Trapped-Mode Resonance in Electromagnetic Arrays for Wireless Communication Systems

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Abstract—**We present a theoretical study of reflection and transmission characteristics of array of two concentric rings supported by a dielectric slab. This array possesses unusual high quality factor transmission resonance with azimuth angle polarization insensitivity for normally incident plane wave. It is a promising element for development of novel wireless communication systems. The structure is analyzed for normal and inclined incidence. The Spectral Domain Moment Method and the commercial software Computer Simulation Technology (CST) were used for numerical computations.**

Keywords electromagnetic array; trapped-mode; high quality factor; method of moments; CST.

I. INTRODUCTION

Planar arrays consisting of a single resonant element (patch or aperture) in the unit cell, often called as frequency selective surfaces (FSS), posses well known frequency responses and are traditionally used in the microwave and optical regions as filters, antenna radomes and in the design of reflect-array antennas, and in the far-infrared region, as polarizers, beam splitters and laser cavity mirrors [1]. An intrinsic feature of these FSSs is a resonance with low quality (Q) factor. The reasons of the low quality factor are that a thin open structure cannot have inner resonating volumes and the resonating inclusions are strongly coupled with free space. However for some applications, it is desired a thin surface with high Q-factor resonance.

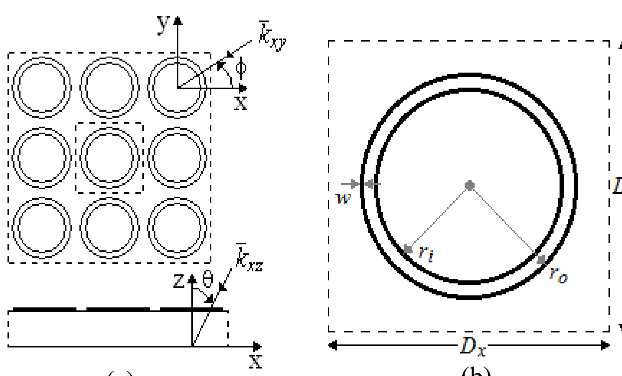
As it is described in [2], there is a method to produce very thin structures possessing high Q-factor frequency resonances using the trapped-mode resonance regime. The trapped-mode can be excited in two element arrays when the resonance frequencies of the elements are approximately equal. This mode is characterized by a sharp resonance and strong current intensities which are of opposite directions in the elements. Due to the almost complete cancelation of the dipole moments, the fields radiated by this current distribution are very weak and also the coupling of this mode with free space is weak. As a consequence, the radiation loss of the trapped-mode resonance is dramatically reduced as compared to the usual resonance, resulting in an unusual high Q-factor.

Some applications related to this planar metamaterial are found in the references [3-4]. In [3] it is shown that this metamaterial combined with a spaser (surface plasmon amplification by stimulated emission of radiation) can be used to produce a spatially and temporally coherent electromagnetic radiation source, designated as laser spaser. In [4] an approach for sensing minute amount of chemical and biochemical material using an array constituted by asymmetrically double split ring (aDSR) elements is presented.

In [5] a detailed study of the trapped-mode in array of two concentric rings is presented and is suggested a new array configuration which is formed by an inner ring and an outer corrugated ring in order to achieve a trapped-mode with higher Q-factor. But in [5], only normal incidence of electromagnetic waves was studied which limits application of the theory. The contribution of this work is a theoretical study of the array of two concentric rings for an arbitrary angle of incidence.

II. DESCRIPTION OF THE ARRAY WITH TWO CONCENTRIC RINGS

The unit cell of the array of two concentric rings analyzed in this work is shown in Fig. 1. The unit cell is of size D_x and D_y, the periodicities of the array. In this work we consider a square cell with the sizes $D_x = D_y = 13$ mm. The middle radius of the outer and inner rings are respectively $r_o = 6$ and $r_i = 5$ mm. Both rings are a strip of width $w = 0.2$ mm and considered to be Perfectly Electrically Conducting (PEC). The substrate is of thickness $h = 1.6$ mm with a dielectric constant of $\varepsilon = \varepsilon' - i\varepsilon''$.



(a) (b)

Figure 1. Array of two concentric rings with the reference coordinate system (a) and an unit cell of the array (b).

III. Results and Comments

A. *Method of Analysis*

To analyze this structure, we developed a program based on the Spectral Domain Moment Method (SDMM) which consists in solving through the Moment Method (MM) the Electric Field Integral Equation (EFIE) in the spectral domain. In this method the periodic boundary conditions are taken into account by transforming the continuous spectral domain variables into harmonics that are multiples of the periodicities of the array. The substrate is modeled through the Green's function which is obtained by applying the boundary conditions on the top and bottom interfaces. This method is described in [1]. For validation of our program we used the commercial software Computer Simulation Technology (CST) which is based on the Finite Integration Technique (FIT) [6].

The structure is excited by a plane wave incident from the half space above the metal array. To describe the direction of the propagation vector of the incident plane wave, we used the spherical angular coordinate variables ϕ and θ shown in Fig. 1. In Fig. 2 we show the reflection and transmission coefficients for the case of ϕ = 45°, θ = 45°, ε = 4.5-i0.1 and horizontally polarized incident plane wave calculated with both SDMM and CST programs.

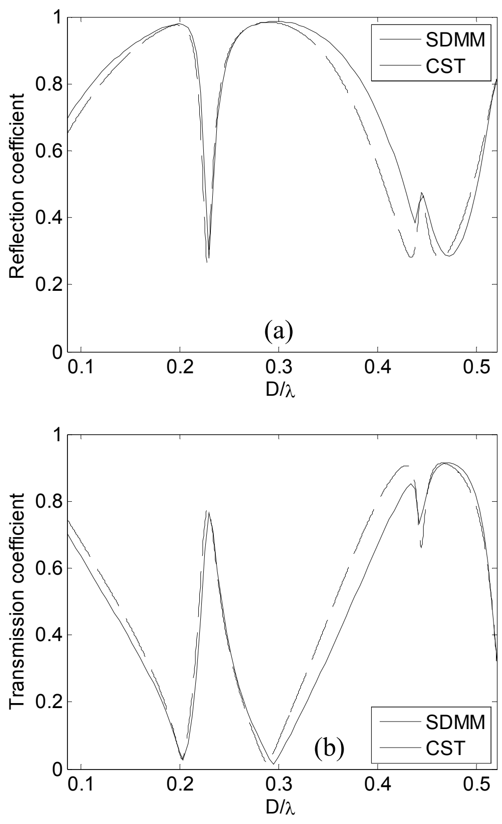


Figure 2. Reflection (a) and transmission (b) coefficients for ϕ = 45°, θ = 45°, ε = 4.5-i0.1 and horizontally polarized incident plane wave.

As it can be seen in Fig. 2, the reflection and transmission coefficients calculated by two programs are in good agreement. The numerical differences between the results may be caused by the fact that in the SDMM the dielectric slab is taken into account analytically through the Green's function while in the CST it is modeled numerically through small finite volumes of constant equivalent current density. To our opinion, the first method is more adequate for the problem. For that reason, we used in the following analyses only the results obtained with the SDMM.

B. *Brief Description of the Trapped-Mode Regime*

To illustrate the trapped-mode regime, we show in Fig. 3a the normalized current distribution on the rings of one unit cell in the trapped-mode resonance frequency for y-polarized plane wave with normal incidence. As explained before, the trapped-mode corresponds to a high asymmetric current mode which is weakly coupled to free space. In Fig. 3b is shown the current density along one half of the outer ring at trapped-mode resonance and at usual resonance of the outer ring.

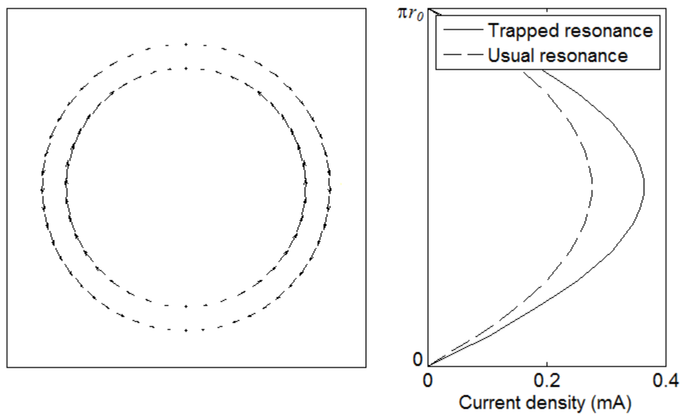
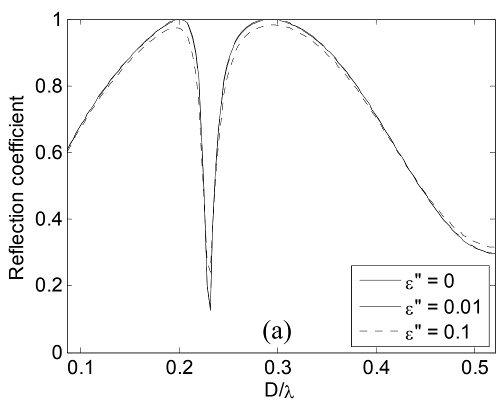


Figure 3. The normalized current distribution on the two rings (a) and the absolute value of current density along one half of the outer ring at trapped resonance and at "usual" resonance of the islolated outer ring (b) for y-polarized plane wave with normal incidence.

C. *Influence of Dielectric Losess on the Trapped-Mode*

To illustrate the influence of the dielectric loss on the trapped-mode we show in Fig. 4 the structure responses for ε' = 4.5 and different values of ε" for the case of normally incident plane wave.



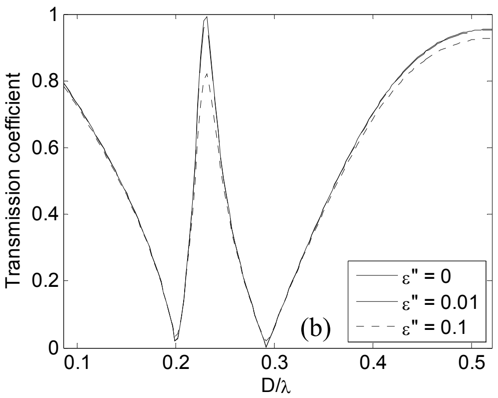


Figure 4. Reflection (a) and transmission (b) coefficients for ε' = 4.5, different values of ε" and normally incident plane wave.

As it can be noted, when ε" = 0.1 the structure transparence at the trapped-mode resonance frequency is significantly reduced due to the dielectric loss. In the following results, we considered the dielectric with permittivity ε = 4.5-i0.1 in order to make an evaluation of the structure responses in the presence of critical dielectric losses.

D. Simulation Results for Horizontal Polarization

In Fig. 5 we show the structure responses for $\phi = 0°$, different values of θ and horizontally polarized incident plane wave, and in Fig. 6, for $\phi = 45°$.

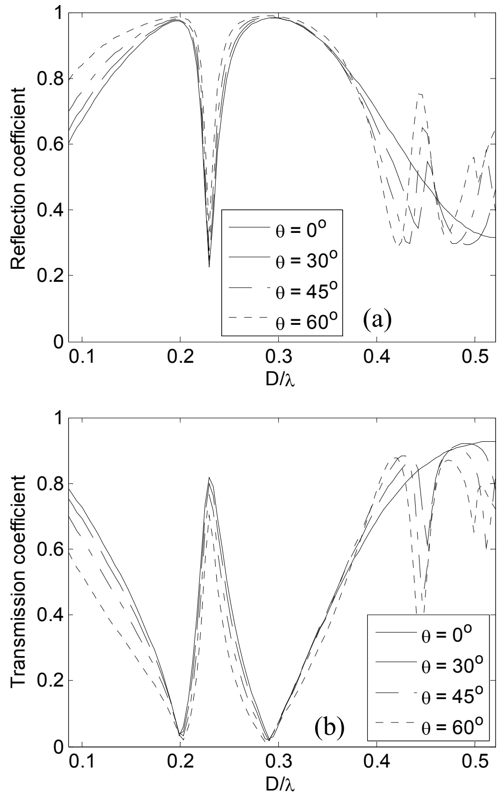


Figure 5. Reflection (a) and transmission (b) coefficients for $\phi = 0°$, different values of θ and horizontally polarized incident plane wave.

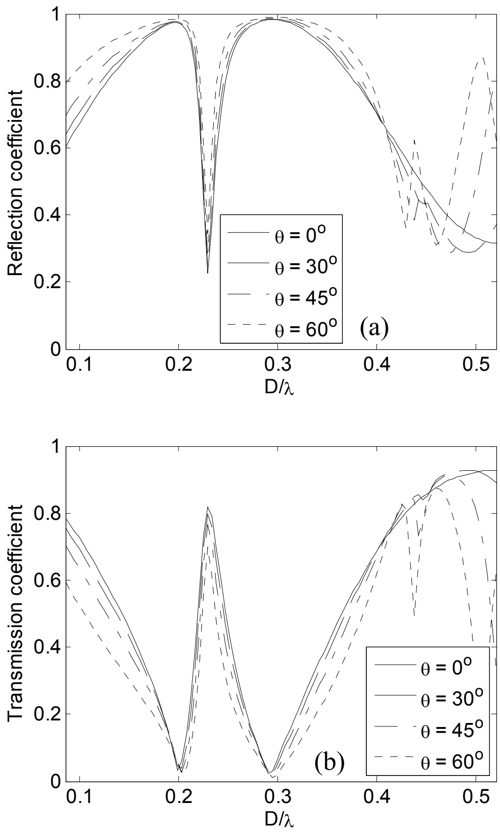


Figure 6. Reflection (a) and transmission (b) coefficients for $\phi = 45°$, different values of θ and horizontally polarized incident plane wave.

As it can be observed in Figs. 5 and 6, for the case of horizontal polarization and θ=30°, the array begins to diffract not specularly, which is manifested as sharp reflection peaks in the reflection coefficient or equivalently as sharp attenuation deeps in the transmission coefficient, when the array period is about 0.44λ. With respect to the trapped-mode, as the angle of incidence is increased the bandwidth of the trapped-mode is reduced as well as the transparence at the resonance frequency.

E. Simulation Results for Vertical Polarization

In Fig. 7 we show the structure responses for $\phi = 0°$, different values of θ and vertically polarized incident plane wave, and in Fig. 8, for $\phi = 45°$.

For the case of vertical polarization shown in Figs. 7 and 8, we observe an opposite behavior of the trapped-mode in comparison to the case of horizontal polarization, i.e., its bandwidth is increased and also the transparence at the trapped-mode resonance frequency. Another fact that can be observed is that the wavelength where the structure starts to diffract is almost unchanged with respect to the angle of incidence in comparison to the case of horizontal polarization.

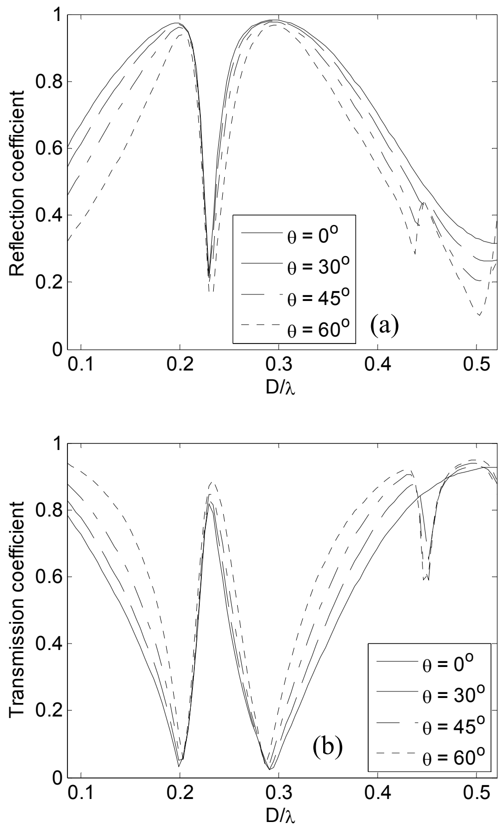


Figure 7. Reflection (a) and transmission (b) coefficients for $\phi = 0°$, different values of θ and vertically polarized incident plane wave.

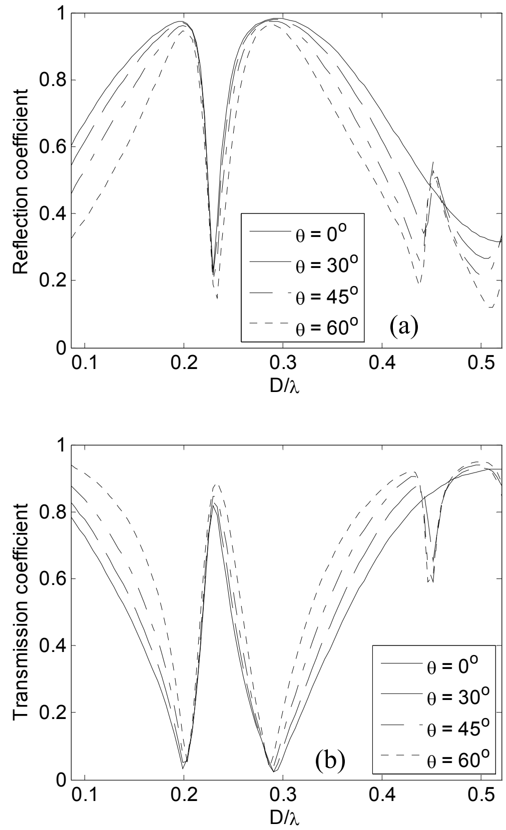


Figure 8. Reflection (a) and transmission (b) coefficients for $\phi = 45°$, different values of θ and vertically polarized incident plane wave.

IV. Conclusion

A theoretical study of reflection and transmission characteristics of array of two concentric rings supported by a dielectric slab was presented. The structure was analyzed for normal and inclined incidence of the plane waves. It was observed that the trapped-mode bandwidth and maximum transparency at the resonance frequency are reduced when the angle of incidence is reduced for the case of horizontal polarization and are increased for the case of vertical polarization but these changes are of order of tens percents.

Acknowlegment

We would like to acknowledge the financial support of the Brazilian agencies CAPES and CNPq.

V. References

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[6] The program's web page is www.cst.com