,\Delta E_g$ where $\Delta E_g = 1.247\, X(eV)$ is the band gap difference between $GaAs$ and $Al_X Ga_{1-X} As$ materials [35].

Ultimately, using the finite element method, the numerical solving of the Schrödinger equation $\hat{H}\psi = E\psi$ is performed and the eigenvalues and the corresponding eigenfunctions are obtained. After that, within the density matrix approach, the LAC for a transition between two levels with energies $E_1 = \hbar\omega_1$ and $E_2 = \hbar\omega_2$, is given as follow[11, 36]:

$$\alpha(\omega)=\omega\sqrt{\frac{\mu}{\varepsilon_R}}\frac{e^2|M_{12}|^2\sigma\hbar\Gamma}{(E_{12}-\hbar\omega)^2+(\hbar\Gamma)^2} \tag{3}$$

where μ, Γ, ε_R and σ express the permeability of electromagnetic field, the phenomenological relaxation rate, the relative dielectric permittivity and the electron density, respectively. Furthermore, $M_{12}=\langle\psi_1|x\hat{x}|\psi_2\rangle$ is the electric dipole moment matrix element per electronic charge and $E_{12}=E_2-E_1$ is the transition energy between two levels [36, 37, 38, 39].

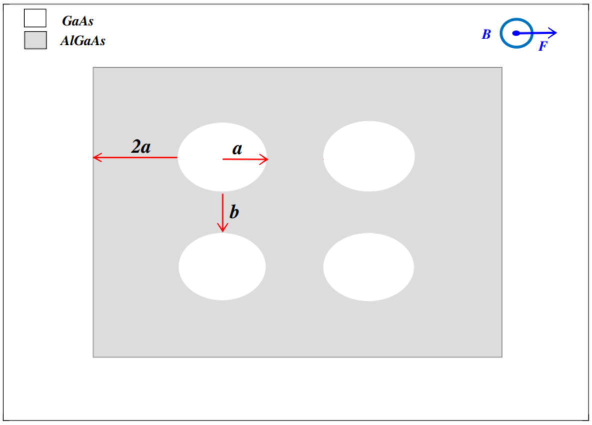
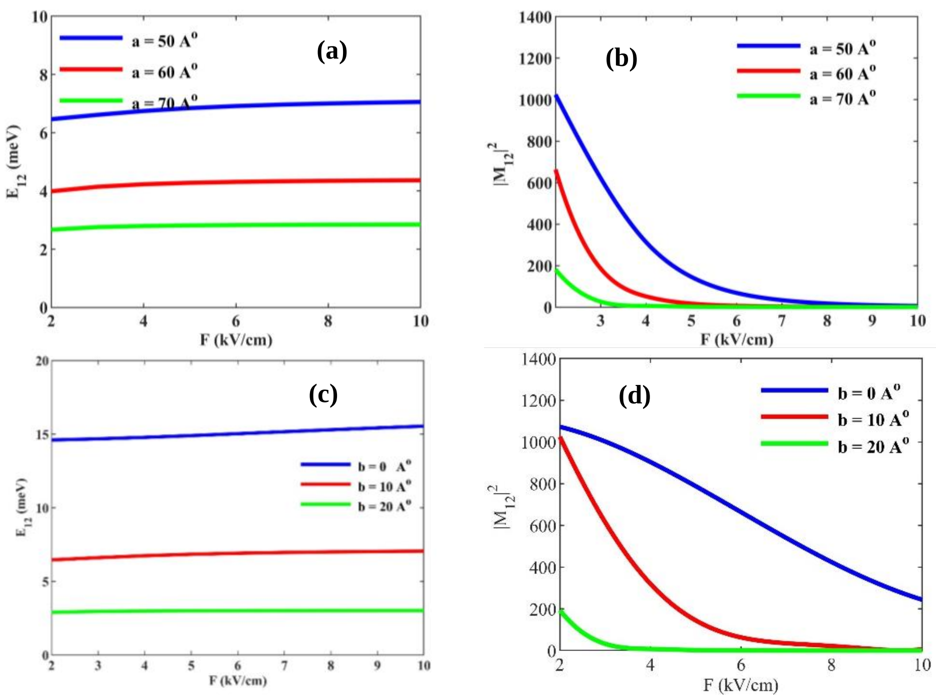


Fig. 1. Schematic diagram of an 2×2 array of quantum wires.

3. RESULTS AND DISCUSSION

The parameters used in computations are as follows: $\varepsilon_R=12.58$, $\sigma=3.0\times10^{22}m^{-3}$, $\mu=4\pi\times10^{-7}Hm$, $\Gamma_2=\frac{1}{T_0}$ where $T_0=0.14ps$ [36, 38].

Fig. 2 and Fig. 3 present the E_{12} and $|M_{12}|^2$ versus the electric (F) and magnetic (B) fields for different values of wires' radius (a), distance between wires (b), array number (N), and aluminium composition (X). These figures show that for each value of the fields, E_{12} reduces with increasing the parameters a,b,N, and X. The reason is that the electron quantum confinement reduces with the increase of the geometrical parameters (a,b,N) and thus the energy eigenvalues as well as E_{12} decrease. However, the energies increase by increasing X, which is due to the enhancement of the electron quantum confinement, the energy difference between states (E_{12}) reduces with increasing X. Thus, one can conclude that the resonant peak of the AC shifts to the lower photon energies with an increase of a, b, N, and X. From Fig. 2 and Fig. 3, it is also seen that the energies enhance (reduce) with the electric (magnetic) field, which is due to the form of their corresponding potential energy. This figure also indicates that $|M_{12}|^2$ reduces significantly with the electric field. However, with the enhancement of B, $|M_{12}|^2$ increases, reaches a higher value and decreases again. In comparison, the influence of the electric field on the $|M_{12}|^2$ is larger than that of the magnetic field. This is because the electric field displaces the electron wave function and destroys the symmetry of the states [34].



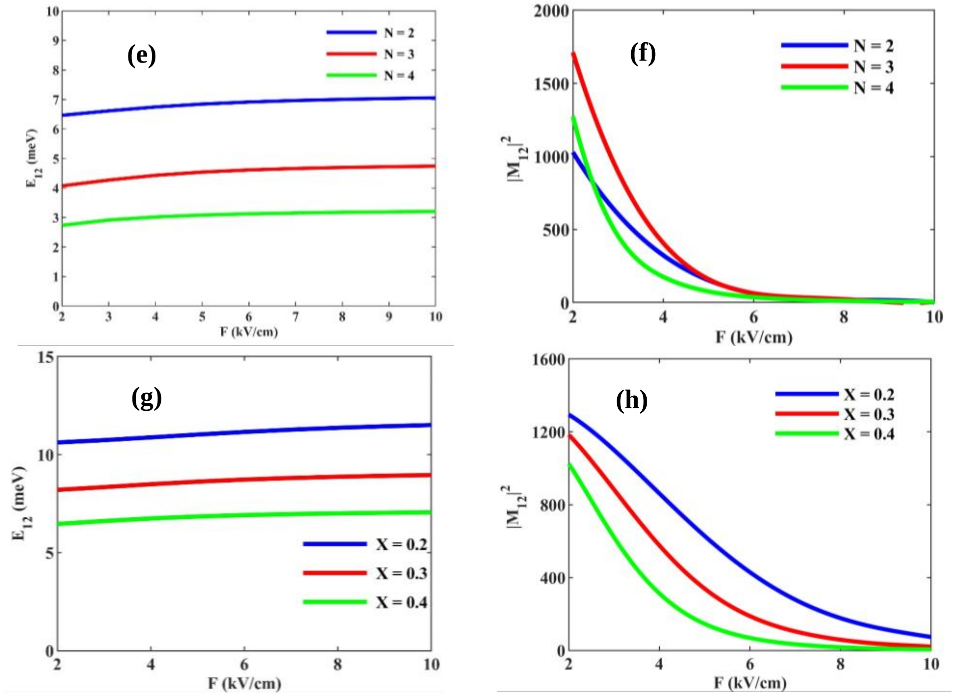
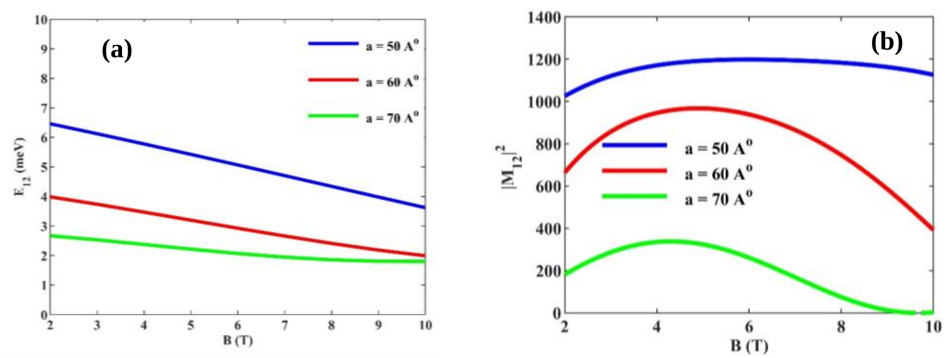


Fig. 2. E_{12} and $|M_{12}|^2$ versus the electric field: (first row) $N=2, b=10\,A^0, X=0.4$; (second row) $N=2, a=50\,A^0, X=0.4$; (third row) $a=50\,A^0, b=10\,A^0, X=0.4$; (fourth row) $N=2, a=50\,A^0, b=10\,A^0$.



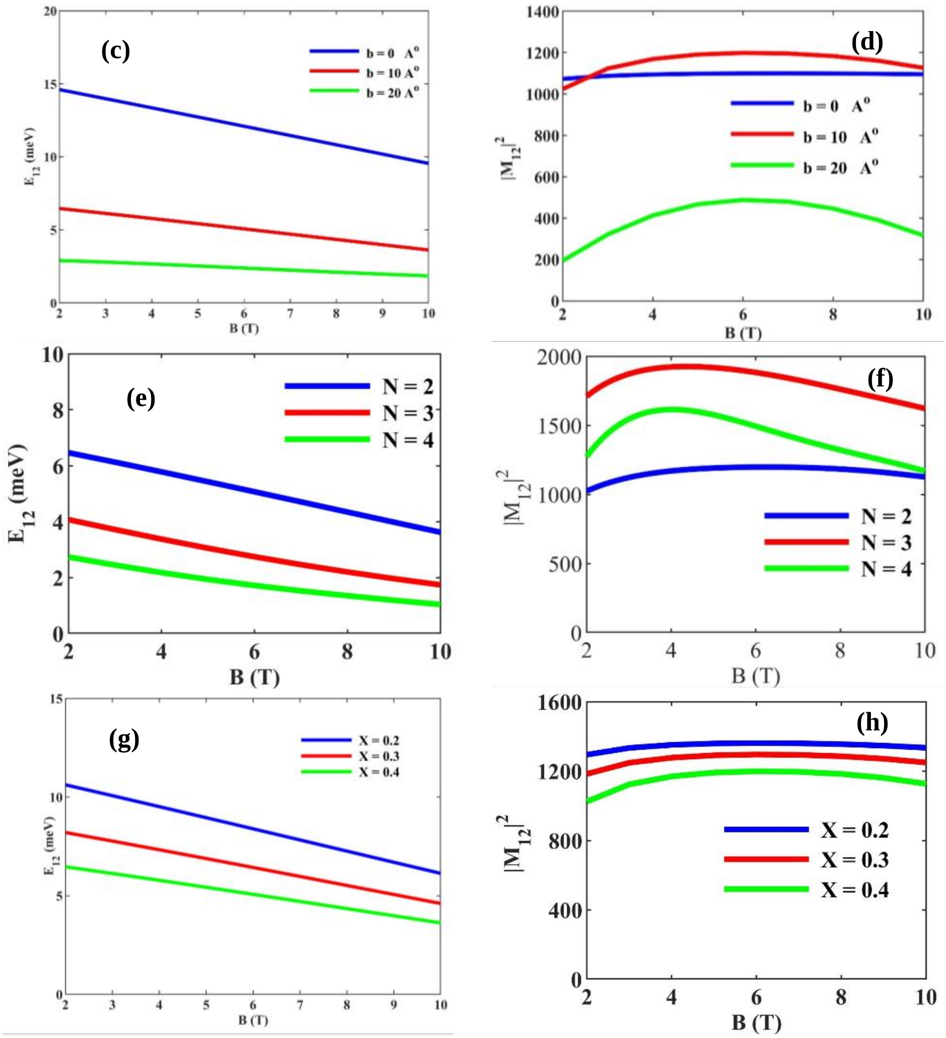


Fig. 3. E_{12} and $\left|M_{12}\right|^2$ versus the magnetic field: (first row) $N=2, b=10\,A^0, X=0.4$; (second row) $N=2, a=50\,A^0, X=0.4$; (third row) $a=50\,A^0, b=10\,A^0, X=0.4$; (fourth row) $N=2, a=50\,A^0, b=10\,A^0$.

In Fig. 4, the resonant peak of the LAC is plotted versus the electric and magnetic fields for three different values of wires' radius $a = 50A^0$, $a = 60A^0$ and $a = 70A^0$. Based on the graphs, the LAC reaches the maximum in the range of $B < 5.0T$ and $F < 3.0\frac{kV}{cm}$. According to the Eq. 3, the LAC is proportional to $E_{12}\left|M_{12}\right|^2$. By increasing the radius, the quantum confinement decreases, therefore E_{12} and $\left|M_{12}\right|^2$ experience a reduction. As the radius rises, the LAC declines with different ranges turning to $a = 50\,A^0$ diagram in which the LAC is maximum and the variation range is more extensive than two other cases, because E_{12} and M_{12} have the highest values. According to Fig. 2(a) and 2(b), by increasing F, E_{12} has the upward trend and M_{12} shows the downward trend. Since the changes of M_{12} is dominant, the LAC reduces with the electric field. However, in the presence of the magnetic field, E_{12} reduces (Fig. 3(a)) and M_{12} varies non-monotonically (Fig. 3(b)). Thus, the LAC has a non-monotonic behavior and is large at $3.0 < B < 5.0T$.

In Fig. 5, the frequency of the absorption peak is shown as a function of the electric and magnetic fields for different values of array's radius with $N = 2$, $b = 10\,A^0$, and $X = 0.4$. The results indicate that the absorption peak of the structure is in the terahertz frequency range. As mentioned before, by an increment of the radius, due to the reduction of the quantum confinement, E_{12} reduces and thus the absorption frequency declines the same as E_{12}. Also, the variation extent of the peak frequency reduces as the radius increases. Since E_{12} experiences a reduction with increasing the magnetic field, the peak frequency has a declining trend with the magnetic field. With increasing the electric field, E_{12} increases slightly and hence the peak frequency enhances. For other parameters like edge spacing (b), Al composition (X), wire radius, and the number of wires, the behavior of the absorption frequency is almost similar.

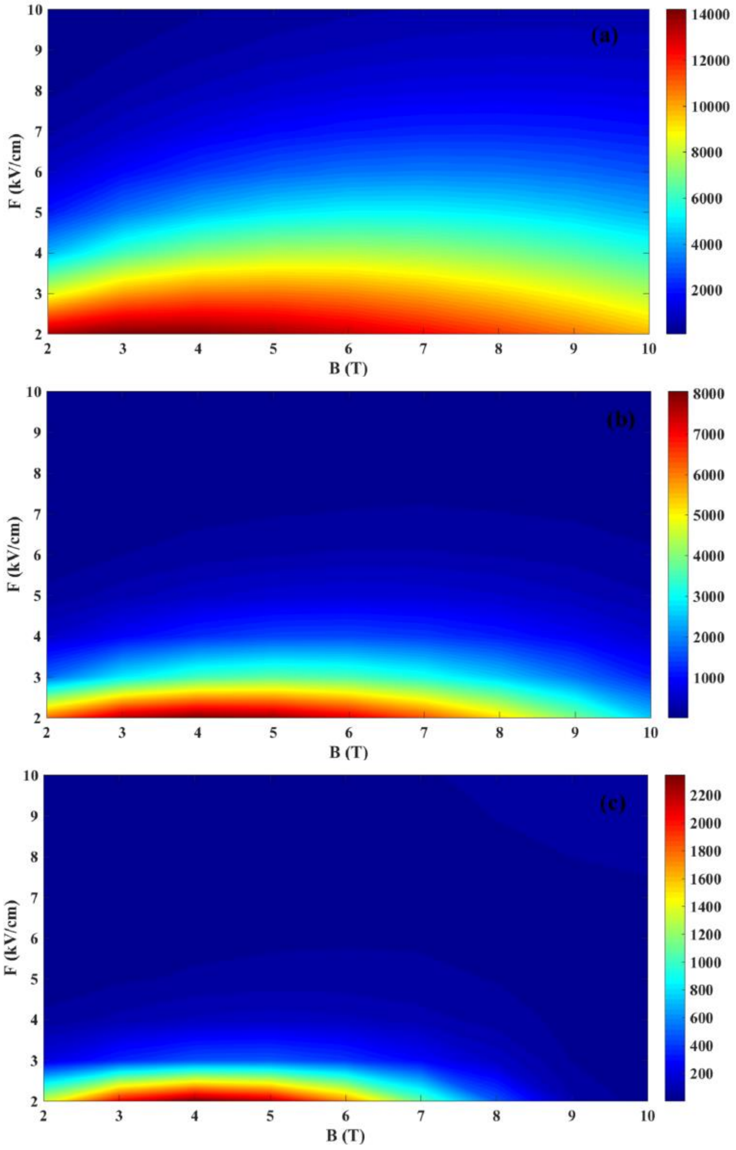


Fig. 4. Contour plots of the LAC versus F and B for $a = 50\,A^0$ (a), $a = 60\,A^0$ (b) and $a = 70\,A^0$ (c) with $N = 2$, $b = 10\,A^0$, $X = 0.4$.

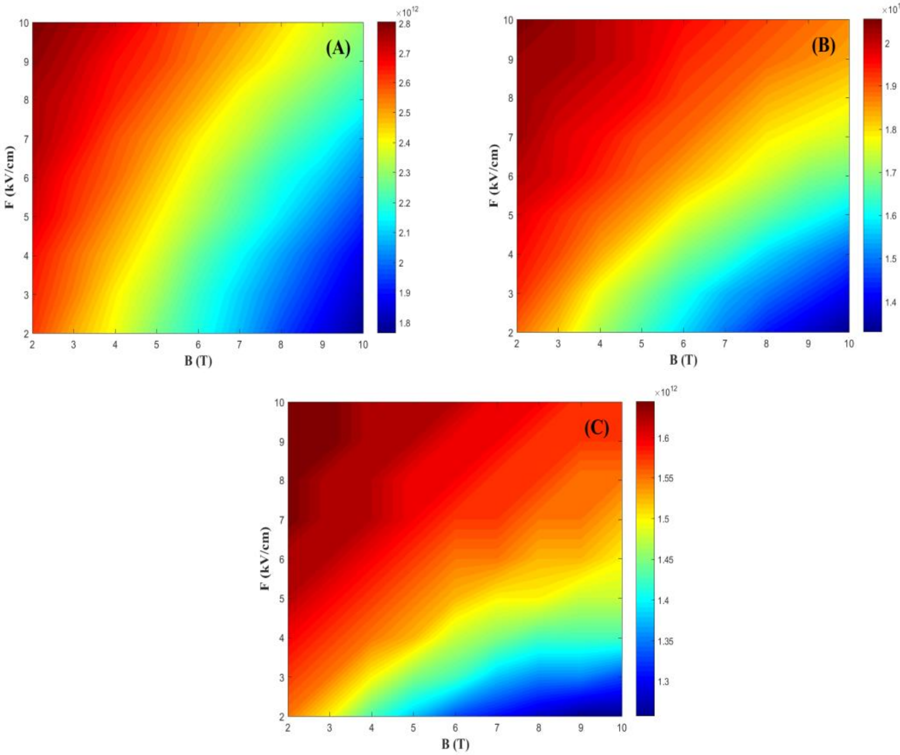


Fig. 5. The corresponding absorption frequency of Fig. 4.

Fig. 6 presents the resonant peak of the LAC versus the electric and magnetic fields for various values of b, with $N = 2$, $a = 50\,A^0$, and $X = 0.4$. With the enhancement of b, the overlap of the wave functions reduces, which causes the reduction of the LAC. Thus, for $b = 0$, the LAC has higher values and its variation range is broader than that of other values of b. Figs 2(d) and 3(c) reveal that M_{12} and E_{12} reduces considerably with the variation of electric and magnetic fields, respectively. Therefore, the LAC similar to the leading term, suffer a reduction by increasing fields (see Fig. 6), especially for the electric field due to the drastic behavior of M_{12} (see Fig. 2(d)).

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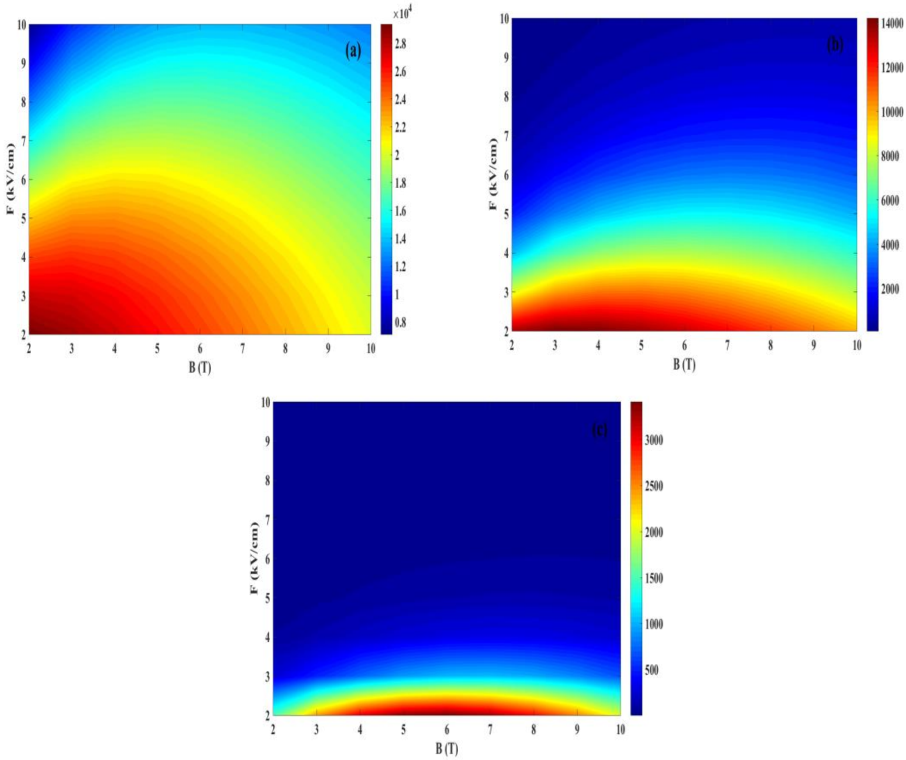

Fig. 6. The color map of the LAC versus B and F for $b=0$ (a), $b=10\,A^0$ (b), and $b=20\,A^0$ (c).

The LAC as a function of the F and B is illustrated in Fig. 7 for $N=2$, $N=3$, and $N=4$. Based on the graphs, as the number of arrays changes the LAC experiences an irregular behavior that it first rises and then falls, which is due to the non-monotonic behavior of M_{12} (see Figs. 2(f) and 3(f)). Since M_{12} declines significantly by the enhancement of F (Fig. 2(f)), M_{12} plays an important role in the reduction trend of LAC with the electric field. In addition, the LAC change versus F for $N=4$ is more than two other values of arrays' number because the variation slope of M_{12} is larger than that of ones (see green line of Fig. 2(f)). In the presence of the magnetic field, E_{12} becomes dominant and the LAC reduces with the magnetic field, similar to the E_{12} (see Fig. 3(e)).

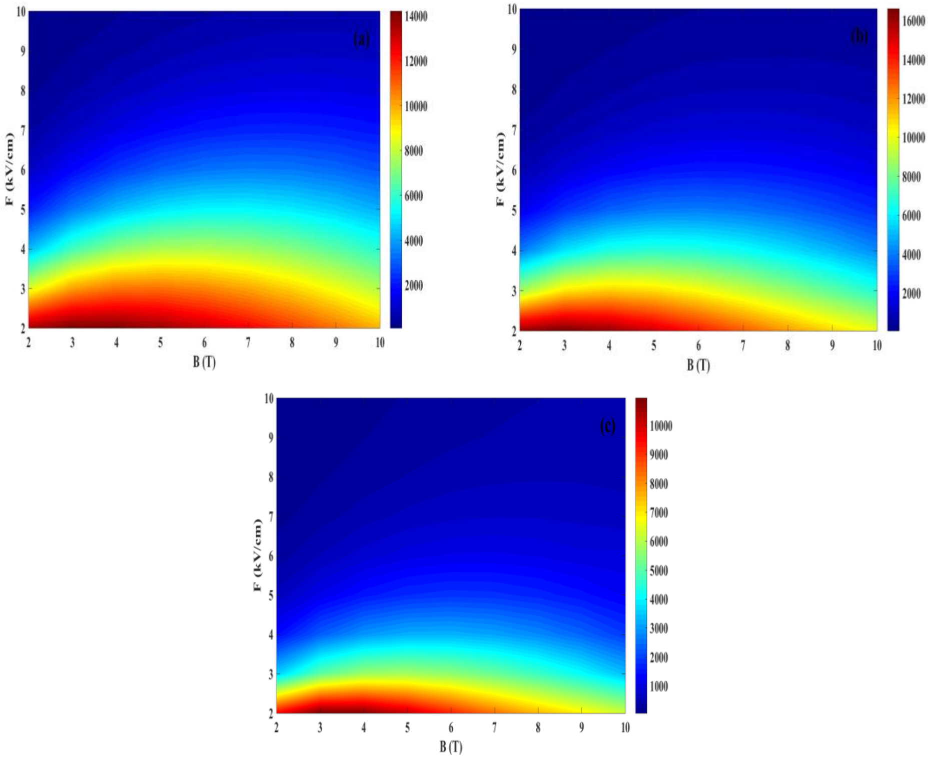

Fig. 7. The LAC of an $N \times N$ array of quantum wires for $N = 2$ (a), $N = 3$ (b), and $N = 4$ (c).

In Fig. 8 the resonant peak value of the LAC is plotted for three different values of the Al composition (X) in the case $N = 2$, $a = 50\,A^0$, and $b = 10\,A^0$. It is seen that the LAC decreases with increasing the Al composition due to the reduction of both E_{12} and M_{12} terms (see the fourth rows of Figs. (2) and (3)). For all three values of X , by increasing the electric field, the variation of M_{12} dominates over that of E_{12} , decreasing with nearly the same grades (see Fig. 2(h)). Thus, the LAC changes versus the electric field show a reduction in behavior which is approximately identical for each value of X . It is also seen that for all values of X , the LAC reduces with the magnetic field due to the declining behavior of M_{12} with the magnetic field (see Fig. 3(h)). Fig. 8 also indicates that the variation of the LAC with the electric field is greater than that of the magnetic field. The reason is that the M_{12} decreases substantially with F (Fig. 2(h)), but varies slightly with B (Fig. 3(h)).

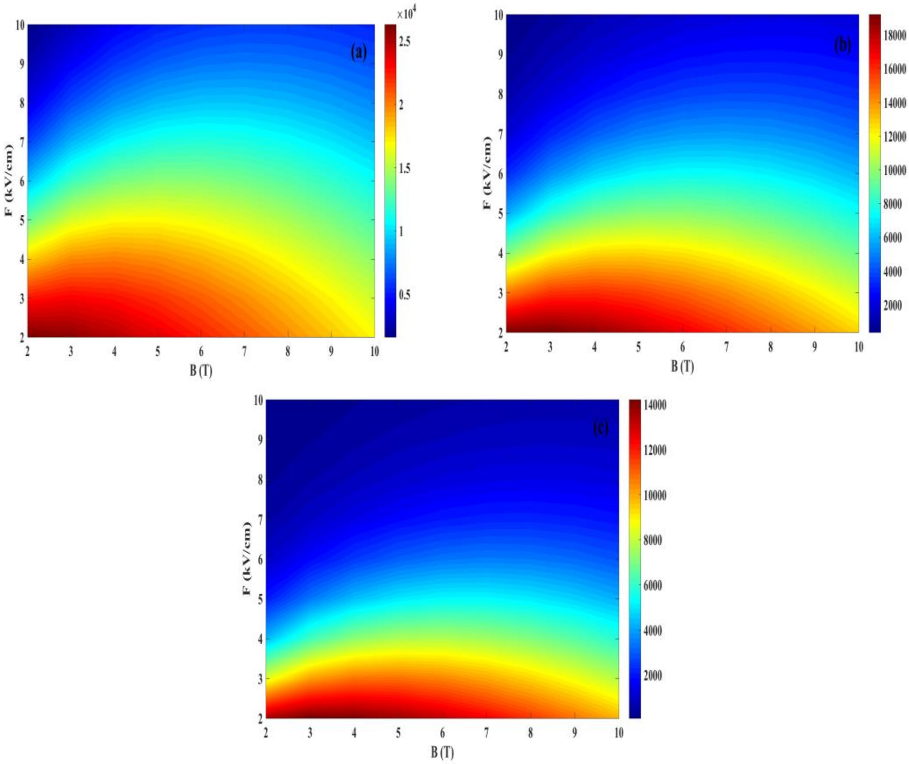

Fig. 8. The LAC for $X = 0.2$ (a), $X = 0.3$ (b), and $X = 0.4$ (c).

4. CONCLUSION

To sum up, we have studied the LAC in a $GaAs/Al_XGa_{1-X}As$ quantum wire with $N \times N$ arrays. Initially, the two-dimensional Schrödinger equation of this system has been solved numerically to achieve the eigenvalues and the corresponding eigenfunctions. Following this, the optical AC within the density matrix approach will be obtained. Then, the effects of the electric and magnetic fields, size and the number of arrays, and Al composition on the LAC and the absorption frequency are investigated. All in all, the enhancement of the wires' radius, the distance between wires and Al composition cause the reduction of the LAC. However, the LAC has a non-monotonic behavior with the increment of arrays' number. The LAC experiences a reduction by the growth of the electric field. But, the LAC is large in certain intervals of the magnetic field, which depends on the structural parameters. Also, the LAC variation in the presence of the electric field is greater than that of the magnetic field. Compared to the LAC changes, the behavior of the absorption frequency under the mentioned parameters is approximately the same as that of the LAC. What's more, the results indicate that the absorption frequency of the system is in the Terahertz region.

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