Analysis of Subwavelength Slit Transmittances on Ag and Au Plates at Terahertz Range

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***Abstract*—The behavior of power transmission of a normally incidence plane wave with transverse magnetic polarization through subwavelength slits on silver and gold plates at 30 terahertz is investigated for various slit widths and plate thicknesses. The analysis is performed based on a rigorous mode matching technique which is appropriate to this geometry. The transmission patterns versus plate thickness in the range 0.25 to 4 free-space wavelengths are contrasted to those of a slit on perfectly conducting plate.**

***Keywords*—slit transmittance; mode matching technique; MIM (Metal-Insulator-Metal) waveguide**

I. Introduction

The subwavelength slit transmittance problem can be analyzed by "brute-force" techniques such as finite-difference time-domain (FDTD) and finite elements. However, brute-force techniques can only provide a posteriori physical insight, and are less suitable for conducting parametric or convergence studies since any changes of parameters require rerun of an entire simulation. The mode-matching technique (MMT) is a good alternative to tackle this problem being naturally suited to geometries involving a junction of two or more layered regions. Besides being more computationally efficient than FDTD or finite elements for this class of problems, the MMT provides direct insight into the physics of the problem. In this work, we utilize a rigorous MMT to provide a detailed characterization of the transmittance through subwavelength slit apertures on Ag and Au plates as a function of the gap width and plate thickness at 30 THz.

II. Problem Geometry and Permittivities of Metals

The geometry to be studied here is described in Fig. 1. Regions 1 and 3 are air, and Region 2 comprises a Metal-Insulator-Metal (MIM) waveguide with gap width $2g$ and thickness d. The structure is consistent along y. Junctions 1 and 2 are defined the boundaries between Regions 1 and 2 and Regions 2 and 3, respectively. A plane-wave is normally incident from Region 1 and transmitted into Region 3. Usually, the TM polarization is more interesting for this geometry. The transmittance, dimensionless, is defined as usual by [1]

$$\tau = \frac{1}{2g}\frac{P_t}{W_i} = \frac{1}{4gW_i}\int_S \mathrm{Re}[\vec{E}\times\vec{H}^*]\cdot\hat{z}dS \qquad (1)$$

where P_t is transmitted power into Region 3 and W_i is power density of the incident plane-wave.

The relative permittivities [2] of Ag and Au utilized at 30 THz are −3738.3 − j1487.3 and −3496.4 − j1464.7, respectively, with $e^{+j\omega t}$ phasor convention.

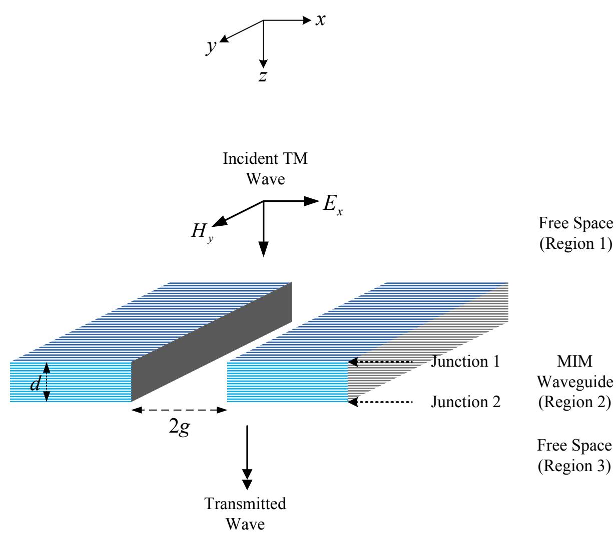

Fig. 1. Geometry of the problem. The dispersion equation in the MIM waveguide depends on g and the metal plate permittivity ε_m.

III. Eigenmode Analysis

We consider TM modes, with field component H_y, E_x, and E_z. To apply MMT, eigenmodes of Region 2 in Fig. 1 should be determined. This region corresponds to a MIM waveguide, where the permittivity is a function of x, i.e. $\varepsilon(x) = \varepsilon_0\varepsilon_r(x)$. The dispersion equation for the waveguide is written as [3]

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$$\tanh(\kappa_{i,n} g) = -\frac{\kappa_{m,n} / \varepsilon_m}{\kappa_{i,n} / \varepsilon_i} \tanh(\kappa_{m,n} h). \quad (2)$$

The magnetic field now reads

$$H_{y,n}(x) = \begin{cases} H_0 \dfrac{\cosh(\kappa_{i,n} x)}{\cosh(\kappa_{i,n} g)}, & 0 < x < g \\ H_0 \dfrac{\cosh(\kappa_{m,n}(x - g - h))}{\cosh(\kappa_{m,n} h)}, & g < x < (g+h) \end{cases} \quad (3)$$

for both point and discretized continuous spectra [3].

IV. Mode Matching Technique

The MMT [4, 5] obtains modal coefficients by applying (after expanding the fields in each region into the set of discrete modes with unknown coefficients) the proper boundary conditions, i.e. continuity of the transverse electric and magnetic field components, at Junctions 1 and 2. For Junction 1, the equations from the boundary conditions [4] are given as follows.

$$(1+\rho_k) a_k \vec{e}_{Fk} + \sum_{\substack{i=1 \\ i\neq k}}^{N_F} a_i \vec{e}_{Fi} = \sum_{j=1}^{N_M} b_j \vec{e}_{Mj} \quad (4)$$

$$(1-\rho_k) a_k \vec{h}_{Fk} - \sum_{\substack{i=1 \\ i\neq k}}^{N_F} a_i \vec{h}_{Fi} = \sum_{j=1}^{N_M} b_j \vec{h}_{Mj} \quad (5)$$

A similar equation can be obtained for Junction 2 in Fig. 1. This multi-junction problem can then be solved in a standard fashion in [5], exploring mode orthogonality [4], to determine the resulting reflected and transmitted waves in Regions 1 and 3, respectively.

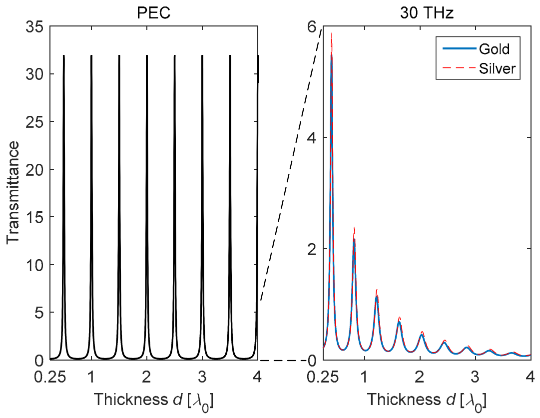

Fig. 2. Transmittance vs. plate thickness d for $2g = 0.01\lambda_0$. Note that the ordinate in the right plot is expanded.

V. Transmittance Results

Figs. 2-4 show the transmittance results for various combinations of frequency, gap width, and plate thickness. In all these results, h is set so that $2(g+h) = 5\lambda_0$. Table I shows the normalized propagation constant k_z/k_0 of the first mode in point spectrum, TM_0, for each slit width considered. The transmission pattern periodicity with respect to d/λ_0 becomes shorter as the gap width $2g$ decreases. This is explained by Table I, which shows a decrease on the real part of the propagation constant of the dominant mode with increasing gap width.

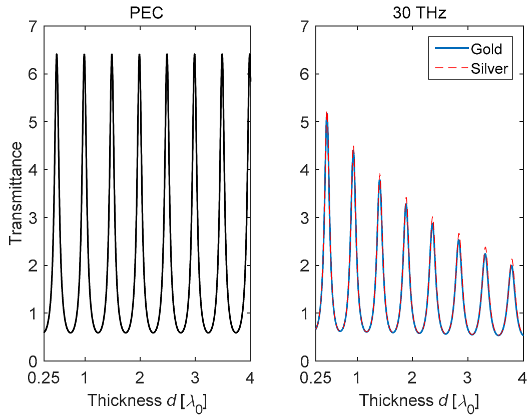

Fig. 3. Transmittance vs. plate thickness d for $2g = 0.05\lambda_0$.

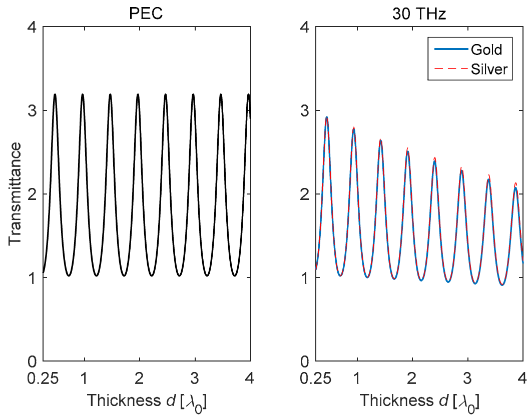

Fig. 4. Transmittance vs. plate thickness d for $2g = 0.1\lambda_0$.

TABLE I. Normalized Propagation Constants K_z/K_0

Gap Width $2g$	Gold	Silver
$0.01\lambda_0$ (Fig. 2)	$1.2283 - j0.0415$	$1.2225 - j0.0387$
$0.05\lambda_0$ (Fig. 3)	$1.0496 - j0.0097$	$1.0482 - j0.0090$
$0.1\lambda_0$ (Fig. 4)	$1.0251 - j0.0050$	$1.0244 - j0.0046$

VI. Conclusion

This work investigate subwavelength slit transmittances on Ag and Au plates in the terahertz range for various plate thickness and slits. The MMT allows for a better understanding of the physics on the transmittance results, including mode patterns and the eigenvalues distribution variations with the geometric parameters (thickness, width). The results from Au plates show lower transmittances than those of Ag due to the higher losses in the former. The transmittance peaks degrade with an increase on the Ag and Au plate thickness, an effect which is not present in the PEC case. This degradation is another consequence of ohmic losses.

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