Magnetic-field-induced plasmon polaritons in finite quasiperiodic conducting superlattices

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We consider the effects of an external magnetic field on the plasmon polaritons in finite quasiperiodic superlattices consisting of alternate degenerate semiconductor or metallic layers. The magnetic field is applied parallel to the interfaces. A type of magnetoplasmon polariton that is not present in the conductor-insulator-conductor configuration is discussed. The spectrum is composed of three main bands in which the modes exhibit different localization properties. The modes at higher frequency are extended, but those at lower frequency are critical or localized. Some surface modes have been found in the finite system.

In recent years, the electromagnetic surface modes of superlattices have been widely studied. The major interest has been focused on the nonradiative polaritons bound to the interfaces. It is known that in multilayered systems, the excitations in individual layers are coupled to each other by the tails of evanescent field. Since the coupling of different layers depends critically upon the structure of superlattices, numerous works concerning different configurations have been carried out.

The bulk and surface plasmons of superlattices now are well known. For a simple infinite periodic system stacked by two kinds of alternate dielectric slabs, the plasmon spectrum is composed of two continuous bands.[1] If the unit cell of an infinite periodic system is a quasiperiodic multilayer, the bands will split into a Cantor set.[2-5] The spectrum becomes discrete in a finite system,[6,7] and the discrete spectrum shows rich self-similar patterns if the finite system is layered in a quasiperiodic sequence.[8]

Several research groups have investigated the effects of an external magnetic field on the collective excitations of superlattices. The magnetoplasmons of a superlattice generated by alternate doped and undoped semiconductor layers were considered in the situation in which the magnetic field is parallel to the interfaces.[3-5,7-10] The periodic conductor-conductor structure was considered by Wallis *et al.* in the Voigt geometry[11] and by Kushwaha, who takes the magnetic field perpendicular to the interfaces.[12] It was shown that when a magnetic field is applied, the dispersion curves of polaritons are shifted and the propagation of surface waves becomes nonreciprocal.

In this paper, we will further investigate the dependence of the magnetoplasmon polaritons on the carrier concentrations (or plasma frequencies) of the constituent materials. In addition, we will examine the effects of the nonperiodicity on the spectrum and the localization of the modes. The calculations presented here can be regarded as an extension of our recent work,[8] where we have investigated the magnetoplasmon polaritons of a finite quasiperiodic Fibonacci superlattice, which is composed of doped and undoped semiconductors. The calculation can be conveniently extended to finite quasiperiodic conducting superlattices in which the plasma frequencies of both constituents are nonzero. Since the expression of the dispersion equation is the same as in Ref. 8, we give only numerical results in this paper. For details of the theoretical treatment we refer the reader to Ref. 8.

The quasiperiodic superlattices under consideration are composed of two alternate materials A and B characterized by the plasma frequencies ω_{PA} and ω_{PB}, respectively. We assume that the superlattices are generated along the z axis and the external magnetic field is applied parallel to the y axis. The in-plane wave vector of the polaritons propagating along the x axis direction is q. As in Ref. 8, we choose the plasma frequency of material A as a unit of frequency. The dimensionless frequency, wave vector, and length are, respectively, defined as $\Omega=\omega/\omega_{PA}$, $Q=qc/\omega_{PA}$, and $D_j=d_j\omega_{PA}/c$. Since we are interested in conducting superlattices, the background dielectric constants for all media are taken to be unitary. This means that our results are appropriate for superlattices containing degenerate semiconductors or metallic layers.

The Fibonacci superlattices under consideration are generated following the recursion relation $\{C_n\}=\{C_{n-1}C_{n-2}\}$, with $C_0=S$, $C_1=L$, as described in Refs. 3 and 8, but here the dielectric functions of the alternate materials are both frequency dependent. The dimensionless thickness D_{AL} is chosen to be 0.1, and the

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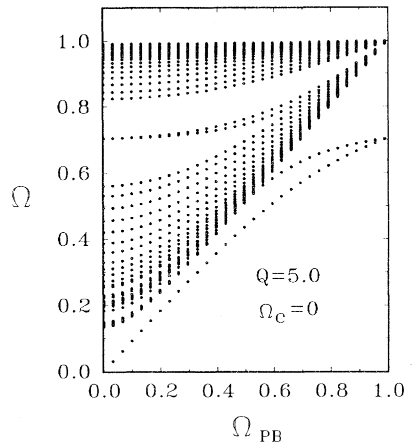

FIG. 1. Polariton frequency of the eighth-order Fibonacci superlattice vs plasma frequency Ω_{PB} of material B in the absence of an external magnetic field. The given in-plane wave vector $Q=5.0$.

other parameters are $D_{BL}=0.5D_{AL}$, $D_{BS}=0.5D_{AS}$, and $(D_{AL}+D_{BL})/(D_{AS}+D_{BS})=(\sqrt{5}+1)/2$ (golden mean).

To understand the relationship of the polaritons to the plasma frequencies of the constituents we first plot the curves of polariton frequency versus the plasma frequency Ω_{PB} of material B in Fig. 1, where we assume the external magnetic field is absent, the given in-plane wave vector $Q=5.0$, and the superlattice is the eighth-order Fibonacci superlattice. The modes, as shown in the figure, shift to higher frequency as Ω_{PB} increases. A branch of surface modes emerges in the low-frequency region when $\Omega_{PB}\neq 0$. The surface mode between the quasicontinuous bands of bulk modes splits into two branches and they merge into the lower band at $\Omega_{PB}\simeq 0.7$. On the other hand, another branch of surface modes separates from the lower band at $\Omega_{PB}\simeq 0.6$. When $\Omega_{PB}=1$, which means that the system reduces to a bulk material of A, only the bulk frequency $\Omega=1$ ($\omega=\omega_{PA}$) and the surface frequency $\Omega_{PB}=1/\sqrt{2}$ ($\omega=\omega_{PA}/\sqrt{2}$) are allowed.

The effects of an external magnetic field on the modes are shown in Fig. 2. The superlattice is the same as was stated above but now the cyclotron frequency $\Omega_c=0.2$. We see that two bands of bulk modes converge at $\Omega=\sqrt{1+\Omega_c^2}$ $(\omega=\sqrt{\omega_{PA}^2+\omega_c^2})$. Between these bands there are two branches of surface modes having different frequencies at $\Omega_{PB}=0$. They merge into the lower band at different values of Ω_{PB}. Below the low band there are also two branches of surface modes that arrive at different frequencies when $\Omega_{PB}=1$. This is different from the case of zero magnetic field. The cause is that when the magnetic field is switched on, the carriers at two surfaces of the bottom and the top of the superlattice are no longer equivalent, which leads to the different excitation frequencies of the polaritons localized at the different surfaces.

We note that a band of bulk modes appears in the low-frequency region, as shown in Fig. 2. The frequency of these modes decreases as Ω_{PB} increases, and the modes do not exist when $\Omega_{PB}=1$. Below these modes another branch of surface modes can be seen. These magnetic-field-induced polaritons occur only in the superlattice containing two different alternate conductor materials. To understand the dependence of the polaritons on the magnetic field, we plot in Fig. 3 the curves of polariton frequency versus cyclotron frequency for a given Ω_{PB}. Again, the superlattice is the eighth Fibonacci superlattice and the in-plane wave vector $Q=5.0$. We find that all curves start at the origin, which means the modes vanish when we remove the magnetic field. The frequencies of the modes increase with Ω_c at first, then they decrease

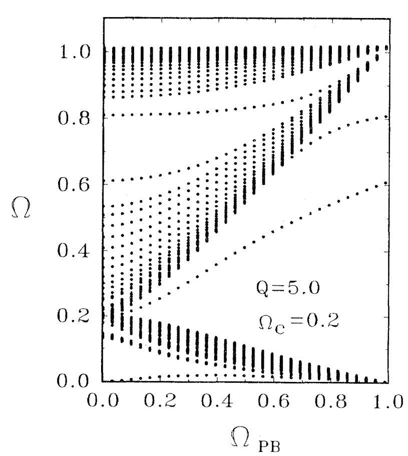

FIG. 2. Polariton frequency of the eighth-order Fibonacci superlattice vs plasma frequency Ω_{PB} of material B in the presence of an external magnetic field. The cyclotron frequency $\Omega_c=0.2$, and the given in-plane wave vector of $Q=5.0$.

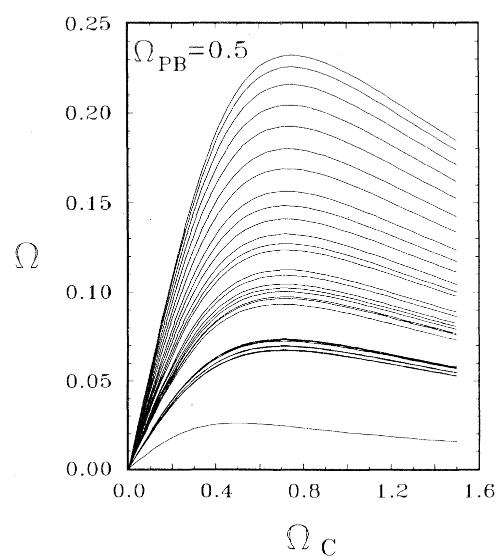

FIG. 3. Polariton frequency of the eighth-order Fibonacci superlattice vs cyclotron frequency Ω_c. The plasma frequency of material B is $\Omega_{PB}=0.5$, and the given in-plane wave vector $Q=5.0$.

when Ω_c becomes large.

Now we consider the effects of nonperiodicity on the spectrum and the localization of the magnetic-field-induced polaritons. The bulk modes, in fact, form three quasicontinuous bands when the generation of the quasiperiodic sequence becomes large. The Cantor-set spectrum of the plasmons in quasiperiodic Fibonacci superlattices was investigated in the literature,[2,3] but the quasiperiodic superlattices were treated as a big unit cell of an infinite-periodic array, which results in continuous Cantor-set-like bands. We find from our numerical calculations that the discrete modes of a real finite system form quasicontinuous bands that obey the same branching rule as the Cantor-set spectrum under the periodic boundary condition. When we count the modes from the high frequency, we find that the main gaps occur at positions of (F_{n-2})th and (F_{n-1})th modes for the nth-order Fibonacci superlattice, where F_n is the nth-order Fibonacci number defined as $F_n = F_{n-1} + F_{n-2}$ with $F_0 = F_1 = 1$.

In order to explore the localization of the polaritons we plot the amplitude profiles for some selected modes. The amplitudes of the first four modes for the 11th-order Fibonacci superlattice are presented in Fig. 4, where we take the cyclotron frequency $\Omega_c = 0.2$ and the in-plane wave vector $Q = 5.0$. It is shown that the envelope functions of the amplitudes are almost sinusoidal functions. These standing-wave-like amplitudes are very similar to the case of finite periodic superlattices. Examining the density of modes, we find that the distribution in the high-frequency band is almost uniform, as in the case of a periodic system. The modes in this high-frequency band are extended. In Fig. 5(a) we describe a typical extended mode, the 40th mode of the 11th-order Fibonacci superlattice. In the middle band, the distribution of the modes is not so uniform as in the upper band, and the amplitudes tend to localization. We illustrate this case by plotting the amplitudes of the 74th mode in Fig. 5(b).

The frequency spectrum in the low band has a rich self-similar structure, and amplitudes of the modes in real

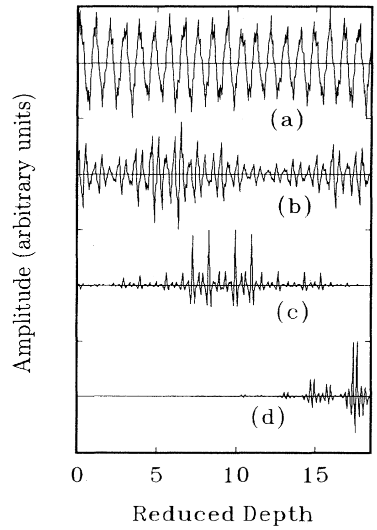

FIG. 5. Amplitudes of four polaritons of the 11th-order Fibonacci superlattice with different localization properties: (a) The 40th mode, extended, $\Omega = 0.074\,423\,426\,8$; (b) the 74th mode, extended, but having a tendency to localization, $\Omega = 0.053\,460\,786\,8$; (c) the 111th mode, critical, $\Omega = 0.037\,575\,706\,9$; and (d) the 136th mode, localized, $\Omega = 0.036\,271\,349\,8$. The other relevant parameters are the same as for Fig. 4.

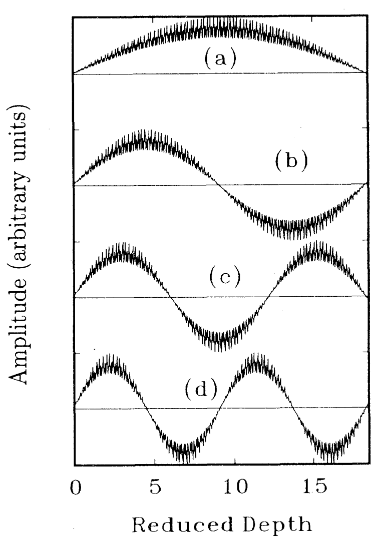

FIG. 4. Standing-wave-like amplitudes of the first four modes for the 11th-order Fibonacci superlattice. The total (dimensionless) thickness of the superlattice $D = 18.45$. The relevant parameters are $\Omega_c = 0.2$, $\Omega_{PB} = 0.5$, $Q = 5.0$, and (a) $\Omega = 0.109\,410\,825\,6$; (b) $\Omega = 0.109\,281\,962\,3$; (c) $\Omega = 0.109\,068\,542\,9$; (d) $\Omega = 0.108\,771\,543\,1$, respectively.

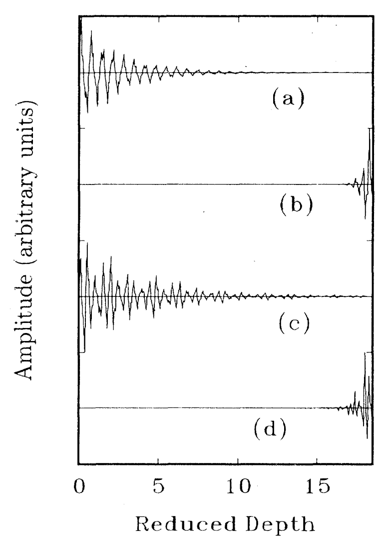

FIG. 6. Surface polaritons of the 11th-order Fibonacci superlattice with different penetration depths: (a) the 55th mode, $\Omega = 0.064\,361\,445\,5$; (b) the 89th mode, $\Omega = 0.040\,852\,418\,4$; (c) the 76th mode, $\Omega = 0.053\,120\,175\,3$; and (d) the 123th mode, $\Omega = 0.036\,862\,904\,2$. The other relevant parameters are the same as for Fig. 4.

space become critical or localized. The 111th and 136th modes shown in Figs. 5(c) and 5(d) stand for these critical or localized polariton modes. These results tell us that the high-frequency modes are not obviously affected by the nonperiodicity. The nonperiodicity affects only the low-frequency modes. In the low-frequency band, the polaritons exhibit various properties of quasiperiodic system, such as scaling and self-similarity.

A feature of finite systems is that surface states exist. As indicated above, the gaps open at the (F_{n-2})th and the (F_{n-1})th modes. It is found that these modes are separated slightly from the bands, and they are localized at the surface of the bottom or top, that is, they are surface modes. In Fig. 6, we show the surface modes of the 11th-order Fibonacci superlattice corresponding to $F_{n-2}=55$ (a) and $F_{n-1}=89$ (b), respectively. In the main bands there are still some subbands and the gaps open at the jth modes, with j being a combination of the Fibonacci numbers. The modes in these gaps are also surface modes. For example, the 76th modes (F_9+F_7) and 123th modes $(F_{10}+F_8)$, as shown in Figs. 6(c) and 6(d), are such surface modes with different penetration depths.

In conclusion, we have investigated the effects of an external magnetic field on the plasmon polariton in finite quasiperiodic Fibonacci superlattices consisting of alternate degenerate semiconductor or metallic layers. A type of magnetic-field-induced plasmon polariton that is not present in the conductor-insulator-conductor configuration has been discussed. The spectrum is composed of three main bands in which the modes exhibit different localization properties. We have plotted the amplitude profiles to explore the localization of the polaritons. It is shown that the nonperiodicity does not obviously influence the modes in the high-frequency band. The modes in the high-frequency band are extended, but the others in the low-frequency band are critical or localized. Some surface modes are found in the gaps. The effects of the external magnetic field on the plasmon polaritons can in principle be observed experimentally using either attenuated total reflection or Raman scattering.[13,14] We hope the theoretical results presented in this paper stimulate the interest of experimentalists.

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