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Selective transmission through very deep zero-order metallic gratings at microwave frequencies

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Zero-order metal grating structures are found to give extraordinary selective transmission at microwave frequencies through the resonant excitation of coupled surface waves. The metal slat structures with dielectric spacings as small as 250 μm strongly transmit wavelengths of several millimeters. A simple interpretation of these novel results which treats the deep grating structures as ''filled'' Fabry–Perot cavity systems gives model transmissivities which agree very well with the experimental data. © *2000 American Institute of Physics.* [S0003-6951(00)01044-5]

Over the past few decades, interest has grown in enhanced transmission through periodic metallic samples, such as hole arrays[1–5] and deep metallic gratings.[6,7] Recently[6] this has been attributed to the resonant coupling of surface plasmon polaritons (SPPs) within the cavities of such samples causing the transmission of radiation through structures with cavity widths much smaller than the wavelength.

The study of the excitation of SPPs on metallic gratings has been carried out for over a century—Wood[8] in 1902 observed anomalies in the reflected spectra of ruled metallic gratings using a white light source, and these were later identified as SPPs. Since then many experiments have been conducted in order to fully understand and utilize this phenomenon.[9–13] However, nearly all of these experiments have been with relatively shallow gratings having a pitch which produces real diffracted orders. If the pitch of the grating λ_g is made shorter than half the incident wavelength λ_0 (the grating thus becoming zero order) while at the same time it is made very deep, then the sides of the grooves come so close together that it is possible for the evanescent fields of excited SPPs on each side of a single groove to interact across the narrow cavity. Then for certain grating depths the SPPs set up standing waves within the cavity, causing a large field enhancement within the grooves.[14] The deep zero-order grating provides a large number of such grooves and, in the form of a slat structure (see Fig. 1), will then give strong resonant transmission of long wavelength radiation provided that it is incident polarized with a component of the electric field orthogonal to the groove surfaces.

Studying the resonant transmission process at microwave frequencies allows for ease of fabrication of deep samples. In addition, power loss by joule heating of the metal will be very limited. The gratings discussed in this letter are all zero order, constructed of aluminum slats (which are almost perfectly conducting) with a depth-to-pitch ratio of greater than 16:1 (Fig. 1). As a consequence of the high conductivity of the aluminum, the fields of the SPP are excluded from the metal, thus there is no coupling between fields in neighboring grooves and the fields are concentrated within the cavities.

Consider a single cavity formed by two slats open at both ends. The real part of the wave vector of the coupled SPPs in the air gap, width D, between the slats can be shown to be[15]

$$k_{\mathrm{SPP}} \approx k_0 \left\{ 1 + \frac{1}{2}\eta^2 \left[1 + \sqrt{1 + \frac{4}{\eta^2}(1 + |\varepsilon_{\mathrm{metal}}|)} \right] \right\}, \qquad (1)$$

where

$$\eta \approx \frac{2}{k_0 D |\varepsilon_{\mathrm{metal}}|}.$$

Since at microwave frequencies, $|\varepsilon_{\mathrm{metal}}|$ is of the order of 10^7 and here D is approximately 10^{-4} m, it is clear that the coupled SPPs will have a wave vector very close to the free space wave vector k_0. Therefore, the coupled SPPs will be resonantly excited when the free space wavelength λ_0 satisfies

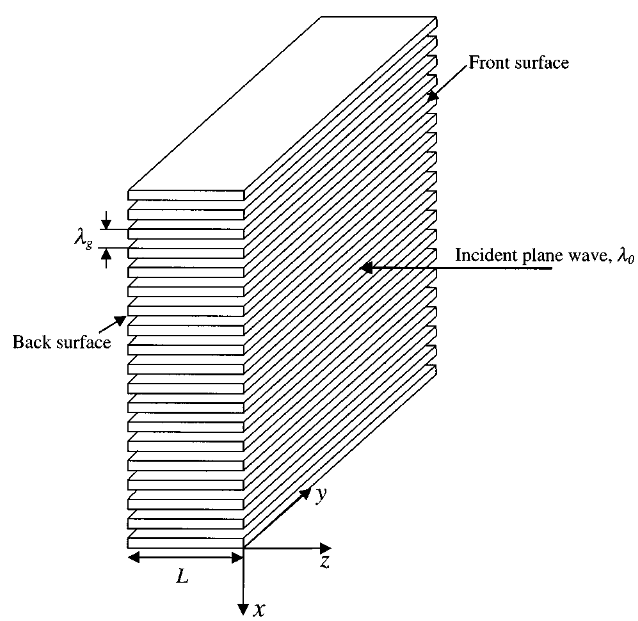

FIG. 1. The sample is constructed from aluminum slats stacked upon one another, $L \gg \lambda_g$ and $\lambda_g < \lambda_0/2$ (λ_0 is free space wavelength).

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$$\lambda \approx \frac{2L}{N}, \tag{2}$$

where N is the number of nodes (regions of zero field) within the cavity and L is the cavity length.

The type of sample for which there is no diffraction, $\lambda_0 > 2\lambda_g$, may be described as a pseudo-Fabry–Perot interferometer: the two highly reflecting surfaces being the front and back surfaces of the aluminum slats. Thus, the ratio of transmitted intensity to incident intensity may be approximately written as[16]

$$\frac{I_t}{I_i} = \left(\frac{1-R-A}{1-R}\right)^2 \left[\frac{1}{1+F\sin^2\frac{\delta}{2}}\right], \tag{3}$$

where R is the reflectivity of each surface and A is the fraction of radiation absorbed by the sample. δ is the phase factor which for an air filled cavity of length L and normal incidence is just $\delta = (4\pi L/\lambda_0) + 2\varphi(\lambda_0)$, where φ is the phase change at each boundary, and

$$F = \frac{4R}{(1-R)^2}.$$

The samples are constructed using slats 3 mm×64.7 mm×600 mm which are aligned vertically in a wooden frame with spacers of thicknesses 1 mm, 500, and 250 μm at the ends.

A collimated beam of variable frequency microwave radiation is incident on the sample perpendicular to the plane of the tops of the aluminum slats. The zero-order transmitted beam is collected by a spherical aluminum mirror and focused to a detector, which is connected to a scalar network analyzer. A detailed description of the experimental apparatus may be found in Ref. 17. Here only transverse magnetic (TM)-polarized radiation was used, defined to be radiation whose electric vector lies perpendicular to the groove direction [whilst the electric vector of transverse electric (TE) polarized radiation lies along the grooves], since—as expected—no transmission was obtained for TE polarization. Transmission data were taken as a function of wavelength for each sample.

Figure 2 shows the wavelength-dependent transmissivity for the sample with air gaps of 500 μm. The Fabry–Perot nature of the strong resonant transmissivity is apparent and of course is considerably higher than would be normally expected for a sample with cavity dimensions so much smaller than the wavelength. The continuous line is a fit of Eq. (3) using $R=0.505$ and $A=0.05$.

Figure 3 shows the transmissivity of the sample with air gaps of 1 mm as a function of wavelength, fitted to theory based on Eq. (3). Figure 2(b) illustrates the regularity of the resonant peaks as a function of $1/\lambda_0$, the gradient of this graph being $1/(2L)$. This gives an L of 64.85 mm while the directly measured L is 64.7 mm, in excellent agreement for this simple model. The resonances are essentially the same resonances as those excited on the 500 μm sample, and their positions in wavelength have changed very little. However, due to the larger air gap the reflectivity coefficient of the top surface has decreased to 0.36 (A having decreased to 0.038). Thus, since the positions of the resonances depends primarily on the length L of the cavities and the coupling strength depends on the air gaps, it is easy to specify and optimize both the wavelengths transmitted and their coupling strengths independently.

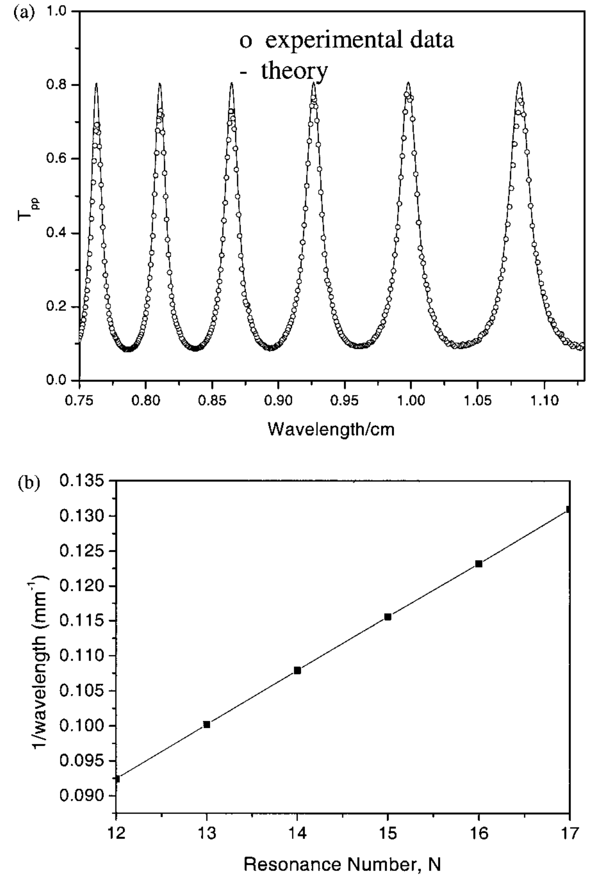

FIG. 2. (a) TM transmissivity data (T_{pp}) as a function of wavelength for the sample with 500 μm air gaps, compared with theory based on Eq. (3) using $R=0.505$ and $A=0.05$. The value of cavity length L used, 64.85 mm, is taken from the gradient of (b): a plot of 1/wavelength against resonance number, N.

The resonances excited on this sample are of relatively high order, having 17 nodes (regions of zero electric field) within the cavities at the lower wavelength and 12 nodes at the upper.

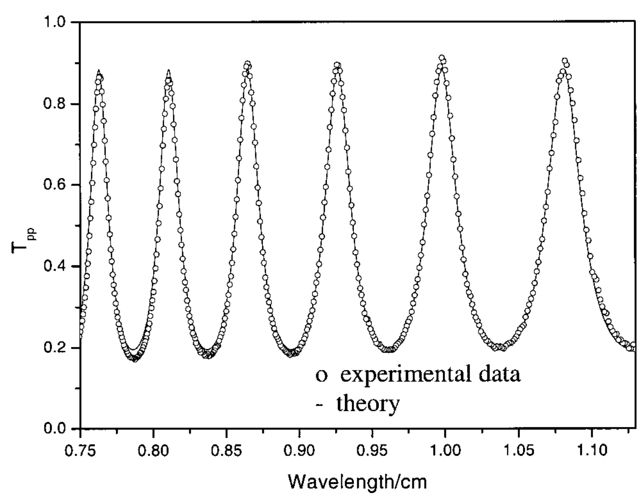

FIG. 3. TM transmissivity data T_{pp} for the sample with 1 mm air gaps, fitted to theory based on Eq. (3) now with $R=0.36$ and $A=0.038$ and again, $L=64.85$ mm.

Strong resonant transmission of long wavelength radiation through deep zero-order aluminum slat gratings has been demonstrated at microwave frequencies. The samples may be described as Fabry–Perot resonators, through the excitation of resonant standing waves of coupled SPPs in the cavities between the metal slats. This excitation of resonant coupled surface plasmons in the cavities allows for extraordinary transmission of radiation through samples whose cavity widths are less than 1% of the wavelength transmitted.

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