Optical Tamm states above the bulk plasma frequency at a Bragg stack/metal interface

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We demonstrate theoretically that surface-plasmon polaritons, a form of optical Tamm state, can occur at the interface between a metal and a Bragg reflector at frequencies above the bulk plasma frequency of the metal. The frequencies of the excitations are within the photonic band gap of the Bragg reflector which provides the required evanescent decay on that side of the interface. At finite in-plane wave vector, the low value of the permittivity of the metal above its plasma frequency can lead to an imaginary normal wave vector component in the metal, which provides the localization on the other side of the interface. It is proposed that the necessary conditions can be realized using a GaAs/AlAs Bragg stack coated with a suitable conducting metal oxide having a bulk plasma frequency of 1 eV, but the concept is valid for other systems given an appropriate plasma frequency and photonic band-gap structure. The dispersion relations of the plasmon polaritons in the structures considered are calculated for both possible polarizations, and it is shown how the excitations result in distinct features in the predicted reflectivity spectra.

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I. INTRODUCTION

There has long been an interest in surface states and excitations at interfaces and thin films, as exemplified by the early work of Tamm[1] and also of Ritchie[2] who studied purely electronic effects. Later, a theoretical analysis of optical surface states by Yeh *et al.*[3] was followed by an experimental demonstration of these by the same group at an air/multilayer GaAs-AlGaAs (Ref. 4) interface. More recently, Kavokin *et al.*[5] demonstrated the theoretical existence of lossless optical surface states between a pair of two different periodic dielectric multilayer structures and further suggested how such states could be utilized in the construction of a polariton laser.[6] In analogy with and to distinguish them from the purely electronic excitations, such states can be called optical Tamm states. Although no longer lossless because of the finite conductivity of the metal, surface-plasmon polaritons are a related form of surface state formed at a metal/dielectric interface. The interaction/coupling of the electronic excitations in the metal with light in the form of surface-plasmon polaritons constitutes a means of investigating such excitations as well as promising the potential for device applications such as polariton lasers. A recent review of surface-plasmon polaritons and some of the associated applications can be found in the work of Pitarke *et al.*[7]

A key result relating to the interaction of surface plasmons with light at a conventional vacuum or metal interface is that they can only be observed with the use of attenuated total reflection (ATR) prism coupling or with an appropriately structured surface in order to ensure the necessary wave vector conservation condition parallel to the interface. In addition, it is found that in the standard frequency-wave vector dispersion plot the maximum frequency of the surface plasmon asymptotically tends to $\omega_p/\sqrt{2}$, where ω_p is the bulk plasma frequency of the metal (see, e.g., Pitarke *et al.*[7]). Recently Kaliteevski and co-workers[8,9] proposed that Tamm plasmon polaritons should be observable at the interface between a metal and a dielectric Bragg mirror without the use of ATR or the alternative surface structuring approach. This has now been confirmed by subsequent experimental work.[10] As in the case of a conventional surface-plasmon polariton at a bulk dielectric-metal interface, the confinement in the metal is a result of its negative dielectric constant at frequencies below its bulk plasma frequency, but the confinement in the dielectric multilayer structure is due not to total internal reflection, but rather the photonic band gap (PBG) of the Bragg mirror. The original proposal considered a Bragg mirror consisting of a GaAs/AlAs stack, having a PBG centered on 1 eV, with a gold metallic surface layer with a bulk plasma frequency corresponding to an energy $\hbar\omega_p=8.9$ eV. The structure provided the necessary decay of the surface state into both the metal and the dielectric structure at the energies of interest near 1 eV. Although gold and silver, with plasma frequencies above the visible or infrared part of the electromagnetic spectrum, are the metals typically employed in surface-plasmon studies, recent experimental work has revealed the existence of a surface-plasmon resonance at an interface involving a thin film of a conducting metal oxide[11] assumed to have $\hbar\omega_p\approx 1$ eV. In the current work we consider a similar structure to that studied by Kaliteevski *et al.*,[8] but take the metal to have the smaller bulk plasma frequency given by $\hbar\omega_p=1$ eV, which can occur in materials such as indium tin oxide. In particular, we show that it is possible to excite an interface plasmon polariton with a frequency *above* the bulk plasma frequency of the metal, in marked contrast to the standard results. At frequencies just above the bulk plasma frequency the relative permittivity of the metal is positive and smaller than unity and plasmon polaritons can be confined at the interface by the PBG of the Bragg stack on one side and by total internal reflection at the metal on the other. The theoretical results presented predict the existence of states above the bulk plasma frequency and could potentially impact on a broad range of surface-plasmon–polariton-related phenomena in essentially any of the applications where surface plasmons are currently employed.

II. THEORY

We begin by obtaining the plasmon-polariton dispersion relations for the structure illustrated in Fig. 1 with a semi-

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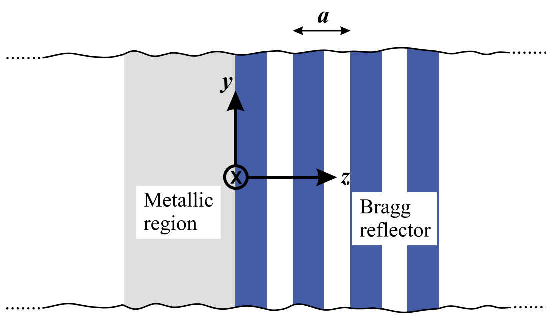

FIG. 1. (Color online) Schematic diagram of the structure, comprising a semi-infinite metallic region on the left and a semi-infinite Bragg stack structure on the right with their interface at $z=0$. The shaded layers on the right correspond to the lower refractive index regions. The period of the Bragg reflector is a.

infinite metallic region on the left ($z<0$) and a semi-infinite Bragg stack reflector on the right ($z>0$), and then we calculate the reflection and transmission coefficients for a finite Bragg stack with a thin metallic layer on its surface. The relative permittivity of the metal is taken to be of the Drude form

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega + i\omega_c)},$$

where ω_c is the electronic collision frequency. This is the conventional starting point for all standard treatments (see, e.g., Pitarke *et al.*[7]) involving surface plasmons and their resultant dispersion relationship. For the initial calculations, we take $\omega_c=0$, so $\varepsilon(\omega)$ is real, but we subsequently relax this condition to assess the effect of losses.

Consider first the case of TM-polarized light with wave vector $\underline{k}$ in the y-z plane and the H field parallel to the interface in the x direction (into the plane of Fig. 1). Within the metal we take

$$\underline{H}^M(\underline{r},t) = \begin{pmatrix} H_x \\ 0 \\ 0 \end{pmatrix} \exp[i(\underline{k}\cdot\underline{r} - \omega t)] \quad \text{with} \quad \underline{k} = \begin{pmatrix} 0 \\ k_y \\ k_z' \end{pmatrix} = \begin{pmatrix} 0 \\ k_y \\ -ik_z \end{pmatrix}.$$

As we are only interested in states confined to the interface region, we have defined $k_z'=-ik_z$ with k_z real and positive to ensure that the field decays to the left in the metal. It then follows from Maxwell's equations for nonmagnetic material that

$$\underline{E}^M(\underline{r},t) = \begin{pmatrix} 0 \\ E_y \\ E_z \end{pmatrix} \exp[i(\underline{k}\cdot\underline{r} - \omega t)],$$

with $E_z=-i(k_y/k_z)E_y$, $E_y=i(\omega\mu_0 k_z/k^2)H_x$, where $k^2=k_y^2-k_z^2$, and to satisfy the condition on k_z it is necessary that

$$k_y^2 > \varepsilon(\omega)\omega^2/c^2, \tag{1}$$

where c is the speed of light in free space.

A simplified one-dimensional (1D) version of the complex photonic band-structure approach described elsewhere[12] is employed to obtain a solution for the complex band structure of the Bragg stack. Although the approach is somewhat more involved than the method used in our previous work,[8,9] it can be straightforwardly extended to deal with interfaces with two-dimensional (2D) structures. At frequency ω the complex band-structure method gives the x component of the H field to be of the form

$$H_x^{\mathrm{BR}}(\underline{r},t) = \sum_g H_g \exp(ik_y y)\exp[i(k_z^{\mathrm{PBG}} + g)z]\exp(-i\omega t)$$

where the H_g are the H-field Fourier coefficients and the summation is over the reciprocal-lattice vectors of the infinite periodic 1D structure given by $g=2\pi n/a$, where a is the period of the Bragg stack. To ensure an appropriate surface-confined state we only consider solutions in which ω is within the PBG of the structure, and the z-component wave vector, k_z^{PBG}, describes a field that decays to the right within the Bragg stack. Matching the tangential (x) components of the H fields in the metal and in the Bragg reflector at the interface $z=0$ gives

$$H_x = \sum_g H_g.$$

Matching the tangential (y) component of the E fields at the interface then leads to the additional requirement that

$$i\frac{\omega\mu_0 k_z}{k^2}H_x = -\frac{1}{\omega\varepsilon_0}\sum_{g,g'} H_g \varepsilon_{g'}^{-1}(k_z^{\mathrm{PBG}} + g),$$

where the Fourier expansion

$$\frac{1}{\varepsilon(z)} = \sum_{g'} \varepsilon_{g'}^{-1} \exp(ig'z)$$

has been used to represent the inverse of the relative permittivity as a function of position within the Bragg stack. Thus, in order to find a state confined to the interface it is necessary to locate a frequency within the PBG at which the relationship

$$\sum_g H_g = i\frac{k^2c^2}{\omega^2 k_z}\sum_{g,g'} H_g \varepsilon_{g'}^{-1}(k_z^{\mathrm{PBG}} + g) \tag{2}$$

is satisfied.

In the case of TE polarization, with the E field parallel to the interface in the x direction, we obtain the alternative condition

$$\sum_g E_g = \frac{i}{k_z}\sum_g E_g(k_z^{\mathrm{PBG}} + g). \tag{3}$$

To obtain a solution, it is again possible to scan through ω seeking to satisfy Eq. (3). In this case, the E_g are the coefficients in the Fourier expansion of the field component E_x,

$$E_x^{\mathrm{BR}}(\underline{r},t) = \sum_g E_g \exp(ik_y y)\exp[i(k_z^{\mathrm{PBG}} + g)z]\exp(-i\omega t)$$

and, like the H-field coefficients, can be obtained from a simplified 1D complex photonic band-structure calculation.

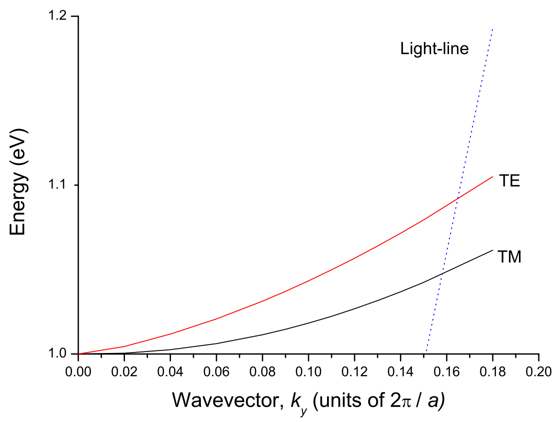

FIG. 2. (Color online) The TM (H field entirely parallel to the interface) and TE (E field entirely parallel to interface) plasmon-polariton dispersion curves for the structure shown in Fig. 1.

III. RESULTS

We have carried out calculations for a specific semi-infinite Bragg reflector with alternate layers of GaAs (relative permittivity=13.69, refractive index $n=3.7$) and AlAs (relative permittivity=9, refractive index=3), a period of $a=1.87\times10^{-7}$ m, and a first PBG between 0.933 and 1.067 eV (for zero in-plane wave vector, $k_y=0$), centered at 1 eV. The photon energy range of the PBG is below the electronic band gaps of bulk AlAs and GaAs and hence the materials are assumed to be transparent to light at the frequencies of interest. An interface plasmon-polariton state can only be found if the Bragg reflector surface layer adjacent to the metal is the lower refractive index material, AlAs. This can be understood in terms of the argument presented by Kavokin *et al.*[5] and Kaliteevski *et al.*,[8] where it was noted that in order to obtain a confined state in a cavity composed of a left reflector with amplitude reflection coefficient r_L and right reflector with reflection coefficient r_R, it is necessary that $r_Lr_R=1$. For reflection from the Bragg stack on the right with a low index first layer material there is zero phase shift (see Kavokin *et al.*[5]) and $r_R\approx1$ near the center of the photonic band gap ($r_R\approx-1$ and the phase shift is π with the higher index material at the interface). For reflection from the metal on the left with ω very close to but above ω_p, the phase shift is near zero and $r_L\approx1$ near the critical angle, which is close to zero in this case due to the small refractive index of the metal just above the plasma frequency. Thus $r_Lr_R=1$ pertains, as required. Note that in the case considered by Kaliteevski *et al.*,[8] where $\omega<\omega_p$, the reflection from the metal gives $r_L\approx-1$ and the reverse scenario with the larger refractive index Bragg stack layer at the interface is required in order to obtain a surface state below the plasma frequency. It is also worth pointing out that in the situation where two metallic layers form the interface with, say, $\omega_p^R>\omega_p^L$, there is no interface state with $\omega_p^L<\omega<\omega_p^R$ because $r_Lr_R\approx-1$ in this case.

The solutions of Eqs. (2) and (3) are obtained by carrying out the frequency scans described and are shown for both TM and TE polarizations in Fig. 2 together with the associated free space light line. The key result is that there exist surface plasmon-polariton solutions for both TM and TE polarizations which lie above the bulk plasma frequency of the metal. The dispersion curves for both the TM and TE modes are near parabolic and, for the range of results shown, are mainly within the light line, indicating that in a finite structure the associated modes are accessible to direct excitation by incident radiation without the need for prism coupling.

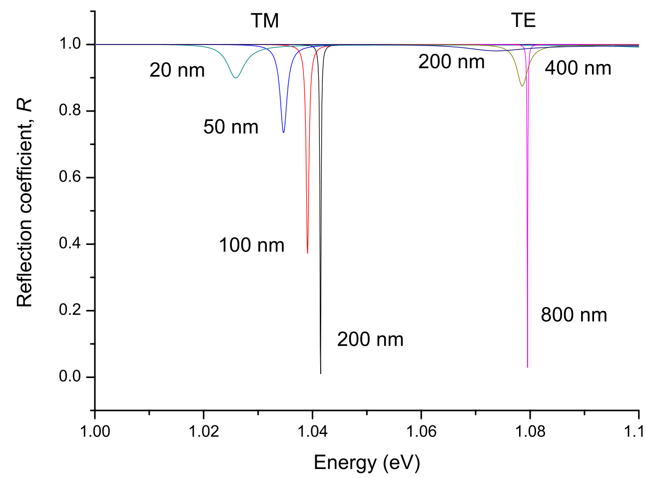

FIG. 3. (Color online) The TM and TE reflection coefficients, R, for a set of structures with different metal overlayer thicknesses (as labeled) on a 20-period AlAs/GaAs Bragg reflector on a GaAs substrate. Light is incident from the left, in air, at an angle of 72.47° to the normal for the TM polarization and 67.06° for the TE polarization.

In support of the above results we have also performed standard transfer-matrix calculations of the power reflection and transmission coefficients of finite structures consisting of a metallic layer on the surface of a 20 period AlAs/GaAs Bragg reflector grown on a GaAs substrate. As an example, we choose an in-plane wave vector $k_y=0.15\times2\pi/a$, just within the light line for the energies considered. For this in-plane wave vector the PBG of the infinite Bragg stack is between 0.99 and 1.10 eV for the TM polarization and 0.97 to 1.11 eV for TE polarization. The corresponding energies for the TM and TE plasmon-polariton modes at this wave vector are 1.042 eV (free space wave vector $k=0.1573\times2\pi/a$) and 1.079 eV (free space wave vector $k=0.1629\times2\pi/a$), respectively, and we thus expect to see appropriate features in the reflectivity near these energies when the incident angles in free space are 72.47° and 67.06° to the normal of the interface, respectively.

The results for the reflection coefficient, R, as a function of metal overlayer thickness are shown in Fig. 3 for both the TM and TE polarizations. In the case of the TM results, it can be seen that for the larger layer thickness of 200 nm the reflectivity drops sharply to almost zero (and there is a corresponding rise in the transmission, which is not shown here) at an energy just above 1.04 eV, which is in excellent agreement with the infinite metal overlayer dispersion curve results. The full width at half maximum of the transmission peak is 2.4×10^{-4} eV. As the thickness of the layer is reduced and becomes insufficient to confine the interface state effectively, the reflectivity minimum increases and broadens and shifts to lower energy, with corresponding changes in the transmission spectrum. For the TE polarization a similar trend can be seen. For a metal layer of thickness 800 nm a very narrow dip is observed in the reflection coefficient, giving a corresponding near 100% transmission at an energy just below 1.08 eV, as expected from the infinite metal overlayer calculations. Again, as the thickness is reduced the reflectivity dip becomes less marked, broadens, and moves to lower energies. Similar results can be observed in both polarizations for lower energy states (corresponding to smaller in-plane wave vector and smaller angles of incidence), but thicker metallic overlayers are then required in order to obtain comparably narrow spectral features. The decay length of the electromagnetic field in the metal is similar for the two polarizations (although somewhat larger for TE) and thus the different behaviors of the TM and TE modes, in particular the metal overlayer width dependence, are largely a consequence of the boundary conditions at the interface.

To consider the effect on the spectra of losses in the metallic layer, we have carried out calculations with different values of the collision frequency, ω_c. As the losses are larger in the case of the TE polarization, due to the larger metal overlayer widths required to produce sharp features, we consider only the more favorable TM case, which is likely to be more readily observed in experiment. The results are shown in Fig. 4 for a metal layer thickness of 50 nm and an angle of incidence of 72.47°. As the collision frequency is increased from zero (curve a), corresponding to the original results in Fig. 3, up to a maximum value of $\omega_c = 1 \times 10^{14}$ rad s^{-1} (which is somewhat larger than the value for gold employed in previous calculations,[8] $\omega_c \approx 4.1 \times 10^{13}$ rad s^{-1}), there is an initial trend to a deeper but broader reflectivity minimum, but for the largest ω_c modeled (curve d), there is a very broad feature which is still clearly visible above the energy corresponding to the bulk plasma frequency. In the latter case our calculations show that there is negligible transmission through the structure and 1-R very nearly equates to the losses due to absorption within the metal. For the lower ω_c values, significant transmission can be observed although, in general, the dip in reflectivity is associated with a corresponding loss peak for the structure.

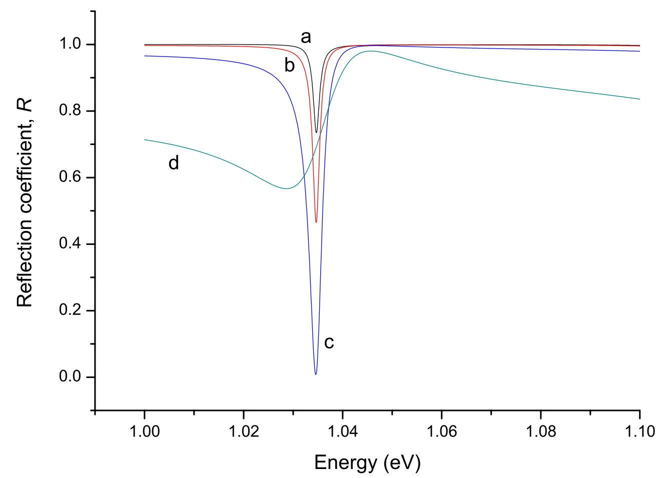

FIG. 4. (Color online) The TM reflection coefficient, R, at an angle of incidence of 72.47° for the structure with a 50 nm metal overlayer as a function of collision frequency: (a) $\omega_c=0$ rad s^{-1}; (b) $\omega_c=1\times10^{12}$ rad s^{-1}; (c) $\omega_c=1\times10^{13}$ rad s^{-1}; (d) $\omega_c=1\times10^{14}$ rad s^{-1}.

IV. CONCLUSIONS

In summary, we have presented a series of model calculations to demonstrate the existence of surface plasmon-polariton modes and their associated reflectivity features above the bulk plasma frequency at the interface between a Bragg stack and a metallic layer. The key conditions required to obtain such states are that the bulk plasma frequency must lie within the photonic band gap of the Bragg stack, Eq. (1) must be satisfied, and the low refractive index material must be adjacent to the metallic surface. The linewidth of the states is significantly broadened when the finite conductivity of the metal is taken into account but the consequence of the presence of such states is nevertheless clearly visible in the reflection spectra. Although we have considered a particular model system the results should be more generally valid provided that the required conditions are satisfied.

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