Efficient circuit models for extraordinary transmission structures

F. Medina[1], F. Mesa[2], and R. Rodríguez-Berral[2]

[1]Microwaves Group, Department of Electronics and Electromagnetism, University of Seville
41012, Seville, Spain
Fax: + 34-954239434; email: medina@us.es
[2]Microwaves Group, Department of Applied Physics I, University of Seville
41012, Seville, Spain
Fax: + 34-954239434; email: mesa@us.es, rrberral@us.es

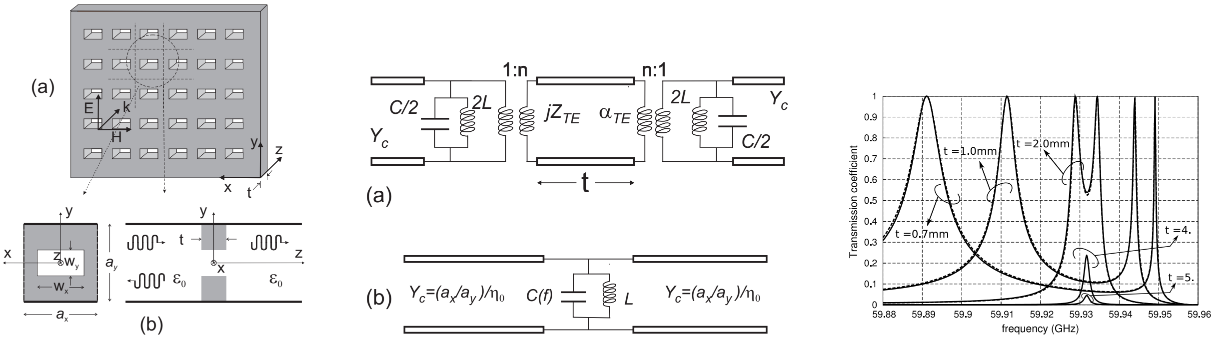
Abstract

In this contribution we review the application of circuit modeling techniques to the characterization of extraordinary transmission through metal screens perforated with periodic arrays of subwavelength apertures . A number of practical situations are analyzed using quasi-analytical and fully analytical models. The method provides an in-depth understanding of the underlying physics as well as accurate values of the transmissivity, reflectivity, and absorptivity of this kind of structures. Free-standing and dielectric loaded metal screens are considered.

1. Introduction

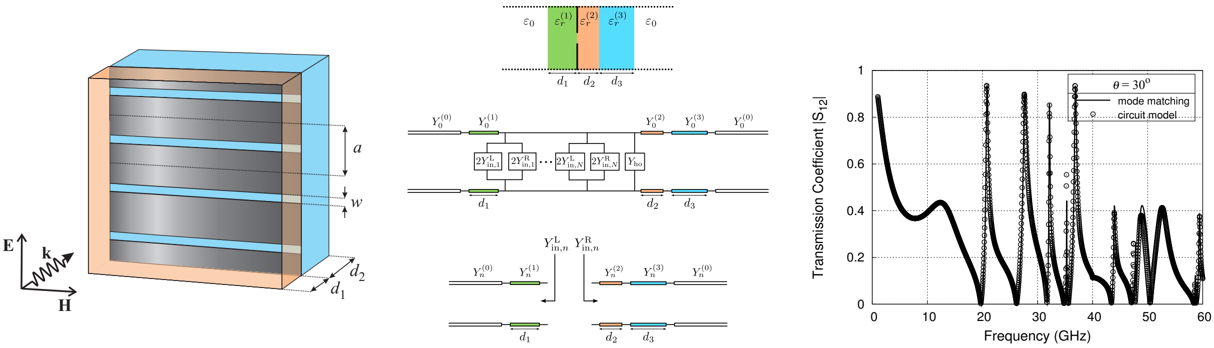
The study of the extraordinary transmission (ET) of electromagnetic waves through periodically distributed sub-wavelength apertures has been a hot topic during the last fourteen years (since the discovery of the phenomenon by T. W. Ebbesen and coworkers [1]). Presently, the phenomenon is well understood and a number of comprehensive and valuable reviews on the topic are available [2, 3, 4]. Surface plasmon-polaritons (SPP) are considered key in the explanation of the presence of exotic transmission peaks in the transmission and reflection spectra of opaque screens periodically perforated with subwavelength apertures. Thus, from the knowledge of the dispersion curves of those surface waves linked to the structured metal surfaces (sometimes called *spoof* plasmons [5]), it is possible to understand the frequency behavior of the observed transmission/reflection spectra. Nevertheless, an alternative point of view has arisen in the last few years that leads to a very simple and systematic modeling of the kind of periodic structures under consideration. A quasi-analytical circuit model based on a microwave engineering approach was first proposed by some of the authors in [6]. This model accounts for ET through periodic arrays of sub-wavelength holes made in thin/thick perfectly conducting plates. Even the most fine details of numerically obtained spectra are reproduced by the analytical circuit model. This is possible using a reduced set of circuit parameters that are known in closed form or extracted from data numerically generated for a few frequency points. These parameters are independent of the selected frequency samples. This methodology was soon extended to deal with simple/compound one-dimensional metallic gratings [7], and it was used to predict ET in non-periodic systems without surface plasmons (such as small diaphragms inside hollow-pipe waveguides [8]). The influence of the presence of dielectric slabs (first studied in [9]) has recently been incorporated to the circuit model approach [10, 11] as well as the effects of non-perfect conductors [12]. This modeling technique has also been used by other authors to solve electromagnetic problems of similar features (see, for instance [13, 14, 15, 16]). The purpose of this work is to provide an overview of the state of the art of the application of circuit modeling methods to the analysis of ET and related structures. Advantages and limitations of this modeling strategy will be highlighted in the presentation.

ISBN 978-952-67611-2-1



(a) Structure (b) Equivalent circuit (c) Typical results

Fig. 1: (a) A typical ET perforated metal screen, (b) its equivalent circuit model, and (c) typical set of results showing the comparison between numerical and analytical data (solid and dashed lines). This analysis was first reported in [6].



(a) Structure (b) Equivalent circuit (c) Typical results

Fig. 2: (a) A subwavelength-slits periodic structure loaded with dielectric slabs, (b) its circuit model, and (c) typical set of results. The analytical data (solid lines) perfectly accounts for numerical data (circles) generated using a very accurate mode matching solution. This type of models are described in [11].

2. Circuit models for periodic structures

As mentioned above, a number of ET structures have been characterized by means of simple circuit-like analytical models with a high degree of success. In Fig. 1 and Fig. 2 we show a couple of examples of the type of structures and models here considered. Figure 1 shows an example of a free-standing metal structure. In particular, it is shown the periodic structure and the basic unit cell as well as a suitable circuit model and a set of typical results. The circuit model results are compared with full-wave numerical calculations. After determining the circuit parameters, extremely accurate analytical results are obtained accounting for very fine details of the transmission spectra, as it can be seen in Fig. 1(c). In Fig. 2 an array of subwavelength slits sandwiched between dielectric slabs is considered. The circuit model and an example of transmission spectrum are also shown. In this case, all the parameters of the circuit models can be obtained in closed form. This is possible for parallel and perpendicular polarizations, and for narrow slits (as in the example) or narrow strips, both for normal and oblique incidence. The influence of the dielectric slabs, which drastically modify the spectra, is incorporated in the model in a very simple manner. Moreover, the circuit model provides a very convenient physical insight to understand all the details of the computed complicated spectra. This methodology can also be extended to 2D arrays of simple planar scatterers (such as dipoles or patches), but in this case some of the parameters have to be extracted from a few numerically generated scattering parameter samples. Several other cases will be considered in the presentation.

3. Conclusion

Circuit models are proposed to explain the behavior of the transmission spectra through metal screens perforated with periodical distributions of subwavelength slits or holes. Excellent qualitative and quantitative agreement is observed between analytical (or quasi-analytical) models and numerical calculations. The models have been successfully applied to explain a wide variety of physical situations, which are expected to be extended in forthcoming works. These models do not only provide useful practical tools to design devices based on periodic structures but an in-depth physical insight on the behavior of such electromagnetic systems.

Acknowledgements

This work has been funded by the Spanish Ministry of Science and Innovation with European Union FEDER funds (projects TEC2010-16948 and CSD2008-00066) and by the Spanish Junta de Andalucía (project TIC-4595).

References

[1] T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolff, Extraordinary optical transmission through sub-wavelength hole arrays, *Nature*, vol. 391, pp. 667-669, 1998.
[2] C. Genet and T. W. Ebbesen, Light in tiny holes, *Nature*, vol. 445, pp. 39-46, 2007.
[3] F. J. García-de-Abajo, Colloquium: Light scattering by particle and hole arrays, *Rev. Modern Phys.*, vol. 79, pp. 1267-1290, 2007.
[4] F. J. García-Vidal, L. Martín-Moreno, T. W. Ebbesen, and L. Kuipers, Light passing through subwavelength apertures, *Rev. Mod. Phys.*, vol. 82, pp. 729-787, 2010.
[5] J. B. Pendry, L. Martín-Moreno, and F. J. Garcia-Vidal, Mimicking surface plasmons with structured surfaces, *Science*, vol. 305, pp. 847-848, 2004.
[6] F. Medina, F. Mesa, and R. Marqués, Extraordinary transmission through arrays of electrically small holes from a circuit theory perspective, *IEEE Trans. Microw. Theory Tech.*, vol. 56, no. 12, pp. 3108-3120, 2008.
[7] F. Medina, F. Mesa, D. C. Skigin, Extraordinary transmission through arrays of slits: a circuit theory model, *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 1, pp. 105-115, 2010.
[8] F. Medina, F. Mesa, J. A. Ruíz-Cruz, Jesús M. Rebollar, and J. R. Montejo-Garai, Study of extraordinary transmission in a circular waveguide system, *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 6, pp. 1532-1542, 2010.
[9] V. Lomakin and E. Michielssen, "Enhanced transmission through metallic plates perforated by arrays of subwavelength holes and sandwiched between dielectric slabs," *Phys. Rev. B*, vol. 71, p. 235117, 2005.
[10] R. Rodríguez-Berral, F. Medina, F. Mesa, Circuit model for a periodic array of slits sandwiched between two dielectric slabs, *Appl. Phys. Lett.*, vol. 96, p. 161104, 2010.
[11] R. Rodríguez-Berral, F. Medina, F. Mesa, M. Carcía-Vigueras, Quasi-analytical modeling of transmission/reflection in strip/slit gratings loaded with dielectric slabs, *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 3, pp. 405-418, 2012.
[12] R. Yang, R. Rodríguez-Berral, F. Medina, and Y. Hao, Analytical model for the transmission of electromagnetic waves through arrays of slits in perfect conductors and lossy metal screens, *J. of. Appl. Phys.*, vol. 109, p. 103107, 2011.
[13] A. Khavasi and K. Mehrany, Circuit model for lamellar metallic gratings in the sub-wavelength regime, *IEEE J. of Quantum Elect.*, vol. 47, no. 10, pp. 1330-1335, 2011.
[14] M. Beruete, M. Navarro-Cía, S. A. Kuznetsov, and M. Sorolla, Circuit approach to the minimal configuration of terahertz anomalous extraordinary transmission, *Appl. Phys. Lett.*, vol. 98, p. 014106, 2011.
[15] M. Beruete, M. Navarro-Cía, and M. Sorolla, Understanding anomalous extraordinary transmission from equivalent circuit and grounded slab concepts, *IEEE Trans. Microw. Theory Tech.*, vol. 59, no. 9, pp. 2180-2188, 2011.
[16] C. Argyropoulos, G. D'Aguanno, N. Mattiucci, N. Akozbek, M. J. Bloemer, and A. Alu, Matching and funneling light at the plasmonic Brewster angle, *Phys. Rev. B*, vol. 85, p. 024304, 2012.