Tamm plasmon-polaritons: Possible electromagnetic states at the interface of a metal and a dielectric Bragg mirror

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Conventional surface plasmons have a wave vector exceeding that of light in vacuum, and therefore cannot be directly excited by light that is simply incident on the surface. However, we propose that a plasmon-polariton state can be formed at the boundary between a metal and a dielectric Bragg mirror that can have a zero in-plane wave vector and therefore can be produced by direct optical excitation. In analogy with the electronic states at a crystal surface proposed by Tamm, we call these excitations Tamm plasmons, and predict that they may exist in both the TE and TM polarizations and are characterized by parabolic dispersion relations.

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I. INTRODUCTION

Plasmonics is a rapidly developing branch of optics. Surface plasmons attract particular interest due to their potential applications in medicine and chemistry[1–3] as well as for optical switching[4] and near-field photonics.[5] Further, the recent experimental demonstration of the strong coupling regime for plasmon-polaritons in dielectric nanospheres embedded in gold films[6] shows the potential of surface plasmons as the basis of new light sources similar to polariton lasers.[7]

A conventional surface plasmon-polariton is formed with a TM polarization at the boundary of metallic and dielectric media.[8] The decay of the surface plasmon into the metal is the result of the metal's negative dielectric constant, while the decay into the dielectric has the same origin as in total internal reflection. The dispersion of the surface plasmon lies outside the light cone given by $k=\omega/c$, where k is the in-plane component of the wave vector of light and ω is the angular frequency, and it is for this reason that simple direct optical excitation of surface plasmons in planar structures composed of isotropic dielectric media is impossible. Although surface plasmons can be excited at a metal-dielectric interface using prisms or diffraction gratings, this approach is not always very convenient, or even practical, in experiments or device applications.

Recently, a simple, planar multilayer structure has been proposed for the creation of surface waves within the light cone. It has been shown that such states can be formed at the interface between a dielectric Bragg mirror and a periodic structure having layers of optical thickness close to half the wavelength of light.[9] These states have been called optical Tamm states in analogy with electron states predicted by Tamm[10] that can occur in the energy band gap at a crystal surface. The linear and nonlinear optical properties of similar electronic interface states have been studied theoretically by Garanovich *et al.*[11] In contrast to a conventional surface plasmon polariton, optical Tamm states can be formed in both the TE and TM polarizations. Their in-plane dispersion is parabolic with an effective mass of the order of 10^{-5} of a free electron mass and the splitting between the TE and TM polarized Tamm states increases quadratically with the in-plane wave vector. It has been shown theoretically that strong coupling[12] between the optical Tamm states and the excitonic resonance in a quantum well can be achieved in realistic structures, and consequently it is possible that the states could find application in the realization of a polariton laser without a cavity.

In this paper we consider the formation of a confined electromagnetic mode at the boundary between an isotropic medium with negative dielectric constant, such as a normal metal below the plasma frequency, and a dielectric Bragg mirror. As in the case of a conventional plasmon-polariton, the confinement in the metal is achieved as a result of its negative dielectric constant, but the confinement in the dielectric multilayer structure is due, not to total internal reflection, but rather to a photonic stop band of the Bragg mirror. In analogy with Tamm electronic surface states in a semiconductor, and the recently described Tamm photonic states at the interface of two optical superlattices, we call such a state a Tamm plasmon (TP). Electromagnetic states of this type were first mentioned at an international workshop.[13] Here we describe an experimentally feasible system where TPs could be realized, and predict the results of experiments where such states could be observed and report the results of additional calculations.

II. OPTICAL STRUCTURE AND METHODS OF CALCULATION

We consider the planar multilayer structures of the type shown in Figs. 1(a) and 1(b), which are grown along the x axis and comprise a Bragg mirror on a metal layer. The Bragg mirror has alternate dielectric layers of thicknesses a and b, with refractive indices n_A and n_B, respectively, such that $n_A a = n_B b = \pi c / 2\omega_0$, where ω_0 is the Bragg frequency. A layer of type A in the Bragg mirror is adjacent to the metal. We now consider the possibility of the existence of an electromagnetic state with a frequency below the plasma fre-

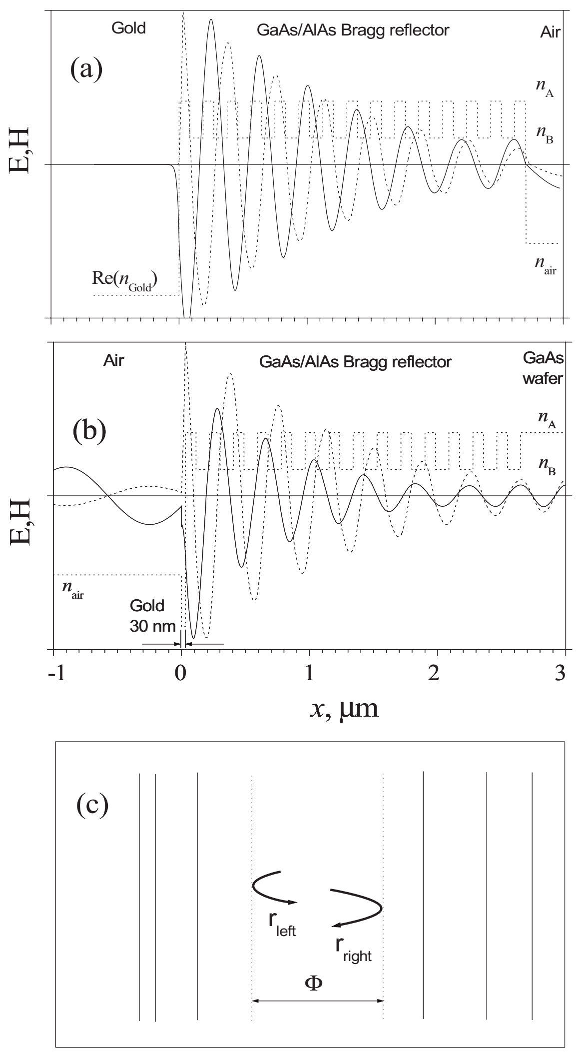

FIG. 1. (a) The profile of the electric (solid line) and magnetic (dashed line) fields for a Tamm plasmon at the interface between a semi-infinite metal layer and a 14-period Bragg reflector. The real and imaginary parts of the eigenenergy are $\mathrm{Re}(\hbar\omega_{TP})=0.9572$ eV, $\mathrm{Im}(\hbar\omega_{TP})=-1.5$ meV which correspond to $Q\approx 320$. The profile of the real part of the refractive index is shown by the dotted line where $n_A=3.7$ and $n_B=3.0$ for the GaAs/AlAs structure. (b) The profile of the electric (solid line) and magnetic (dashed line) fields for a Tamm plasmon at the interface between a 30-nm-thick metal film and a 14-period Bragg reflector. $\mathrm{Re}(\hbar\omega_{TP})=0.95271$ eV, $\mathrm{Im}(\hbar\omega_{TP})=-2.4$ meV ($Q\approx 200$). The profile of the real part of the refractive index is shown by the dotted line. (c) The general layered structure used in the derivation of Eqs. (1a)–(1d). The virtual interfaces in a single uniform layer, with amplitude reflection coefficients r_{left} and r_{right}, are shown by dotted lines. The wave gains a phase Φ in propagating from the left to the right virtual interface.

quency of the metal and close to the Bragg frequency of the periodic dielectric structure that is localized near the boundary of the metal and dielectric.

The eigenmodes of the structure can be obtained using a procedure similar to that described in Ref. 14. For the arbitrary layered structure shown in Fig. 1(c), we introduce two virtual interfaces in one of the uniform layers and call the amplitude reflection coefficient of a left propagating wave at the left interface r_{left} and of a right propagating wave at the right interface r_{right}, as indicated in the figure. Using the transfer matrix method, we can write the equation for the field of the eigenmode in terms of the amplitudes of right and left propagating waves as

$$A\begin{pmatrix} 1 \\ r_{\mathrm{left}} \end{pmatrix} = \begin{pmatrix} \exp(i\Phi) & 0 \\ 0 & \exp(-i\Phi) \end{pmatrix}\begin{pmatrix} r_{\mathrm{right}} \\ 1 \end{pmatrix}, \qquad (1a)$$

where A is a constant and $\Phi=nx\omega/c$ is the phase change of the wave of angular frequency ω in propagating a distance x between the virtual interfaces if the refractive index of the layer is n. Eliminating A from the two equations that follow from Eq. (1a) gives

$$r_{\mathrm{left}}r_{\mathrm{right}}\exp(2i\Phi)=1. \qquad (1b)$$

Now reducing x to zero, or in other words merging the virtual boundaries, one has

$$r_{\mathrm{left}}r_{\mathrm{right}}=1. \qquad (1c)$$

Thus, the condition for an eigenmode of the layered structure is that the product of the amplitude reflection coefficients for the two waves incident from the left and the right on the virtual interface (where the refractive index has no discontinuity) is equal to unity. It follows that joining two structures characterized by amplitude reflection coefficients that satisfy Eq. (1c) will result in an eigenmode. We now show that the condition of Eq. (1c) can be achieved at Bragg reflector-metal junctions of the type shown in Fig. 1.

The amplitude reflection coefficient of a metal, at frequencies well below its plasma frequency, is close to minus one and the Bragg mirror has an amplitude reflection coefficient close to minus one near the Bragg frequency, if the refractive index of its first layer (A) is greater than that of the second layer (B), as is the case in Fig. 1. Placing the virtual interface in the first layer of the Bragg reflector (with refractive index n_A) infinitesimally close to the metal interface, we can rewrite Eq. (1c) in the form

$$r_M r_{BR}=1, \qquad (1d)$$

where r_M is the amplitude reflection coefficient for the wave incident on the metal from the medium with refractive index n_A and r_{BR} is the amplitude reflection coefficient of the wave incident from the medium with refractive index n_A on the Bragg mirror starting with a layer of the same refractive index n_A.

The reflection coefficient r_M is given by the usual Fresnel formula $r_M=(n_A-n_M)/(n_A+n_M)$ where n_M is the refractive index of the metal, which in the Drude model is given by ${n_M}^2=\varepsilon_b\left(1-\frac{\omega_p^2}{\omega(\omega+i\gamma)}\right)$ in terms of the frequency ω, background dielectric constant ε_b, plasma frequency ω_p, and plasma collision rate γ. When $\omega\ll\omega_p$ and the collision rate is small, n_M is given approximately by $n_M\approx i\sqrt{\varepsilon_b}\frac{\omega_p}{\omega}$ and we can write

$$r_M\approx -1-\frac{2in_A\omega}{\sqrt{\varepsilon_b}\omega_p}\approx -\exp\left(\frac{2in_A\omega}{\sqrt{\varepsilon_b}\omega_p}\right)=\exp\left[i\left(\pi+\frac{2n_A\omega}{\sqrt{\varepsilon_b}\omega_p}\right)\right]. \qquad (2)$$

The reflection coefficient r_{BR} can be obtained by the transfer matrix method. If the Bragg mirror is assumed to have a large number of layers, a wave with frequency ω sufficiently close to the Bragg frequency ω_0 has a reflection coefficient r_{BR} defined by

$$r_{BR} = \pm \exp[i\beta(\omega - \omega_0)/\omega_0], \tag{3}$$

where the negative (positive) sign in Eq. (3) corresponds to the case $n_A > n_B$ $(n_A < n_B)$. One can also show using the transfer matrix method[15] that, if the wave is incident from a medium with refractive index n_A,

$$\beta = \frac{\pi n_A}{|n_A - n_B|}. \tag{4}$$

Inspection of Eqs. (1a)–(1d), (2), and (3) shows that it is only possible to obtain a solution corresponding to a localized photonic state near the center of the Bragg reflector's first stop band, where the reflection is high for a realistic structure and consequently the radiative decay of the TP will be small, if $n_A > n_B$. In this case Eq. (1d) becomes

$$\pi + \beta\frac{\omega - \omega_0}{\omega_0} + \pi + \frac{2n_A\omega}{\sqrt{\varepsilon_b}\omega_p} = 2\pi l, \tag{5}$$

where l is zero or an integer. For a solution close to the Bragg frequency ω_0, where the decay is small, l should be taken as zero, and then

$$\omega \approx \frac{\omega_0}{(1 + 2n_A\omega_0/\sqrt{\varepsilon_b}\beta\omega_p)}. \tag{6}$$

For an interface between gold (for which we take $\hbar\omega_p = 8.9$ eV) and a quarter-wave GaAs/AlAs Bragg reflector ($n_A = 3.7, n_B = 3$) with a Bragg frequency given by $\hbar\omega_0 = 1$ eV, Eq. (6) predicts a TP frequency given by $\hbar\omega_{\mathrm{TP}} \approx 0.95$ eV.

The exact complex eigenfrequencies of the structure [where the imaginary part of the eigenfrequency determines the decay rate of the mode and is related to the quality factor Q by the relationship $Q = |\mathrm{Re}\ \omega/(2\ \mathrm{Im}\ \omega)|$] can be obtained by carrying out a numerical solution of Eq. (1d) which we have done using the transfer matrix method.

III. RESULTS AND DISCUSSION

Figure 1(a) shows the profile of the electric and magnetic fields of a TP near the interface of semi-infinite gold and a free-standing 14-period GaAs/AlAs quarter-wave Bragg reflector characterized by a Bragg frequency $\hbar\omega_0 = 1$ eV. The complex frequency of the TP in this case, obtained by numerical solution of Eq. (1d), is $\hbar\omega_{\mathrm{TP}} = (0.9572 - 0.0015i)$ eV ($Q \approx 320$). The nonzero imaginary component of the eigenfrequency (corresponding to decay) is explained by the flow of radiation from the right side of the structure and by absorption in the metal. It should be noted that the electromagnetic field of the TP decays much faster in the metal than in the Bragg reflector; the penetration depth in the gold is $c/\omega_p \approx 20$ nm, while that in the Bragg reflector is (in terms of the period D of the structure) $D/2|n_A - n_B| \approx 1500$ nm.

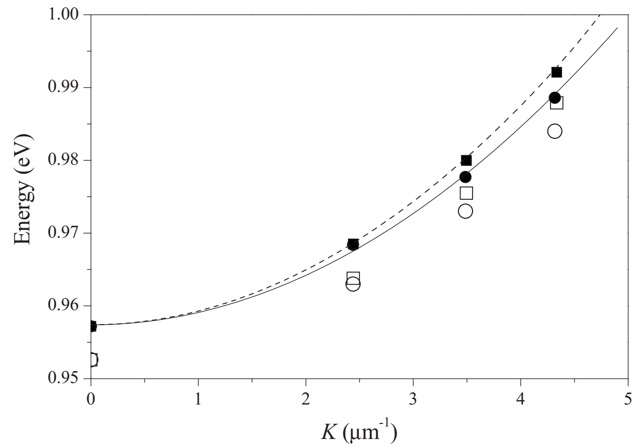

FIG. 2. The dispersion relation for Tamm plasmons at the interface between a semi-infinite gold layer and a semi-infinite GaAs/AlAs Bragg reflector for the TE (solid line) and TM (dashed line) polarizations. The squares and circles show the positions of the features in optical spectra for the TM and TE polarizations, respectively. Solid symbols correspond to the interface of semi-infinite gold and a 14-period Bragg reflector (see Fig. 3), while the open symbols correspond to the thin gold film on a 14-period Bragg reflector (Fig. 4).

Figure 1(b) shows the profiles of the electric and magnetic fields of the eigenmode of a 14-period GaAs/AlAs quarter-wave Bragg reflector grown on a GaAs substrate covered by 30-nm-thick gold film. The complex frequency of the TP in this case is $\hbar\omega_{\mathrm{TP}} = (0.9527 - 0.0024i)$ eV ($Q \approx 200$). The larger decay in this case is explained by the additional leakage through the metal film, which is now of finite thickness.

For both the semi-infinite metal and thin metal film cases, it is apparent from Figs. 1(a) and 1(b) that there is a near-quarter-wavelength shift between the maxima of the electric and magnetic fields near the metal. In other words the TP shows standing wave type behavior near the interface. However, near the outer edge of the Bragg mirror the maxima of the electric and magnetic fields are close to each other, corresponding to propagating wave behavior. Note that the time-averaged Poynting vector remains the same throughout the Bragg reflector with the change in phase difference in the fields through the reflector being compensated for by the changing field amplitudes. For the semi-infinite metal and a semi-infinite Bragg reflector case, the field profiles in the Bragg reflector have the structure of standing waves with exponentially decaying magnitude; the nodes of the electric field coincide with the antinodes of the magnetic field and vice versa; and the time-averaged Poynting vector vanishes.

Figure 2 shows the dependence of the TP energy on the in-plane wave vector K for the TE- and TM-polarized cases in a structure formed by a semi-infinite gold layer and a semi-infinite Bragg reflector. Both modes exist within the light cone and have parabolic dispersions in the vicinity of $K = 0$. The parabolic shape of the dispersion curve allows us to define a TP effective mass m, and describe the dispersion relation by the formula $\hbar\omega = \hbar^2K^2/(2m)$. For the TE-polarized case, the TP effective mass m is approximately $0.17m_0$, where m_0 is the electron mass, and for the TM-

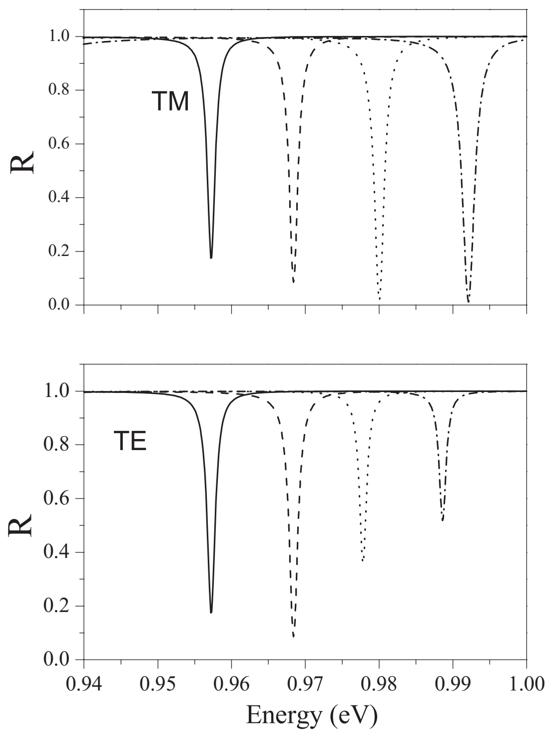

FIG. 3. Reflection spectra of the AlAs/GaAs Bragg reflector on a semi-infinite gold layer for TE- and TM-polarized light for various angles of incidence: normal incidence (solid line); 30° (dashed line); 45° (dotted line); and 60° (dash-dotted line). Light is incident from the right side of the structure.

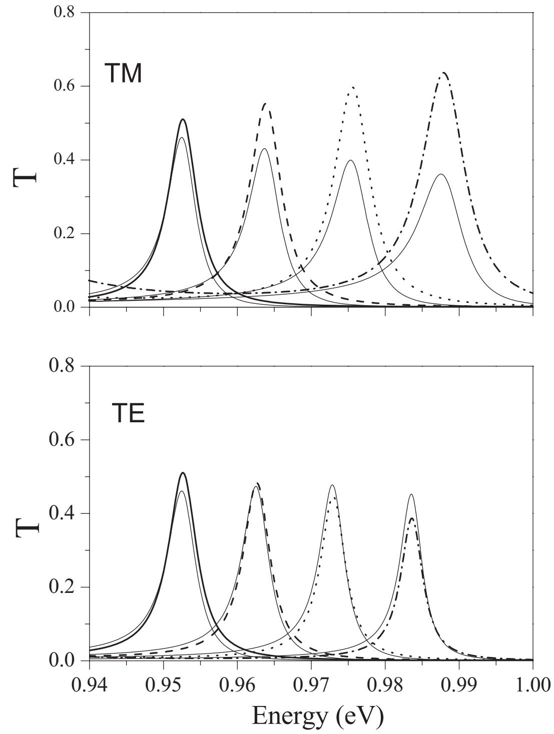

FIG. 4. Transmission spectra of the free-standing AlAs/GaAs Bragg reflector covered by a 30-nm-thick gold film for TE and TM polarized light for various angles of incidence: normal incidence (solid line); 30° (dashed line); 45° (dotted line); and 60° (dash-dotted line). Thin solid lines show absorption spectra for each case. Light is incident from the left side of the structure.

polarized case, the TP has a slightly smaller value. There is only a small decay of the TP modes due to absorption in the metal, which is found to be less than 1 meV. When the Bragg reflector is finite, there will be a contribution to the decay from radiative loss through it but that is insignificant for the 14-period structure considered here. Even when both the metal film and Bragg reflector are finite, the decay of the TP is as small as a few meV, corresponding to a Q factor of several hundred.

Figure 3 shows the calculated reflection spectra for a 14-period Bragg reflector on a semi-infinite gold layer for different angles of incidence. For frequencies that are not eigenfrequencies of the structure, the reflection is determined by the reflection coefficient of the metal, which is close to unity despite its nonzero absorption. At the eigenfrequencies, the absorption increases and each TP is manifested in the spectra by a narrow dip in the reflection spectra. As illustrated in Fig. 2, the positions of the dips in the spectra agree with the dispersion relation obtained using Eqs. (1a)–(1d).

TPs can also be observed in the transmission spectra, despite the structure consisting of two objects which are almost opaque to the radiation at the frequency of the TP. The reason for the appearance of the peaks in the transmission is similar to those for a Fabry-Perot cavity.[15] When the frequency of the incident radiation corresponds to the frequency of the eigenmode, energy is accumulated inside the structure and the magnitude of the field inside the structure is increased compared to the magnitude in the incident wave as illustrated by the profiles of the fields shown in Figs. 1(a) and 1(b). Thus, the flux of radiation incident on the Bragg mirror or metal film at the interface is increased by a Q factor corresponding to the specific eigenmode, and the transmission becomes substantial.

Figure 4 shows transmission and absorption (obtained as unity minus reflection and transmission) spectra for the same 14-period Bragg reflector covered by a 30-nm-thick gold film for different angles of incidence. The positions of the peaks in the transmission spectra are slightly different from the TP energies due to the finite thickness of the gold film resulting in a change of the phase of the amplitude reflection coefficient r_M in Eqs. (1a)–(1d).

Note that the field profiles established in the structure under external excitation by a wave whose frequency corresponds to the eigenfrequency are similar to the field profile of the eigenmode if the imaginary part of the eigenfrequency is much smaller than its real part. There are peaks in the transmission spectra, with frequencies corresponding to the TP modes, but with larger widths than the reflection spectra for the structure used in those studies. The increase in width of the spectral features is a result of the leakage of radiation through the metal film of finite thickness. Note that if the gold film and the Bragg reflector were taken separately they would reflect nearly all the radiation in the frequency range considered.

As well as just considering the situation in which there is a quarter-wavelength high-index layer adjacent to the metal, we can also study how the energy of the TP evolves as the

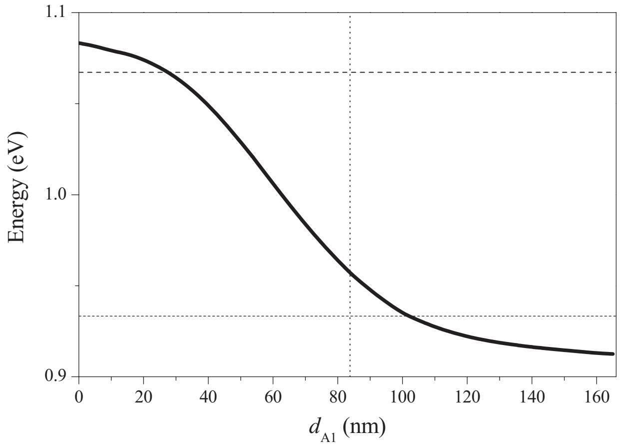

FIG. 5. Dependence on the thickness of the first layer of a 14-period Bragg reflector of the eigenenergy of the TP formed at the interface of a semi-infinite metal and the Bragg reflector. Horizontal dashed lines show the top and bottom edges of the photonic band gap of the infinite Bragg mirror. The vertical dotted line indicates the quarter-wavelength thickness of the layer.

thickness of the first layer is varied. Figure 5 shows the dependence of the TP eigenenergy on the thickness of the first layer of the Bragg mirror as it is varied from zero to half a wavelength. As we have seen, for a quarter-wave high-index first layer, the TP energy is within the photonic band gap. However, if the thickness is reduced, the TP energy passes across the band gap and reaches the top edge, where decay is significant, before the layer thickness becomes zero. It is also interesting to note that when layer A has zero thickness and the Bragg mirror begins with a low-index quarter-wavelength (B) layer, there is no TP in the first band gap, but one is predicted to occur within the second stop band, where the phase of the amplitude reflection coefficient of the metal differs substantially from π. However, such a TP would suffer strong absorption in the semiconductor layers considered here.

IV. CONCLUSIONS

We have studied the possibility of the formation of a confined state of the electromagnetic field at the interface between a metal and a dielectric Bragg mirror, which can be referred to as a Tamm plasmon. It has been shown that for an appropriate order of the layers in the Bragg mirror, a Tamm plasmon appears in the vicinity of the center of the first stop band of the mirror. In contrast to the ordinary surface plasmon, a Tamm plasmon can be formed with either TE or TM polarization and its dispersion lies within the light cone, and thus it can be optically excited without the aid of prisms or gratings.

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