Injection of light into a planar dielectric waveguide of metallic walls

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ABSTRACT

We study the resonant excitation of the electromagnetic modes in a planar waveguide of metallic walls – light incident on the guide from the air can transfer energy through the walls exciting normal modes of propagation. It is found theoretically that radiation propagates along the guide while the reflectivity presents a minimum. The energy of the incident radiation can be transferred to the guide almost completely when the thickness d_m of the metallic wall is around two times the skin depth δ. Experimental evidence of the injection of light is presented for the system $Ag/Al_2O_3/Ag$ that was grown by pulsed laser deposition.

Keywords: Planar waveguides, reflectivity, thin films, electromagnetic waves

1. INTRODUCTION

Guidance of electromagnetic energy by a dielectric region between metallic planar walls is an old problem. It is known that along the homogeneous direction of this system two types of propagation modes can occur: 1) the oscillatory modes, which are characterized by a real transverse component of the wave vector inside the dielectric medium, and 2) the surface plasmon modes, whose electromagnetic fields are localized at the two interfaces dielectric-metal with exponential decay in the transverse direction.

In a guide with walls of finite thickness the excitation of the corresponding modes requires to match the wave vector and frequency of an external radiation with the wave vector and frequency of a mode in the dispersion curve. There are two ways to input energy into the guide to excite the modes: 1) directly by lateral incidence and 2) through the walls. Lateral incidence is a restricted mechanism because of the diffraction limit (it is efficient only when the thickness of the sample is larger than the wavelength). On the other hand, about the excitation of modes through the wall we are aware of surface plasmons only. However, their nonradiative character (localized modes) requires a prism[1] or a corrugated surface[2, 3] in order to increase the wave vector of the light in vacuum to excite them.

The excitation of oscillatory modes by light incident onto a wall of the guide from the air is a less studied topic. The reason is the apparently obvious leakage of energy through the same wall by reflection. However, under resonance conditions, light can be partially guided minimizing the leaky rate. At the same time, the flow of energy along the guide is attenuated due to the losses in the walls of finite conductivity. It happens that the TM waves, which have an electric field component perpendicular to the planar walls, decay more promptly than the TE waves[4]. In fact, such decaying properties have been used to design polarization sensitive devices as waveguide polarizers[5, 6] and in-line fiber polarizers[7].

In this paper we study the excitation of the oscillatory modes by direct incidence of light. Such excitation is observed as a minimum of the angular or spectral reflectivity and a maximum of the Poynting vector parallel to the guide, which means guidance. Experimental evidence supporting the theoretical results is shown for the $Ag/Al_2O_3/Ag$ system.

2. THEORY

Let us begin showing the electromagnetic modes of an air slab - the dielectric medium - of width d = 200 nm bounded by semi-infinite metallic media. By using the Drude real dielectric constant $\varepsilon(\omega) = 1 - \omega_p^2/\omega^2$ to characterize the metallic media and the standard boundary conditions for the electromagnetic fields, we found the following equations that give us the dispersion curves shown in Fig. 1:

$$\left[\frac{k_{z1}}{w_1}-\frac{k_{z2}}{w_2}\right]^2 \exp\{ik_{z2}d\}-\left[\frac{k_{z1}}{w_1}+\frac{k_{z2}}{w_2}\right]^2 \exp\{-ik_{z2}d\}=0, \tag{1}$$

where w_i is 1 or ε_i if the polarization of the incident light is TE or TM, where i = 1,2. The z-direction is perpendicular to the system, and the y-direction is along the guide, thus $k_{z1} = k_{z1}(k_y)$ and $k_{z2} = k_{z2}(k_y)$ are wavevector components perpendicular to the surface, while k_y is the component along the waveguide, and d is the thickness of the dielectric slab**.**

The plasma frequency is ω_p = 10 eV (a typical value for noble metals). The character of the modes for $\omega < \omega_p$ depends on where they lie, to the left (region 1) or to the right (region 2) of the light-line $k_y c = \omega$ (dashed line in Fig. 1). In region 1 the modes correspond to propagation along the guide with fields decaying exponentially only in the metal (we termed them oscillatory modes). In region 2 the modes have the fields confined to the interfaces metal-air and propagate along them (they are surface plasmon modes). Only TM modes can exist in region 2. It is interesting that the second TM curve has modes in both regions.

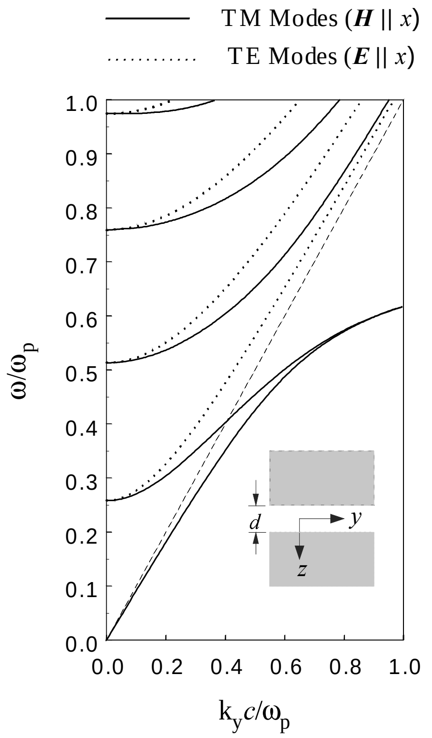

Figure 1. Dispersion relations of the normal electromagnetic modes of a planar metal-vacuum-metal system. In the inset the shaded regions represent the metal. The dashed line is the vacuum light-line. The modes on the left (right) side of this line oscillate (decay exponentially) in the z direction away from the surfaces within the vacuum region. The modes of the lowest TM curve and the modes of the second TM curve lying to the right of the light-line have surface character with maximum field intensities at the two metallic edges.

The dispersion relation of the modes depends on the thickness d of the air region. Wider (thinner) waveguides support more (less) modes with frequencies below the plasma frequency. The cutoff frequency for the mode m, $\omega_m(k_y = 0)$, is the same for both TE and TM polarization and can be obtained from the equation

$$tan\left[\frac{m\pi}{2}-\frac{\omega_m d}{2c}\right]-\frac{\omega_m}{\sqrt{\omega_p^2-\omega_m^2}}=0. \tag{2}$$

Only for $d > \pi c/\omega_p$ will exist at least one curve of modes with the character of region 1 below the plasma frequency.

In order to excite these modes, we modify the system in the following way. A thin film of thickness d_m substitutes one semi-infinite metal. By direct calculation we found for this modified system the occurrence of nonradiative modes only (surface plasmon-like modes). Thus, one might expect that the oscillatory modes of the original system - the system with the semi-infinite walls - could not be excited. However, considering that the fields of the modes penetrate the metallic medium the distance δ, the skin depth, there is a not physical reason to forbid the occurrence of oscillatory modes when the thickness of the film satisfies $d_m > \delta$. On the other hand, if d_m is chosen properly, the incident fields could tunnel the film with large enough amplitude to excite the modes.

Then, with incident light from the airside, as is illustrated in the inset of Fig. 2-(*a*), we can excite such modes resonantly in the guide. This effect is in some way similar to the experiments of Attenuated Total Reflection (ATR) used to excite surface plasmon-polarities.[8] In the present case we excite the modes of the waveguide confined to the air region between the metallic media, while in ATR the excited modes are confined to the interface metal-air.

The equation to calculate the reflection of the system is

$$\mathrm{R}=\left|\frac{U_2{}' D_1 \exp[ik_{3z}d]+U_2 C_1 \exp[-ik_{3z}d\ ]}{V_2{}' D_1 \exp[ik_{3z}d\ ]+V_2 C_1 \exp[-ik_{3z}d\ ]}\right|^2, \tag{3}$$

where

$$\begin{aligned}
V_2 &= D_1 D_2 \exp[+ik_{2z}d_m]+C_1 C_2 \exp[-ik_{2z}d_m],\\
U_2 &= C_1 D_2 \exp[+ik_{2z}d_m]+D_1 C_2 \exp[-ik_{2z}d_m],\\
V'_2 &= D_1 C_2 \exp[+ik_{2z}d_m]+C_1 D_2 \exp[-ik_{2z}d_m],\\
U'_2 &= C_1 C_2 \exp[+ik_{2z}d_m]+D_1 D_2 \exp[-ik_{2z}d_m],
\end{aligned} \tag{4}$$

and

$$\begin{aligned}
D_l &= \left[\frac{k_{lz}}{w_l}-\frac{k_{(l+1)z}}{w_{l+1}}\right],\\
C_l &= \left[\frac{k_{lz}}{w_l}+\frac{k_{(l+1)z}}{w_{l+1}}\right].
\end{aligned} \tag{5}$$

with l = 1,2 and $k_{lz} = \sqrt{(\omega/c)^2\varepsilon_l - k_y^2}$.

Figure 2-(*a*) shows the reflectivity R and the energy transferred to the guide S_y as a function of the angle of incidence for two selected frequency values with d_m = 30 nm. S_y is the component of Poynting vector parallel to the guide and is calculated directly from the Maxwell's equations. In order to obtain well-defined curves we have introduced tiny absorption giving to the dielectric function the form $\varepsilon(\omega) = 1-\omega_p^2/(\omega^2+i\nu\omega)$, where ν = 0.03 eV. Minima reflectivity and maxima transferred energy occur when the wavevector k_y $(=\omega\,\mathbf{sin}\,\theta_i/c)$ and the frequency ω satisfy approximately the dispersion relations of Fig. 1 — the incident radiation couples resonantly to the modes of the guide, no additional devices such as grating or prism are needed. The peaks on the left side of Fig. 2-(*a*) [$\theta_i \approx 9.5^o$ and $\theta_i \approx 11.5^o$] were obtained with ω

$/\omega_p$ = 0.26. They represent the coupling with the TE mode at $k_y c/\omega_p$ = 0.042 and the TM mode at $k_y c/\omega_p$ = 0.054 (see Fig.1). On the other hand, the two peaks at the center and the right of Fig. 2-(*a*) with $\theta_i \approx 50^o$ and $\theta_i \approx 78^o$ correspond to ω/ω_p = 0.40. The wave vectors are $k_y c/\omega_p$ = 0.306 and $k_y c/\omega_p$ = 0.391, respectively (see Fig. 1).

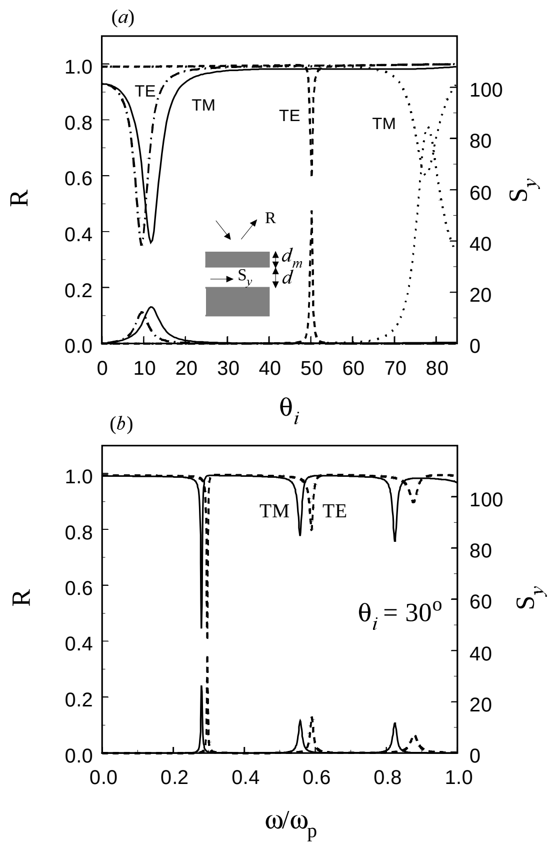

Figure 2. a) Reflectivity R and the flow of energy S_y inside the guide as functions of the angle of incidence. We plot curves for both polarizations at frequencies ω/ω_p = 0.26 (the peaks on the left of the figure) and ω/ω_p = 0.40 (the peaks at the center and the right of the figure). (b) R and S_y as functions of the frequency with angle of incidence $\theta_i = 30^o$. The solid (dashed) lines correspond to the TM (TE) polarization. In each figure the right scale corresponds to S_y

The excitation of the modes in the guide can also occur by varying the frequency of the incident radiation with a fixed angle of incidence. With $\theta_i = 30^o$ we found the curves shown in Fig. 2-(*b*). There are three resonances for each polarization. The frequencies ω/ω_p for the TM coupling are approximately 0.28, 0.56 and 0.82. The wavevectors $k_y c/\omega_p$ are 0.14, 0.28 and 0.41, respectively. These modes — and the TE modes also identified in Fig. 2-(b) — are defined by the crosses of the line $\omega/\omega_p = 2\, k_y c/\omega_p$ with the curves of Fig. 1.

We have mentioned that the thickness d_m of the metallic layer plays the most important role for the efficient coupling of the incoming radiation with the modes of the guide. For a thick film the fields do not reach the guide and the coupling (if this exist) is weak. On the other hand, for a very thin film the coupling of the incident radiation with the guided modes can not be observed because the transferred energy easily leaks and the reflectivity remains near the maximum. Thus, an optimum thickness d_m must be found and it will be a function of the specific material used. In Fig. 3 we plot the reflectivity R of TM waves as a function of both the angle of incidence θ_i and the thickness d_m. The figure shows that the transference of energy to the guide is almost 100% when $d_m \approx$ 43 nm and $\theta_i \approx$ 9 degrees. Thus, practically all the incident energy is forced to propagate along the region between the metals because it couples to the TM mode n = 2, with ω/ω_p = 0.26 and $k_y c/\omega_p \approx$ 0.040 (see Fig. 1). From this result and other, we have found that the optimum thickness of the metallic film that ensures maximum transferred energy to the guide is around two times the skin depth δ of the metal. Effectively, from the equation

$$\omega_p \delta / c = (1 - \omega^2 \cos^2 \theta_i / \omega_p^2)^{-1/2} \tag{5}$$

which is obtained from the condition $k_z\delta = 1$, we obtain for this case $\delta \approx 21$ nm ($\approx d_m/2$).

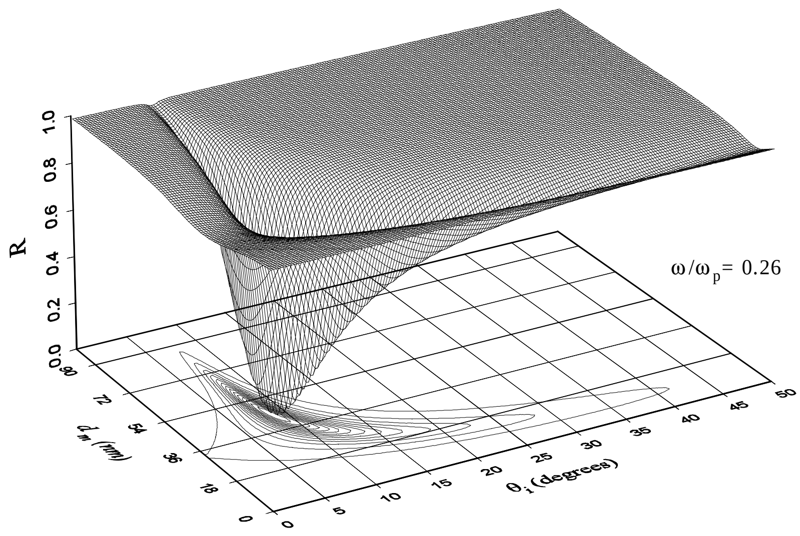

Figure 3. Surface of reflectivity as function of the angle of incidence and the thickness d_m of the metallic film for a constant frequency. The minimum of the surface determines the best parameters to obtain a resonance at this frequency (see the text).

3. EXPERIMENT

Next we consider the experimental results for a system similar to the one considered here, i.e. a silver substrate (a thick silver film), aluminum oxide in the middle (dielectric solid instead the air) and a top thin silver layer. Using Pulsed Laser Deposition (PLD) system, we grew two samples varying the alumina thickness. Then, we measured the reflectivity as a function of the incident angle and compared the experimental spectra with the theoretical one.

Alumina thickness in the samples was measured with the aid of an extra Si substrate placed along with the waveguide samples inside the PLD chamber. It was assumed that the thickness on the Si substrates was the same as that on the samples. Then using ellipsometry, we measured the thickness of Al_2O_3 over the Si. Nonetheless, this measurement is subject to some error (within 10%).

To obtain the reflectivity we used a HeNe laser with wavelength λ = 632.8 nm. At this wavelength the real and imaginary components of the index of refraction for silver are n=0.094, k=3.868, whereas for alumina n=1.7 and k=0. These values were measured for the specific samples and because of the growing conditions, they may differ from published accepted data.

In Fig. 4 we show the measured reflectivity as a function of the angle of incidence. The graph on the left side corresponds to TE polarization, while the other on the right side is for TM polarization. In both cases, two samples are considered: sample 1 is 200 nm Ag / 332 nm Al_2O_3 / 40 nm Ag, and sample 2 is 100 nm Ag / 143 nm Al_2O_3 / 38 nm Ag. For the first sample, the estimated thickness for the alumina with the method mentioned above was 350 nm, but the best fit with theory was for 332 nm. For the second sample, the estimated thickness was 147 nm and the adjusted one for the best fit is 143 nm. The circles and diamonds correspond to sample 1 and 2, respectively, and the solid line corresponds to theory. For theory the minima in reflectivity are close to zero, and for experiment are about 10%. This difference is caused by the inhomogeneities in the samples and surface roughness.

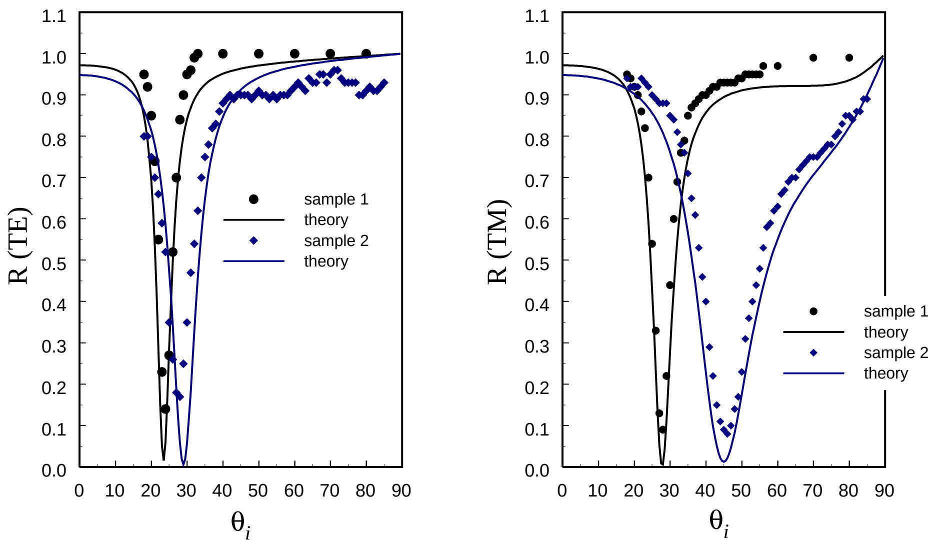

Figure 4 Reflectivity for the sample 1 and 2 as described in text. The graph on the left side corresponds to TE polarization, while the other on the right side is for TM polarization. Solid lines are used for the theoretical results; triangles are used for sample 1 and diamonds for sample 2

We note that light was not detected at the side of the samples due to the their large size (light leaving the guide was not observed). Theoretically we found that the decay length of the light in these samples is approximately 4 and 6 micrometers for TM and TE light, respectively. Thus, no lateral light is expected because the length of the slab is about 1 centimeter.

The experimental results confirm our calculations. Even with the substrate of finite width we did not observe transmission of light through the system when a minimum of reflectivity is obtained. Because such resonance conditions coincide with the frequency and wavevector of the guided modes of the system, we conclude that these modes are being excited. Four or six micrometers are short distances for macroscopic applications. However, this injected light could have potential utility in the nanostructure technology.

4. CONCLUSIONS

In conclusion, we have shown that light can be injected, almost 100%, into a planar waveguide of metallic walls whose thickness is smaller than the wavelength. This is obtained by coupling resonantly the incident light with the modes of the guide. By selecting appropriately the thickness of the metallic wall, we can separate an incident light into a reflected wave and a guided wave with any desired ratio of reflected to guided light. Also, for polychromatic light we can guide a selected frequency with very high efficiency. The theoretical analysis allows to choose the thickness of the top metal film and the dielectric slab in order to get the desired effect.

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