Conversion between EOT and Fabry-Perot Resonances for Light Transmission Peaks through Two-Dimensional Metallic Slit Array

Payman Pahlavan
Department of Electrical and Computer Engineering
University of Florida
Gainesville, USA

***Abstract*—In this paper, two distinct light transmission peaks, named EOT and Fabry-Perot resonances, in slit arrays of metallic films are analyzed using mode matching method and simulated by FEM. These two resonances are known to be different in the transmission bandwidth, resonance frequency, and in the transverse magnetic field pattern in the resonance frequencies. However, it is observed herein that the variation in the structure's thickness can convert EOT resonances to Fabry-Perot and vice versa.**

Keywords—EOT, Periodic structure, Slit arry, InSb, Fabry-Perout

I. INTRODUCTION

Despite the previously believed idea of low transmission efficiency of light through subwavelength apertures [1], Ebbesen et al showed that a 2D periodic array in a metallic film exhibits an extraordinary optical transmission (EOT) even at the wavelengths ten times bigger than the hole dimension [2]. The excitation of surface plasmon polaritons (SPPs) was then suggested to have a crucial role in this phenomenon [3-4]. Following this idea, intensive studies have been later done to expand this topic mostly due to its potential applications in important areas such as light localization, microcavity quantum electrodynamics, near-field optics photolithography, and light extraction from LEDs [5-12]. Later on, as a simpler alternative structure, researchers have further investigated one-dimensional narrow slit array having similar light transmission behavior with similar practical applications mentioned above [12]. It has been shown that the excitation of the surface electromagnetic waves, caused by the incident light, yields in an extraordinary light transmission in the forward direction [14]. Afterwards, analytical studies implied that the diffraction and composition of evanescent waves occur at EOT frequencies too [15]. In this manuscript, we analytically study very narrow slit array using mode matching method and numerically investigate them employing full-wave simulation techniques such as FEM and FIT. In section I, we show the contribution of evanescent diffracted modes and slit guided modes in the transmission peaks for a specific metal thickness considering two distinct types of transmission peaks, e. g, EOT and Fabry-Perot. In section 2, we represent that these two kinds of resonances can be converted to each other by varying the metal thickness in a semi-periodic manner.

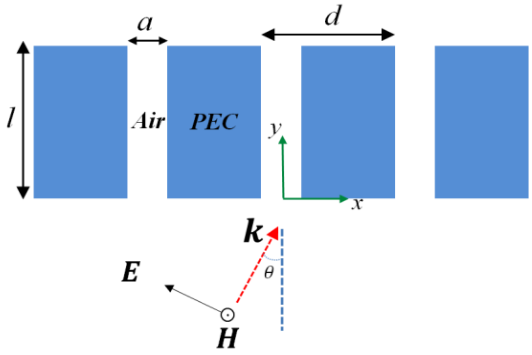

Fig. 1. Periodic air slits cut in the perfect metal film.

II. CONTRIBUTION OF EVANESCENT DIFFRACTED MODES IN EOT

One-dimensional array of narrow slits on the perfect metal, which is surrounded by free space, is considered for this study. As shown in Fig. 1. It is periodic in *x*-direction with period *d*, slit width *a*, and *l* as the thickness. The EOT only appears when a TM polarized wave is incident upon this structure even with very narrow slits [16]. For the sake of simplicity, only the normal incident is studied here with the incident wave expressed with Magnetic field H^i and Electric field E^i as

$$H^i = \frac{\omega\varepsilon_0}{k_y} exp[-j(k_x x + k_y y)] . \vec{a}_z \quad (1.a)$$

$$E^{inc} = exp[-j(k_x x + k_y y)] . (-\vec{a}_x + \frac{k_x}{k_y}\vec{a}_y) \quad (1.b)$$

Based on Floquet-Bloch theory, the reflected (H^r, E^r) and transmitted waves (H^t, E^t) can be written as an infinite series of diffracted modes [17-20]:

$$H^r = \sum_n \left[\frac{\omega\varepsilon_0}{k_y^n} exp[-j(k_x^n x - k_y^n y)] . \vec{a}_z\right] \quad (2.a)$$

$$E^r = \sum_n \left[exp[-j(k_x^n x - k_y^n y)] . (-\vec{a}_x - \frac{k_x^n}{k_y^n}\vec{a}_y)\right] \quad (2.b)$$

$$H^t = \sum_n \left[\frac{\omega\varepsilon_0}{k_y^n} exp[-j(k_x^n x - k_y^n (y-l))] . \vec{a}_z\right], \quad (3.a)$$

$$E^t = \sum_n \left[\frac{\omega\varepsilon_0}{k_y^n} Exp[-j(k_x^n x - k_y^n (y-l))] . \left(-\vec{a}_x + \frac{k_x^n}{k_y^n}\vec{a}_y\right)\right] \quad (3.b)$$

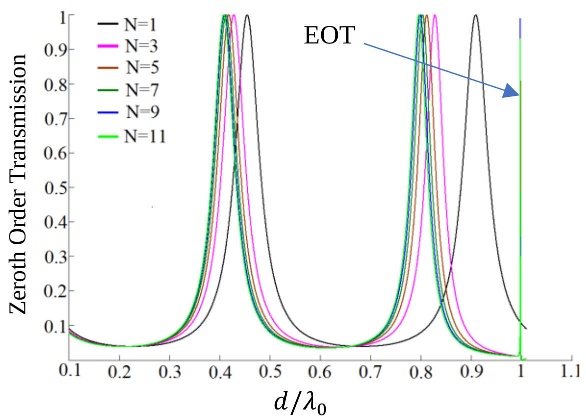

Fig. 2. Zeroth order transmission coefficient calculated by considering the different number of diffracted modes.

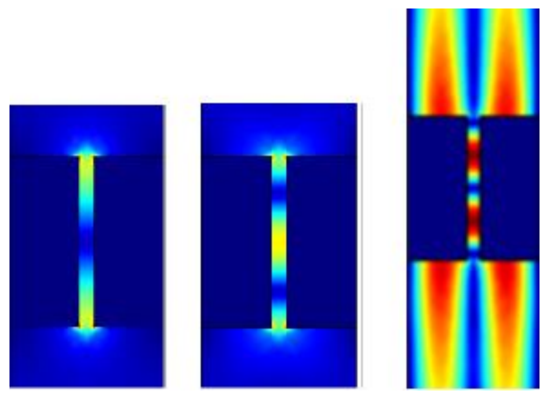

Fig. 3. Magnetic field distribution in a single unit cell. (a) Fabry-Perot resonance at $\lambda \approx 0.4d$. (b) Fabry-Perot resonance at $\lambda \approx 0.8d$. (c) EOT resonance at $\lambda \approx d$.

Note that the (1) and (2) are written for $y < 0$, while the equation (3) is for $y > l$. Also, the wave number components are defined as:

$$k_x^n = \frac{2n\pi}{d}, k_y^n = \sqrt{{k_0}^2 - (k_x^n)^2} \quad (4)$$

The wavelength of the incident wave meets the $d/\lambda < 1$ criterion. In addition, for $0 < y < l$ it is known that by selecting the slit width small enough, i.e., $a << \lambda/2$, only TEM mode is able to propagate in the slit and other modes, which are highly evanescent, can be neglected [14]. Hence, the zeroth order transmission coefficient under a normal TM-polarized wave incidence upon the perfect metal film with cut-through slits is [20]:

$$T_0 = \frac{4k_0{S_0}^2}{\left(1+\sum_n k_0{S_n}^2/k_y^n\right) exp[jk_0L] - \left(1-\sum_n k_0{S_n}^2/k_y^n\right) exp[-jk_0L]} \quad (5)$$

where

$$S_n = \frac{1}{\sqrt{ad}}\int_{-a/2}^{a/2} exp[jk_x^n x]\, dx \quad (6)$$

The term $\sum_n k_0{S_n}^2/k_y^n$ represents the zeroth order modes (incident, reflected, and transmitted) along with all the higher order diffracted modes, which are non-propagating due to their imaginary wave constant k_y^n. Fig. 2 illustrates that the term T_0 fails to calculate the EOT transmission peak if the higher modes are neglected in the $\sum_n k_0{S_n}^2/k_y^n$. It reflects this fact that the constructing superposition of evanescent modes called as spoof surface plasmonic wave comes to play a vital role in this phenomenon [15,22]. On the other hand, Fabry-Perot resonances appear without any contribution of higher-order modes. However, as clearly shown in Fig. 2, they must be considered for more precise calculation of the resonance frequencies. For example, in the case of $d = 0.3mm$, $a = 0.1d$ and $l = 1.1d$, the zeroth order transmission is calculated for the different number of modes. The incident wave frequency is swept from 100GHz up to 1THz satisfying the $d/\lambda < 1$ condition. When only the zeroth-diffracted orders are taken into account, the result includes just two wide Fabry-Perot peaks. EOT peak only appears by adding the first order modes, i.e., $n = \pm 1$ orders. Furthermore, in Fig. 2, the transmission spectrum is calculated considering up to eleven diffracted modes in the mode matching analysis. In fact, the highest orders included in our analysis are $n = \pm 5$.

Magnetic field distribution, obtained by FEM simulation, shows differences in the field confinement in these two resonance types. Fig. 3 depicts the field distribution in a single unit cell. The field intensity is apparently different in these two kinds of resonances.

Fig. 3(a) and 3(b) illustrate the Fabry-Perot resonance that is caused by the resonance of TEM guided mode in the slit. Such resonances happen near the $(n-1)\lambda/2$, which are the resonance wavelengths of a two-dimensional air-filled rectangular cavity [23]. Fig. 3(c) depicts the field contribution in an EOT resonance. In this resonance, which occurs close to $\lambda = d$, the field is confined to the surfaces of the structure in addition to the slits. Keeping in mind that EOT cannot be calculated by neglecting the higher order evanescent modes in mode matching method, this field confinement at the metal surface can be considered as the surface resonance caused by the higher order diffracted modes.

III. METAL THICKNESS EFFECT ON TRANSMISSION PEAKS

Although EOT and Fabry-Perot are believed to be different in their wavelength and Bandwidth, as described in previous section, we here show that the metal thickness variation affects both of these characteristics. For instance, at $l = 0.1d$ there is only a narrow band resonance near $\lambda = d$, known as EOT, but as the thickness increases, the resonant wavelength smoothly shifts to the Fabry-Perot wavelengths with a gradual increase in the resonance bandwidth.

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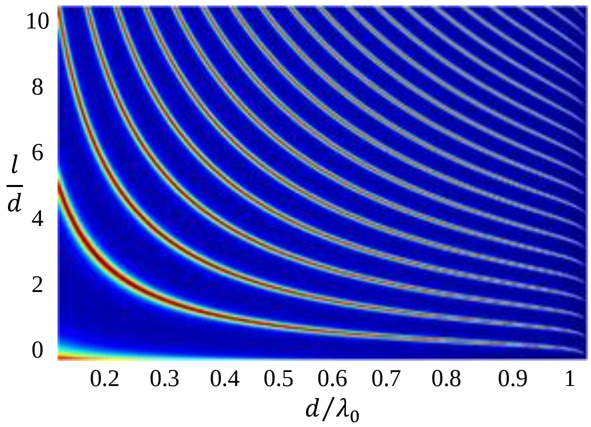

Fig. 4.Simulated semi-periodic behavior of transmission peaks as a function of metal thickness.

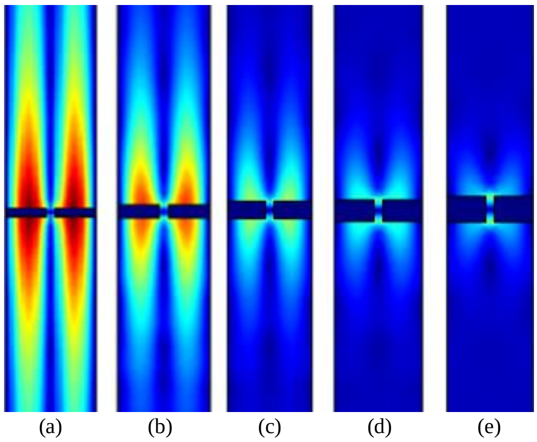

Fig. 5. Simulated transverse magnetic field distribution in EOT resonance for different metal thickness: (a) *l*=0.1*d*, (b) *l*=0.15*d*, (c) *l*=0.3*d*, (d) *l*=0.25*d*, (e) *l*=0.3*d*.

Fig. 4 is the heat map of the zeroth order transmission illustrating the behavior of resonances as a semi-periodic function of metal thickness. Our simulation by COMSOL Multiphysics software shows that every resonance primarily appears as an EOT and then evolves to Fabry-Perot as the thickness increases. We have found that the zeroth order transmission peaks have a semi-periodic behavior with respect to the metal thickness with the periodic constant of $d/2$. In fact, a periodic structure with a thickness of l lying in the $[(n-1)d/2, d/2]$ interval contains n different transmission peaks.

The so-called EOT resonances only appear at specific l values in which the transmission bandwidth is extremely small. However, increasing the l value turns the EOT into the Fabry-Perot. This gradual transformation can be shown in the magnetic field power pattern in and around the unit cells. As the thickness increases from $l = 0.1d$ to $l = 0.3d$, the field confinement decreases on surfaces and is only limited to the air slits.

Fig. 5 shows how the EOT is turning into Fabry-Perot as l increases from $0.1d$ to $0.3d$. The magnetic field which is confined in the surfaces for $l = 0.1d$ is respectively shifted inside the slits. Therefore, not only the metal thickness affects the resonance condition inside the air slits, but also it influences the surface resonance conditions.

IV. CONCLUSION

In this study, we made a deeper look at wave transmission through a metal-air periodic structure. With the assistance of full wave simulations, we have shown the unity and continuity of transmission peaks. In fact, Fabry-Perot and EOT derivate from one formula which includes all the diffracted modes as well as the propagating slit mode. It was shown that the incident light could totally couple into diffracted or propagating modes leading to EOT or Fabry-Perot resonances, respectively. It was also reported that the incident light could couple in both modes equally in which neither EOT nor Fabry-Perot resonances was created. Looking at the field power distribution on the slit confirmed such result later where different types of modes (diffracted or propagating) were observed at different transmission peaks (EOT or Fabry-Perot resonances). The surface resonance that has been repeatedly considered as the result of the existence of surface waves or Spoof Surface Plasmonic wave is unexpectedly related to the metal thickness that was shown to play the most crucial role in determining the characteristics of the transmission peaks.

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