Spectrum Analysis of Slit for Real Metal at Terahertz Frequencies

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***Abstract*—The distribution of the roots in point and discretized continuous spectra is investigated as functions of terahertz frequencies in a metal-insulator-metal waveguide. The shape of the roots distribution affects the various electromagnetic wave transmission through the metal slit. The lossy transmittances in metals are found compared to no loss with a perfect conductor.**

Keywords—subwavelength slit; MIM waveguide; mode matching technique

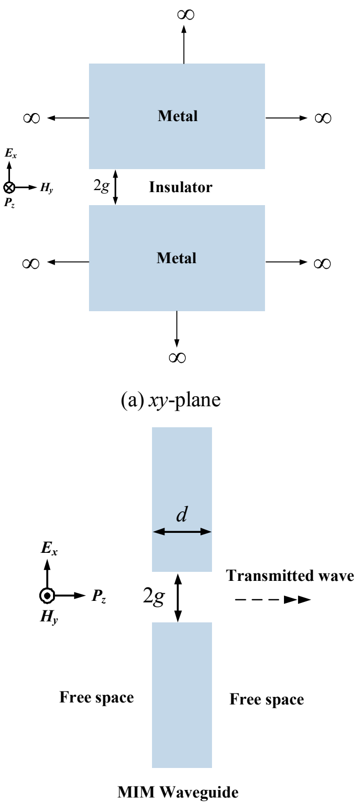
I. INTRODUCTION

There are several previous researches for the electromagnetic wave transmission through an aperture with a perfect electric conductor (PEC) [1], [2]. In recent years, the studies [3] to observe the transmission through a slit with real metal rather than PEC have been discussed by the mode matching technique. In the research for real metal, derivation of the modal spectra is an important process to solve the power transmission. However, these studies are not fully investigated.

In this paper, we analyze the transverse magnetic (TM) modal characteristics of the slit in real metal and later the modes are used to solve transmittances through the aperture. Metal-insulator-metal (MIM) waveguide is introduced and is similar to the dielectric slab waveguide in terms of composition of the modes. The spectra are classified into the point and continuous spectra [4] in the MIM waveguide, which are corresponded to the guided and radiation modes in dielectric slab waveguide. The point and continuous spectra are examined in terms of frequency, gap of aperture, the period, and the types of metal.

II. SPECTRUM ANALYSIS

Figs. 1(a) and (b) show the front and side views of the slit geometry, respectively. The incident and transmitted regions are composed of the free-space and the MIM waveguide that resides between the free spaces. The TM wave is considered for the incident plane wave. The plate thickness d and the gap width $2g$ in the MIM waveguide are considered. The structure is invariant along y-axis, which means the structure in Fig. 1 is a two-dimensional problem.



(a) xy-plane

(b) zx-plane

Fig. 1. Geometry of the MIM waveguide.

TABLE I. RELATIVE PERMITTIVITIES OF METALS [5]

Frequency	Au	Cu	Al
50 THz	−1383.2 – j367.24	−1509.2 – j288.09	−2776.2 – j1294.0
100 THz	−361.45 – j58.599	−389.12 – j59.843	−845.11 – j245.75
200 THz	−90.549 – j10.572	−100.72 – j14.034	−213.96 – j42.987

In order to investigate the modal properties for various metals, the relative permittivities as functions of metals (gold, copper, and aluminum) and frequencies are listed in Table 1 [5]. As can be seen in the table, the values are different in each case and can contribute subtly different modal properties.

Figs. 2 (a), (b), and (c) describe the point spectra in the MIM waveguide, where the metal is aluminum, for 50 THz, 100THz, and 200 THz, respectively. The gap width $2g$ is $0.1\lambda_0$. The eigenvalues in each spectrum can be obtained from a dispersion equation, which is the same equation as the dielectric slab waveguide. Note that the dispersion equation can be written as [3]:

$$\tanh\left(\kappa_{i,n} g\right) = -\frac{\kappa_{m,n} / \varepsilon_m}{\kappa_{i,n} / \varepsilon_i} \qquad (1)$$

The first root, the largest value in real part among the roots, contributes the dominant propagating mode. The other roots in each point spectrum are evanescent modes and slightly contribute to the electromagnetic wave propagation. As the frequency increases, the roots approach the real and imaginary axes since the relative permittivities in metals are small.

Figs. 3 (a), (b), and (c) depict the discretized continuous spectra in the MIM waveguide, where the metal is also aluminum and $2g$ is $0.1\lambda_0$, for 50 THz, 100THz, and 200 THz, respectively. The dispersion equation used in the point spectra are also applied. As can be seen in the figures the roots are distributed regularly, but the rate of increase in 50 THz is smaller than that in 100 THz. On the other hand, the rate of increase in 200 THz is relatively irregular due to the anti-crossing behavior [4]. The behavior is observed at the roots around the value of 10 in the imaginary part. The roots near 10 in the imaginary part tend to be away from the imaginary axis since the 5th root of the point spectrum in Fig. 2 (c) repulses the group of roots in the discretized continuous spectrum. The roots in discretized continuous spectra do not contribute to the wave propagation, but are very important to satisfy the boundary condition by the mode-matching technique in the problem of the wave propagation.

Transmittances are obtained in three metal cases at 50 THz as a function of thickness d of the plate as shown in Fig. 4. The resonant transmission through the deep-subwavelength aperture, where the peaks in the periodic transmittance are shown with the period $d \approx 0.5\lambda_0$, are observed. In the real metal cases, however, the periodic peaks are gradually reduced due to the losses in real metals as listed in Table 1. The significant loss is found in aluminum since the imaginary part of the permittivity is relatively larger than them of the other metals.

III. Conclusion

This paper investigated the point and discretized continuous spectra for several metals and different terahertz frequencies. The various material properties as functions of metals and frequencies made diverse modal properties. The roots in point spectrum tend to approach the imaginary and real axes as the frequency increases for all metals. On the other hand, the roots of discretized continuous spectrum were regularly distributed, however slightly affected by the roots of point spectrum. Lossy transmittances were observed more in the case of aluminum plate.

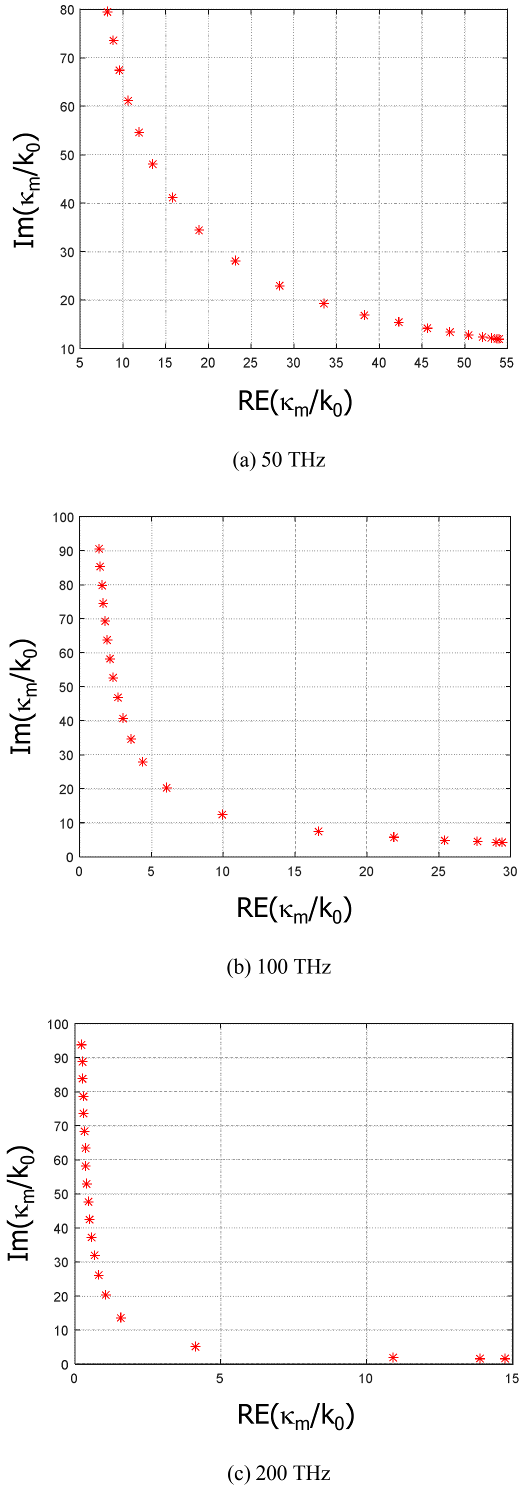
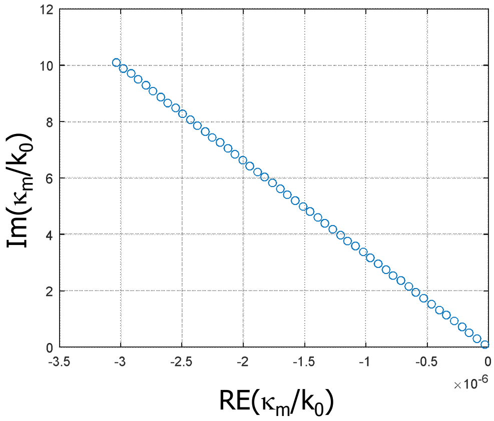
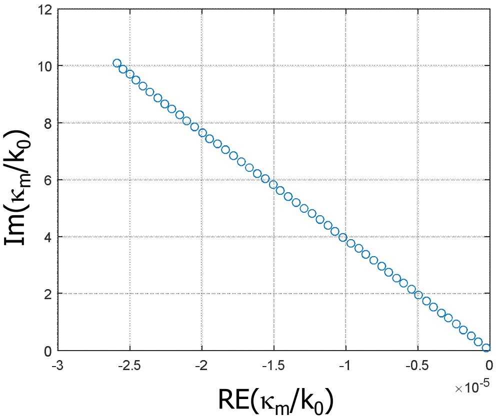


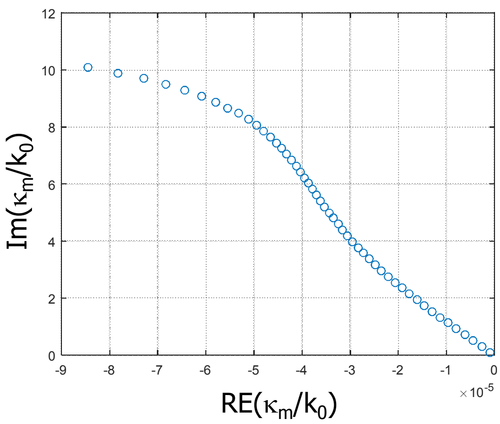
Fig. 2. Roots of point spectra in an aluminum slit case. ($2g = 0.1\lambda_0$)



(a) 50 THz



(b) 100 THz



(c) 200 THz

Fig. 3. Roots of discretized continuous spectra in an aluminum slit case. ($2g = 0.1\lambda_0$)

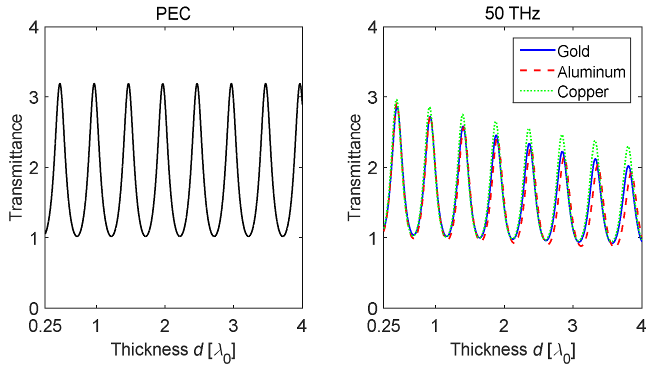


Fig. 4. Transmittance according to the plate thickness *d*. ($2g = 0.1\lambda_0$)

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