# 國防科技學術合作研究計畫成果報告

# 電磁干擾下金屬空腔內印刷電路之電磁耦合分析及模擬

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# 國防科技學術合作計畫研發成果資料表

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| 與軍方研發機構互動之具體研發成果 | | 本計畫執行其間與中山科學研究院電子所尋標器組有良好之互動關係，尤其是在試片之製作與微波量測上，預期將可將此技術直接為該組未來解決電磁屏蔽問題之參考依據。 |
| 可推廣於民間產業之技術或可開發之產品 | | 本研究計畫主要是利用二維金屬週期結構來作為電磁屏蔽結構，由於該結構在週期方向上具有較強之布理格（Bragg）反射，因此對於電磁波之反射效果極佳。預期將可推廣至民間在電子資訊系統之電磁屏蔽應用上。 |
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# 摘要

本研究計畫主要針對金屬空腔中使用於電磁屏蔽及散熱雙重功能之金屬週期結構做電磁特性分析。由於必須考慮到散熱之問題，因此該屏蔽結構必須具有孔洞或槽線之分佈。這些不連續之金屬往往是造成電磁波穿透此屏蔽層而進入空腔結構之主要原因；也是本計畫之研究重點。

本研究利用嚴格之電磁數值分析方法～波模匹配法將具週期孔洞之金屬屏蔽層模擬成電磁學上之邊界值問題，利用槽線結構中之基本波模（平行板波導）來展開結構中之電磁場解。此外，均勻界質層中之電磁場則利用弗開解（Floquet’s solution）來展開，接著利用電磁學上之邊界條件求得週期分佈槽線與均勻界質層中波模之耦合關係式，進一步獲得此不連續介面上之輸出入關係式。由於此一數學式可以利用等效傳輸線網路方法來表示並求得整體結構之輸出入關係式。因此對於單一層或多層屏蔽金屬結構之輸出入關係式將可獲得其散射矩陣，藉以求得反射及透射波之每一個空間諧波振幅，完成穿透波之場強分析。

本研究不僅利用嚴格之理論分析計算，同時也實際設計並製作對應之結構進行實驗之量測比對，獲得當一致的結果。此一研究成果對於屏蔽結構之物理特性及工程設計準則之訂定有相當大之貢獻，預期將可作為軍方及民間工業電子產品電磁相容問題之對策參考。

# Abstract

In this report, we presented the scattering characteristics, including transmission and reflection of an electromagnetic shielding structure. The structures under consideration contain multiple 1-D metallic periodic layers, each of which consisting of metallic strip lines coated on a dielectric slab. If the number of 1-D periodic layers is large enough, and the distance between any two adjacent layers keeps the same. The structure can be regarded as a finite thickness 2-D metallic periodic structure. For the numerical simulation, we employed the rigorous mode-matching method incorporated with the Floquet solution (plane wave method) to carry out the calculation of the scattering characteristics of 2-D metal periodic structures. In addition, we have also performed experimental measurements to verify the theoretical analysis. The excellent agreement between the measured and calculated data confirms the theoretical formulation and numerical analysis. In a word, in this research project, we utilized the stop-band along the direction of wave propagation in a 2-D metal periodic structure to enhance the attenuation of incident waves and the capability in electromagnetic shielding.

Index Terms — electromagnetic shielding, metal periodic structures, two-dimensionally periodic structure, stop-band, metal strips array

## Introduction

The 1-D periodic structure has been a subject of continuing interest in the literature. The main effort in the past was on the scattering and guiding characteristics of a 1-D dielectric periodic waveguide. For example, diffraction gratings and grating couplers employed in optical community to serve as a component in optical integrated circuit. For the grating made up of metallic material, the corrugated metal surface taken as a waveguide wall was used to suppress the excitation of edge current in a horn antenna. Besides, the metallic strips coated on a dielectric substrate was utilized as a polarizer or shielding structure to suppress the incident wave having the electric field along the length direction of the metal strips.

Recently, some researches used 2-D dielectric periodic structures to fabricate artificial crystals to mimic the physical characteristics of nature crystal in microwave region. To mention a few, the waveguide, containing 2-D dielectric periodic structures as its side walls, was invented. The micro-cavity, made up of a point defect in a 2-D periodic structure, was implemented to confine the electromagnetic energy in a local point. The basic theory is to employ the below-cutoff or the stop bands of the 2-D periodic structure to inhibit the propagation of waves.

For the numerical analysis, the electric and magnetic fields in 1-D and 2-D dielectric periodic structures can be calculated by using the plane wave method. Namely, the variation on the dielectric constant can be expressed in terms of the 1-D or 2-D Fourier series expansion, while the field solutions in the periodic and uniform layers are the superposition of plane wave solutions. After resolving the electromagnetic boundary-value problem, we could easily obtain the scattering characteristics of the 2-D periodic structure. However, for the metallic periodic structure, the dielectric function is a singularity at the metal region (which is usually regarded as a perfect electric conductor). The plane wave method fails in this condition.

In this research project, we employed a 2-D metallic periodic-structure as a shielding material to inhibit the transmission of an incident plane wave. Such a 2-D metallic periodic-structure consists of a stack of 1-D periodic layers, each of which includes a metal strips arrays printed on a dielectric substrate. For the theoretical analysis, we employed the rigorous mode-matching method incorporated Floquet solutions to carry out the calculation of scattering characteristics, including the transmission and reflection. Since the metal strip is regarded as a perfect electric conductor, the periodic dielectric function was not valid. In this research, we directly find the electric and magnetic fields distribution within the unit cell of a 1-D metallic periodic layer. That is, the fields within the metal region are null, while those for the region between two metal layers are considered as the superposition of parallel-plate waveguide modes. Therefore, the structure can be considered as a periodic step discontinuities problem in microwave engineering. The mode-matching method can be successfully applied to solve the electromagnetic fields in the structure.

In addition to the numerical simulation, we also perform the experimental measurements to verify the theoretical formulation and numerical computations, as well. A test fixture, including two wideband horn antennas, a vector network analyzer (HP 8722D) and an anechoic chamber, was implemented to measure the transmittance spectra of the electromagnetic wave, penetrating through the 2-D metallic periodic structure. The excellent agreement between the measured and computed results confirms the theoretical approach and numerical simulation of this research work.

This report is organized as follows. The next section will introduce the structure configuration and specified parameters of the shielding structure. The ensuing section will deal with the method of analysis, particularly in the transmission network representation of the overall structure. The fourth section will demonstrate the results obtained by both numerical analysis and experimental measurements. In the final section, we will give some comments to conclude this report.

## Statement of the problem

A 2-D Periodic structure, shown in the Fig.1, can be regarded as finite stack of 1-D metal strips array. As the rectangular coordinate system attached, the infinite metal strip array extends infinitely in z-direction. Each of the metal strips has width $w_m$ and thickness $h_m$; the separation distance between strips is $w_a$. Thus, the periodic of the metal strip array in $x$-direction is $d_x$ ($w_m$+$w_a$). It is noted that the metal strip considered in this report is assumed to be a perfect conductor. Returning to Fig.1, in addition to the metal strips array, a uniform dielectric layer having relative dielectric constant denoted by $\varepsilon_r$ and thickness s, serves as a separator to separate the 1-D metal strip arrays. Furthermore, each of the 1-D metal strips array has a shift distance $l_s$ in the lateral direction along $x$-axis. The lateral shift distance $l_s$ determines the lattice pattern of a 2-D Periodic structure; for instance, if the $l_s$ for each 1-D metal strip array is set to be zero, a 2-D Periodic structure of rectangular lattice is obtained; if the later shift distances between two adjacent layers are $0.5d_x$, it results in a triangular lattice. As shown in this figure, a plane wave is obliquely incident into this structure. The incident angle, $\theta_i$, is defined as the angle between $y$-axis and the propagation vector of the incident plane wave.

Method of analysis

For the theoretical analysis, we employed the rigorous mode-matching method and generalized scattering matrix method to carry out the calculation for the scattering fields including the transmission and reflection waves. To have a systematical approach, the input-output relation for the 1-D metal strips array is resolved and expressed in terms of the generalized scattering matrix. Thus, the scattering characteristic of the 2-D periodic structure can be determined by cascading the input-output relation of each 1-D periodic layers. Returning to the input-output relation for the 1-D periodic layer, since the metal strips are considered as a perfect electric conductor, the electric and magnetic fields only exist inside the air region between two metal strips. Consequently, the fields can be expressed in terms of the superposition of parallel-plate waveguide modes, which are given below:

$$E_t(x,y) = \sum_n \overline{V}_n(y)\overline{\phi}_n(x) \tag{1}$$

$$H_t(x,y) = \sum_n \overline{I}_n(y)\overline{\phi}_n(x) \tag{2}$$

$$\frac{d\overline{V}_n(y)}{dy} = -jk_{yn}\overline{Z}_{yn}\overline{I}_n(y) \tag{3a}$$

$$\frac{d\overline{I}_n(y)}{dy} = -jk_{yn}\overline{Y}_{yn}\overline{V}_n(y) \tag{3b}$$

$$\overline{Z}_{yn} = \begin{cases} \dfrac{\omega\mu}{k_{yn}}; TE \\ \dfrac{k_{yn}}{\omega\varepsilon}; TM \end{cases} \tag{3c}$$

$$k_{yn} = \sqrt{k_o^2\varepsilon_r - \left(\frac{n\pi}{w_a}\right)^2} \tag{3d}$$

$$\phi_n(x) = \begin{cases} \sqrt{\dfrac{2}{w_a}} \sin\dfrac{n\pi x}{w_a}; n = 1,\ldots,\infty \\ \sqrt{\dfrac{\gamma_n}{w_a}} \cos\dfrac{n\pi x}{w_a}; n = 0,\ldots,\infty, \gamma_n = \begin{cases} 1; n = 0 \\ 2; n \neq 0 \end{cases} \end{cases} \tag{4}$$

Where $E_t(H_t)$ represent the tangential electric (magnetic) fields inside the parallel-plate waveguide. The $\overline{V}_n(y)$ and $\overline{I}_n(y)$ are the voltage and current waves, which satisfy the transmission line equations along y direction, while $\overline{\phi}_n(x)$ is the eigen function of in the parallel-plate waveguide.

On the other hand, the fields in the uniform separator are contributed by the Floquet solutions (or plane waves), which yield:

$$E_t(x,y) = \sum_n V_n(y)\exp(-jk_{xn}x) \tag{5}$$

$$H_t(x,y) = \sum_n I_n(y)\exp(-jk_{xn}x) \tag{6}$$

$$k_{xn} = k_{xo} + n\frac{2\pi}{d_x}; n = -\infty,\ldots,+\infty \tag{7}$$

$$\frac{dV_n(y)}{dy} = -jk_{yn}Z_{yn}I_n(y) \tag{8a}$$

$$\frac{dI_n(y)}{dy} = -jk_{yn}Y_{yn}V_n(y) \tag{8b}$$

$$Z_{yn} = \begin{cases} \dfrac{\omega\mu}{k_{yn}}; TE \\ \dfrac{k_{yn}}{\omega\varepsilon}; TM \end{cases} \tag{9}$$

$$k_{yn} = \sqrt{k_o^2\varepsilon_r - k_{xn}^2} \tag{10}$$

Where $E_t(H_t)$ represent the tangential electric (magnetic) fields in the uniform region, $V_n(y)$ and $I_n(y)$ are the voltage and current waves, which satisfy the transmission line equations along $y$ direction. The exponential term in (5) and (6) represent the Floquet mode (or plane waves). By matching the tangential electric and magnetic fields at the interface between 1-D metal strips array and uniform region, we obtain the relationship for the electric and magnetic fields in respective regions, which is so called the input-output relation. Due to the limited page of this report, we neglect the detail mathematical derivation, however, they could be found in the literature. We have developed a computer simulation program to calculate the scattering fields for a 2-D Periodic structure illuminated by a uniform plane wave. In this program, the numerical convergence has been carefully examined.

### *Experimental Measurement*

In addition to the theoretical analysis, we have also setup an experiment to verify the numerical analysis. As shown in Fig.2, this close-loop measurement system consists of a VNA (vector network analyzer), microwave power amplifiers, coaxial cables, board band double ridged horn antennas and anechoic chamber. In the theoretical analysis, we assume the field and structure have no variation along the length direction of the metal strips array. To meet this requirement, a microwave mask, by carving out a rectangular aperture from the foam absorber, was put in front of the 2-D Periodic structure to generate a uniform plane wave and to avoid the edge diffraction form the ends of the metal strips. Besides, in theoretical analysis, the transmission efficiency is defined as the radio of transmitted power to incident power at the input- and output- interface of the Periodic structure. However, the measure data are taken at the input and output ports of the VNA. To have a fair comparison, we should calibrate the physical quantities to the two prescribed interfaces, that is, the antenna factor of the double ridge horn, cable losses, power amplifier gain, and propagation loss must be taken into account.

### Experimental and numerical results

In our experiment, the metal strips are made up of copper foil having 0.6mm in thickness. They were coated on the Polystyrene, which has the relative dielectric constant close to unity. We have two different widths for the metal strip, which are 10mm and 15mm, respectively, while the period of the 1-D periodic structure retains to be 20mm. Since the thickness of the copper foil is greater than the skin depth in the frequency range of operation, the assumption of perfect electric should be valid for the numerical simulation.

Fig.3 shows the variation of transmittance against frequency of operation for both theoretical and experimental results. The uniform plane wave is normally incident with TE ($E_z$) polarization. The width of the metal strip and the period are 15 mm and 20 mm, respectively. The thickness of the separator is 24 mm. Besides, there is no lateral shift distance for these two 1-D metal strips arrays. As shown in this figure, the theoretical calculation depicts two transmission spikes around 6 GHz and 12.3 GHz, respectively. Although not shown the response below 4 GHz, since the transmittance below 6 GHz is very small, the 6 GHz can be considered as the cutoff frequency of this 2-D Periodic structure FSS. In addition, from the results shown in this figure, it can be conjectured that there are two pass bands (two stop bands and one below cutoff band) in the frequency of operation. The wave in the two pass bands exhibits apparently transmitting, however, strongly reflecting in the stop band and below-cutoff regions. This phenomenon can be obviously observed by the measured response as illustrated in this figure.

In the next experiment, we retain the structure; however, change the polarization into TM ($E_x$) polarization. The results of theoretical and experimental studies are shown in Fig.4. Compared with the previous figure, we found this structure seems to be more transparent for the TM polarization; especially, no cutoff frequency is present. In fact, such a 2-D periodic structure typically can be regarded as the stacks of 1-D parallel-plate waveguide arrays (although the thickness is smaller compared with a wavelength, this can still be regarded as a limiting case of a parallel-plate waveguide array). Based on the basic electromagnetic theory, in a parallel-plate waveguide, the TE polarization wave has cutoff frequency; on the contrary, TM polarization can propagate down to DC. This can be evidently confirmed by comparing the transmittance response in figure 3 and 4.

In next example, we increase the number of 1-D metal strips arrays up to 4 layers and change each of the width of metal strip to 10 mm. As shown in Fig.5, it indicates that in the vicinity of the band edges there are three ripples present. As a thumb of rule, the number of ripples equals to N-1, where N is the number of metal strips arrays. Besides, the increasing in the number of 1-D periodic layers, the stop-band behavior will be significant accordingly; and what follows is the enhancement in the selectivity. This will be a great benefit in the design of the spatial filter design.

In recent years, in optics community, many researchers found that defects in a photonic crystal can drastically change its scattering characteristics. The defect is resulted from a small perturbation on the structure: for instance, a fractional variation on the periodicity or constituent medium. As we have known, the defect admits the existence of localized state within a very narrow frequency band. Such a narrow pass-band present within a stop-band shall result in a fairly good selectivity in the incident plane wave.

As shown in Figure 6, it indicates that the distribution of transmittance against frequency for a 2-D Periodic structure FSS having defect. We have carved one layer of metal strips array out of the 2-D periodic structure, that is, the thickness of the separator in the central region is changed to be 48 mm, different from the other ones (24mm). From this figure, we found that the location of stop band remains the same; nevertheless, there is a small region of pass band within it. Although not shown in this report, the transmission peak corresponds to the resonance frequency of the channel waveguide (defect region). Besides, due to the few number of 1-D metal strips array around the channel waveguide, there exists some losses in the transmission peak; however, this can be compensated by increasing the number of 1-D periodic layers.

## Conclusion

In this research, we have employed the 2-D Periodic structure to implement the design of a electromagnetic shielding material. Due to the stop-band in such a 2-D periodic structure, the strong attenuation will enhance the shielding effeteness of the shielding material. To verify the concept of design, the theoretical analysis by using rigorous mode-matching method and experimental measurement both were carried out. The good agreement between those results proves the potential application of 2-D metallic periodic structure in electromagnetic shielding applications.

## Acknowledgment

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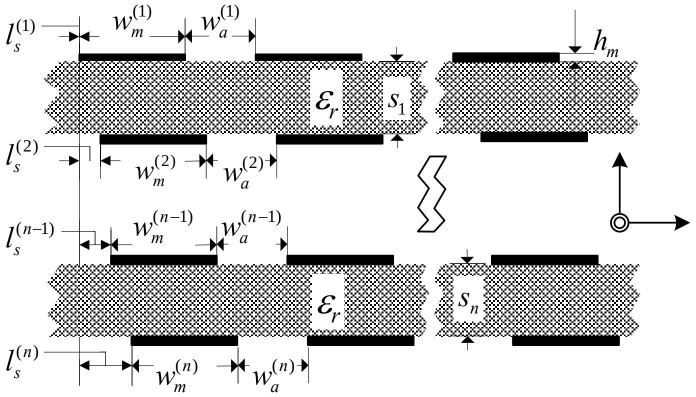

Figure 1(a): structure configuration for the 2-D Periodic structure (the structure is assumed to be uniform along z direction)

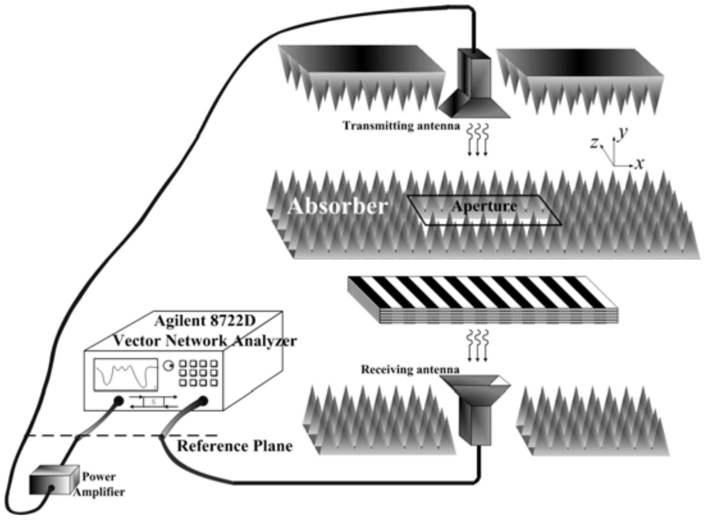

Figure 1(b): experimental setup

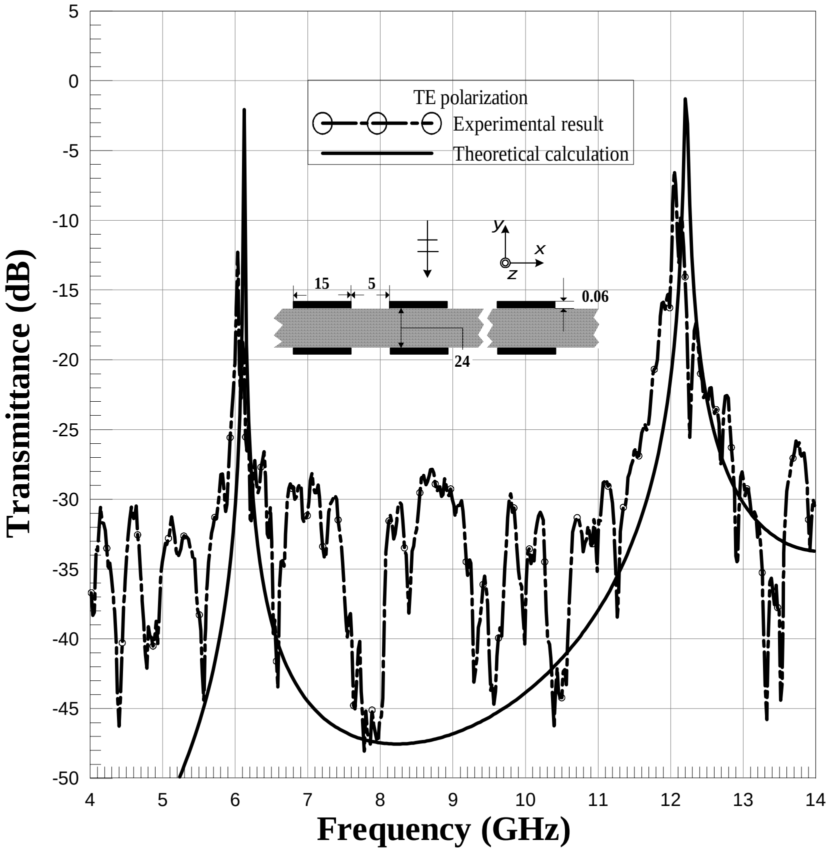

Fig.3 Variation of transmittance against frequency for both experimental measurement and theoretical calculations; two 1-D metal strip arrays with TE plane wave incidence

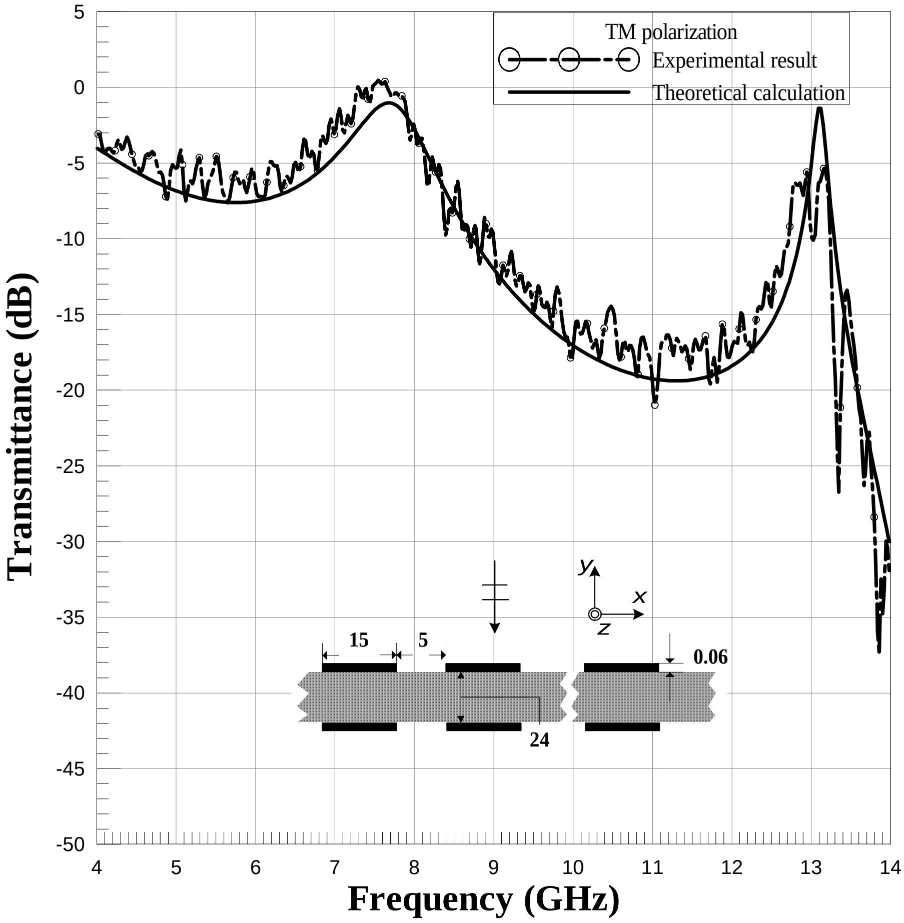

Fig.4 Variation of transmittance against frequency for both experimental measurement and theoretical calculations; two 1-D metal strip arrays with TM plane wave incidence

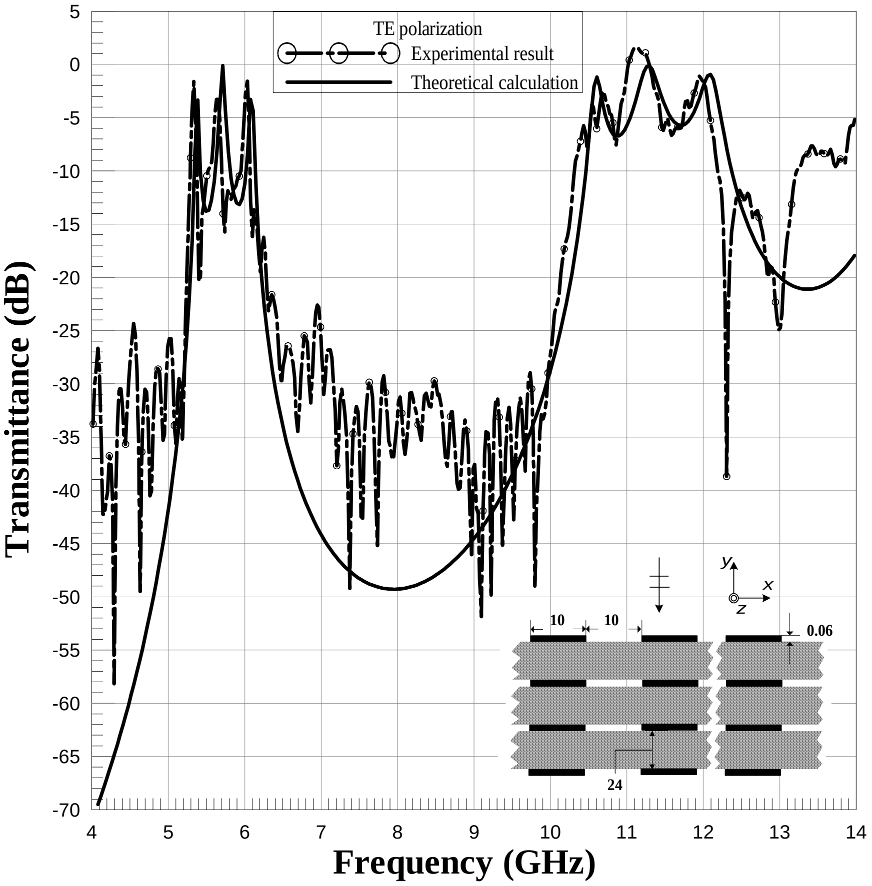

Fig.5 Variation of transmittance against frequency for both experimental measurement and theoretical calculations; four 1-D metal strips arrays with TE plane wave incidence

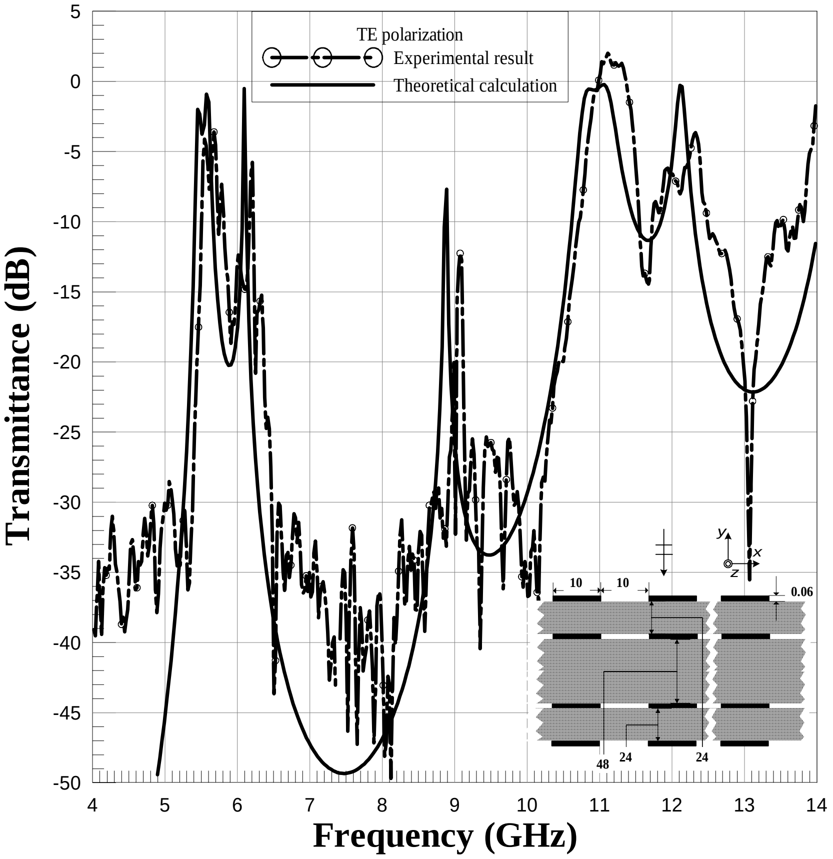

Fig.6 Variation of transmittance against frequency for both experimental measurement and theoretical calculations; four 1-D metal strips arrays having a line defect, under the plane wave incidence of TE polarization