行政院國家科學委員會專題研究計畫　成果報告

超越介質之散射與波導特性研究:理論分析與實驗驗證

(2/2)

計畫類別： 個別型計畫
計畫編號： NSC93-2213-E-009-154-
執行期間： 93 年 08 月 01 日至 94 年 07 月 31 日
執行單位： 國立交通大學電信工程學系(所)

計畫主持人： 黃瑞彬

報告類型： 完整報告

處理方式： 本計畫可公開查詢

中　華　民　國 94 年 8 月 29 日

國科會專題研究計畫報告（計畫編號：93-2213-E-009-154）

超越介質之散射與波導特性研究:理論分析與實驗驗證(2/2)

Investigation on the scattering and guiding characteristics of a meta-material: theoretical analysis and experimental verification (2/2)

計畫主持人：黃瑞彬

國立交通大學電信工程學系

***Abstract* — In this paper, we have studies the scattering characteristics of a two-dimensional Electromagnetic (EM) crystal made up of metal strips arrays. To measure the transmittance of the EM crystal, we have setup a test fixture containing two wide-band double ridged horns and a microwave mask employed to generate a finite size uniform plane wave for illuminating the EM crystal. Besides, we have put this test fixture in an anechoic chamber to avoid the interference and, meanwhile, to suppress the multiple scattering. We have taken numerous measurements by changing some structural parameters in conjunction with the 2-D EM crystal. The good agreement between those measured data and the theoretical computation based on the program ECMRY [18] prove the standard and consistent measurement in this research work.**

***Index Terms* — 2-dimensionally periodic structure, Electromagnetic crystals, uniform plane wave, stopband**

I. INTRODUCTION

Periodic structures have been widely studied in microwave engineering for many years [1-5]. The 1-D periodic dielectric waveguide has been investigated and implemented in the applications of grating coupler in integrated optics [3]; it could also serve as a diffraction grating to diffract the incident beam into a specific direction. However, most of the applications were limited to the 1-D periodic structures. The two and three dimensional ones are seldom tackled in that period. Up to 1970s, the two-dimensionally periodic structures were found to have the capabilities of filtering the incident wave in both the spectral and space domain [6-8]. By suitable designing its periodic pattern of the unit cell, it can allow specific frequency bands to pass through and stop the other ones, so it was named as frequency selective surface.

In 1999, Hwang and Peng [9] first used the 2-D periodic impedance surface model to successfully account for the guiding characteristics of the surface waves supported by the structures. Besides, they believed that the high impedance surface should belong to the class of resonance type periodic structure. They revisited the corrugated metal surface and rigorously calculated the dispersion relation of the wave guided in the structure [10]. More recently, some new and interesting phenomena were discovered in the microwave society for the two and three dimensionally periodic structures, for examples, the arrays having split rings backed with metal strips [11]; the 2-D transmission line network equipped with lumped resonant elements. They were experimentally proved to have the capabilities in lensing the propagation and non-propagation waves [12], as well. Besides, they were shown to be able to focus the incident beam in such a kind of medium, that is, the refraction at the boundary between a conventional and such a kind of medium is abnormal, which contradicts the Snell’s law. Therefore, this medium is named as a left-handed medium to distinguish from the commonly used one. At the same time, many researchers recall a paper published in 1968 by a Russian scientist [13], in that paper he had predicted the wave propagation behavior in a medium simultaneously exhibiting negative permittivity and permeability. In theoretical analysis, he found, in that medium, the wave possesses anti-parallel between the Poynting- and propagation- vector. That is the reason why the wave can be lensed there. As a consequence, many researchers believe the negative permittivity and permeability are the main reasons for the phenomenon of ultra-refraction. Although the refraction anomalous was found, the band with of operation is so narrow, and a strong attenuation is occurring, at the same time. Therefore, the rigorous model for predicting and accounting for the physical mechanism remains to be studied in detail.

From the literatures described previously, we know that the 2-D periodic structure containing metal and dielectric media is the basic one and has not yet studied clearly in the literatures. In 2004, Hwang [14] employed the modematching method invoking the general eigen-value method to rigorous resolve the dispersion relation of wave propagation in a metallo-dielectric medium. From now on, I will call it as 2-D EM (electromagnetic) crystal through this paper. All the higher order modes are considered to figure out the band structure of fundamental modes and higher order modes and their space harmonics, as well. In addition, the relationship between the band structures and the scattering characteristics has also been clearly identified in this paper.

II. STATE OF PROBLEM

A two dimensional EM crystal, shown in the Fig.1, can be regarded as finite stack of one dimensionally periodic structure. As the rectangular coordinate system attached, the infinite metal strip array extends infinitely in z-direction. Each of the metal-strip has width w_m and thickness h_m, and the separation between two strips is w_a. Thus, the periodic of the metal strip array in x-direction is dx (w_m+w_a). It is noted that the metal strip considered in this paper is assumed to be a perfect conductor; namely, there is no electric field distribution in it. However, for the case of metal strip finite conductivity, it should include the contribution of metal modes, which is beyond the scope of this research work, and we will not tackle the problem. Returning to Fig.1, a uniform dielectric layer having relative dielectric constant denoted by εr 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 distance shift l_s in the lateral direction (x-axis). The lateral shift distance l_s determines the pattern of a 2-D EM crystal; for instance, if the l_s for each 1-D metal strip array is set to be zero, a 2-D EM crystal of rectangular pattern is obtained; if the later shift distances for two adjacent layers are 0.0 and 0.5dx, alternatively, is a triangular pattern. For a rectangular pattern, the period in y-direction can be simply figure out by dy=h_m+s. As shown in this figure, a plane wave is obliquely incident into this structure. The incident angle, θ_i, is defined as the angle between y-axis and the propagation vector of the incident plane wave.

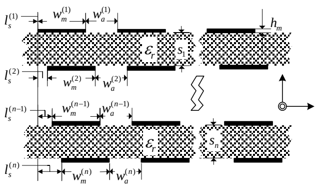

Fig.1 Structural configuration and geometric parameters for 2-D Electromagnetic crystal

III. TEST FIXTURE

In this section, we will present a test fixture for measuring the scattering characteristics of EM crystals by a plane wave normally incident. As shown in Fig.2, this close-loop measurement system consists of VNA, microwave power amplifiers, coaxial cables, board band double ridged horn antennas and anechoic chamber. Besides, we carve out a rectangular hole from a foam absorber to act as an aperture. Since the absorbing material is employed, the wave illuminates on it will be absorbed, while the others will pass through. That is, the aperture used here is to serve as a mask to allow the transmission of uniform field while blocking the others away from the aperture. It is noted that the wave illumination on the aperture, in general, is a Gaussian beam rather than a uniform plane wave. The tapering in the field distribution on the aperture may cause slight difference in the results obtained from theoretical and experimental studies. Since the measurement of transmission efficiency is defined as the radio of transmitted power to incident power at the input- and output- interface of the EM crystal, respectively, thus, we should calibrate the physical quantities to the two prescribed interfaces. We should take away the effects due to measurement accessory, such as the antenna factor, cable losses, amplifier gain and propagation loss with the plane wave. The procedure described previously is so called as calibration in microwave measurement.

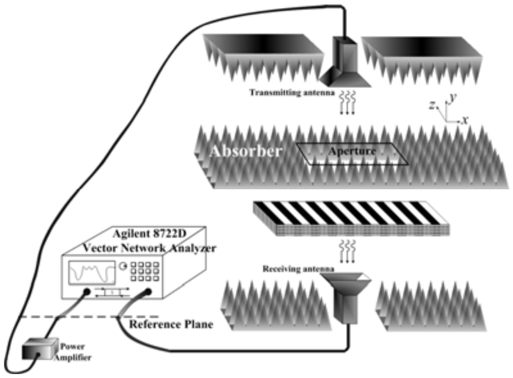

Fig.2 Electromagnetic Crystals measurement system

IV CALIBRATION PROCEDURE

As described previously, the definition of antenna factor stands for the ratio of electric field strength on the aperture to the voltage at the load of antenna. Thus, to have the electric field strength at the input- and output-surface of the sample under test, we should transform the voltage measured by the VNA (the load of antenna) into the electric field strength on the aperture of horn antennas.

Besides, the propagation loss from the aperture of antenna to the surface of sample should also be taken into account. Notice that the reference planes for the VNA are set at the end of the two flexible coaxial cables, therefore, the effects caused by cable losses and the amplifiers should be considered at the same time. In general, the electric field strength at the artificial surface away from the aperture of horn antenna is figured out by the following equation:

$$E\,(dB\,\mu V\ /\ m) = V\,(db\,\mu V\,) + A.F\,.(dB\,) + L_{cables}\ (dB\,) - G_{amplifier}\ (dB\,) + L_{propagation} \quad \ldots\ldots\ldots\ldots(1)$$

Where the E represents the electric field strength at the prescribed artificial surface, which is measured by the unit of $dB\mu V$; V is the voltage measured by the VNA, and $A.\ F.$ is the antenna factor given by the specification of the horn antennas; L_{cables} is the loss due the coaxial cables, and $G_{amplifier}$ is the gain of the amplifier; $L_{propagation}$ is the propagation loss of plane wave.

IV. EXPERIMENTAL AND NUMERICAL RESULTS

In our experiment, we have implemented two set of 1-D metal strips arrays: one for 10 mm in strip width and the other for 15 mm, however, the period retains to be 20 mm. The metal strip used in our experiment is made up of copper. These metal strips with thickness 0.06 mm are coated on the Polystyrene, which has the relative dielectric constant close to unity.

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 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 EM crystal. 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 under consideration; however, change the polarization into TM 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. This may be inferred as the statements given below.

The 2-D EM crystal typically can be regarded as the stacks of 1-D parallel-plate waveguide arrays. As we have known from the basic electromagnetic theory, the TE polarization wave has cutoff frequency; on the contrary, TM polarization can propagate down to DC. As described in the previous example, the cutoff frequency is around 6 GHz for the TE polarization, however, null for TM polarization.

In next example, we increase the number of 1-D metal strips arrays up to 4 layers and decrease the width of metal strips. 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.

In recent years, many researchers found that defects in an electromagnetic crystal can drastically change its scattering characteristics. The defect could be obtained by slightly perturbing the structure, for instance, carve out a 1-D periodic layer or change the dielectric constant in a small region in a crystal. As shown in Fig.6, it indicates that the distribution of transmittance against frequency for a defect 2-D EM crystal. This structure has a defect in the thickness of the separator, that is, the thickness of the central separator is 48 mm, different from the other ones. 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 paper, the transmission spike corresponds to the resonance frequency of the overall structure along y direction. At this frequency, the incident wave couples into the structure and again radiates into the environment (free space). Thus, if there is considerable loss in the separator, the incident power will be absorbed by the lossy medium. In a word, the transmission spike is due to the Wood's anomalous, that is, the phase matching between the incident plane wave and the guided waves supported by the defect waveguide.

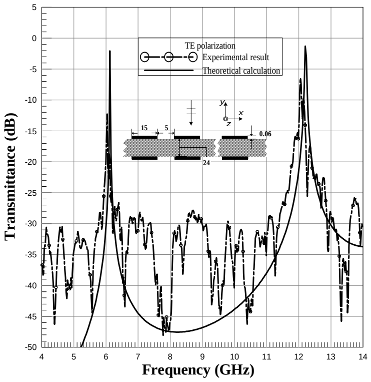

Fig.3 Variation of transmittance against frequency for both experimental measurement and theoretical calculations; TE plane wave incidence

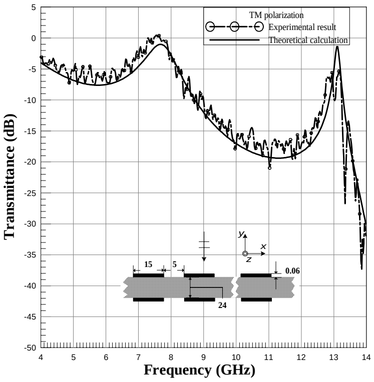

Fig.4 Variation of transmittance against frequency for both experimental measurement and theoretical calculations; TM plane wave incidence

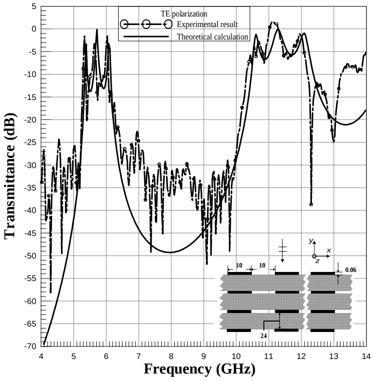

Fig.5 Variation of transmittance against frequency for both experimental measurement and theoretical calculations; TE plane wave incidence

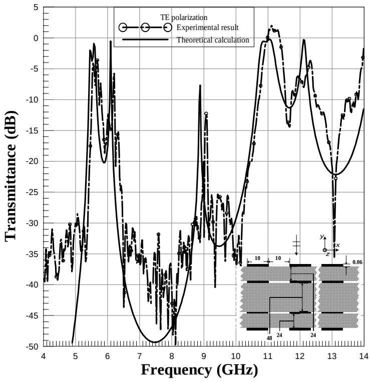

Fig.6 Variation of transmittance against frequency for both experimental measurement and theoretical calculations; TE plane wave incidence

V. CONCLUSION

In this paper, we have implemented a test fixture and the 2-D EM crystals to measure its transmittance characteristics. To compare the experimental results with the theoretical ones on the same basis, the calibration procedure was made to transform the measured voltage at the load of VNA to the electric field strength on the two outer surfaces of EM crystal. The good agreement between the measured and calculated results validates the scattering characteristics of the 2-D EM crystal. Therefore, this paper is the basis conducting to the understanding for the ultra-refraction phenomena behind an EM crystal. .

ACKNOWLEDGEMENT

I would like to thank National Science Council for sponsoring this project, the contract number is 93-2213-E-009-154.

REFERENCES

[1] T. Tamir, H. C. Wang, and A. A. Oliner, “Wave propagation in sinusoidally stratified dielectric media,” IEEE Trans. Microwave Theory Tech., vol. MTT-12, p. 323, May 1964.

[2] A. Hessel and A. A. Oliner, “A new theory of Wood’s anomalies on optical gratings,” Appl. Opt., vol. 4, pp. 1275–1297, 1965.

[3] S. T. Peng, T. Tamir, and H. L. Bertoni, “Theory of dielectric grating waveguides,” IEEE Trans. Microwave Theory Tech., vol. MTT-23, pp.123–133, Jan. 1975.

[4] C. Elach, “Wave in active and passive periodic structures: A review,” Proc. IEEE, vol. 64, pp. 1666–1698, Dec. 1976.

[5] D. Maystre, “Electromagnetic study of photonic band gaps,” Pure Appl. Opt., vol. 3, no. 6, pp. 975–993, Nov. 1994.

[6] Jordi Romeu and Yahya Rahmat-Samii, “A fractal based FSS with dual band characteristics, ”Antennas and Propagation Society. IEEE International Symposium, Vol3, pp. 1734–1737, July 1999

[7] Te-Kao Wu, “Four-band frequency selective surface with double-square-loop patch elements,” IEEE Transactions on Antennas and Propagation, Vol. 42, Issue 12, pp. 1659 – 1663, Dec. 1994.
[8] H. Y. D. Yang, J. A. Castaneda, and N. G. Alexopoulos, “An integral equation analysis of an infinite array of rectangular dielectric waveguides,” IEEE Trans. Microwave Theory Tech., vol. 38, pp. 873–880, July 1990.
[9] Ruey Bing Hwang; Song Tsuen Peng, “Guidance characteristics of two-dimensionally periodic impedance surface,” IEEE Transactions on Microwave Theory and Techniques, Vol 47, Issue 12, pp 2503 – 2511, Dec. 1999
[10] Ruey Bing Hwang; Song Tsuen Peng, “Surface-wave suppression of resonance-type periodic structures,” IEEE Transactions on Antennas and Propagation, Vol 51, Issue 6, pp1221 – 1229, June 2003
[11] D. R. Smith, W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser and S. Schultz, "Composite medium with simultaneously negative permeability and permittivity," Phys. Rev. Lett., vol. 84, no. 18, pp. 4184-4187, May 2000.
[12] J. B. Pendry, “Negative refraction makes a perfect lens,” Phys. Rev. Lett., 85, pp 3966-3969, 2000
[13] V. G. Veselago, “The electrodynamics of substances with simultaneously negative values of ε and μ, Sov Phys Usp , pp 509–514, 1968
[14] Ruey Bing Hwang, “Relations Between the Reflectance and Band Structure of 2-D Metallodielectric Electromagnetic Crystals,” IEEE Transactions on Antennas and Propagation, Vol 52, Issue 6, pp 1454 – 1464, June 2004