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Halim Boutayeb, Tayeb Denidni, Abdelrazik Sebak, Larbi Talbi. Band Structure Analysis of Crystals with Discontinuous Metallic Wires. IEEE Microwave and Wireless Components Letters, 2005, 2005, vol. 15, no7, pp. 484-486. <hal-00149259>

HAL Id: hal-00149259

<https://hal.science/hal-00149259v1>

Submitted on 25 May 2007

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Band Structure Analysis of Crystals with Discontinuous Metallic Wires

Halim Boutayeb, *Member, IEEE*, Tayeb A. Denidni, *Senior Member, IEEE*, Abdel Razik Sebak, *Senior Member, IEEE*, and Larbi Talbi, *Member, IEEE*

Abstract—The band structure for normal propagation of crystals with finite straight metallic wires is studied for different wire diameters and lengths. The crystal is considered as a set of parallel grids. Dispersion characteristics are obtained by using a transmission line model where the parameters are calculated from the reflection and transmission coefficients of the grids. These coefficients are computed rigorously with a Finite Difference Time Domain (FDTD) code. Simulated and experimental results for two structures with the dual behavior, pass-band and stop-band, are presented. This study have potential applications in electrically controlled microwave components.

Index Terms—Metallic crystals, band structure, periodic structures

I. INTRODUCTION

RECENTLY, the propagation of electromagnetic waves in periodic structures has received important interest [1]. Potential applications have been suggested in microwave and antenna domains, such as suppressing surface waves [2], designing directive antennas [3], or creating controllable beams [4,5].

The propagation of waves in periodic structures is described by means of a band theory. Different methods have been proposed for computing the band structure of a periodic structure, *e.g.*, the average field method [6], the order- N method [7], and a hybrid plane-wave-integral-equation method [8]. A particular interest has been given to the dispersion characteristics of periodic structure formed by infinitely long metallic wires [1-10]. To our knowledge, the band structure of periodic materials with finite straight wires have not been studied enough. These materials are interesting for designing reconfigurable microwave components. In [5], the authors have proposed to commute between continuous and discontinuous wire structures for reconfiguring the radiation patterns of an antenna. Indeed, these two structures behave differently at low frequencies, by presenting a pass-band and a stop-band for discontinuous and continuous wires cases, respectively. To obtain the commutation, the authors have placed periodically diodes in the broken wires. When the diodes are switched on, the structure behaves as a continuous wire medium, if the impedance of the diodes are neglected, whereas when the diodes are switched off, the structure behaves as a discontinuous wire medium. However, the band structure of the discontinuous

wire medium for different wire diameters and lengths have not been studied enough.

In this contribution, numerical results are presented for the pass-bands and stop-bands of these 3-D periodic structures, at normal incidence. To compute the propagation constant, a transmission line model is used, where a 2-D periodic structure (grid) of discontinuous wires is modelled by a T-circuit. The T-circuit parameters are written in terms of the S-parameters of the grid, computed rigorously using the FDTD method. Experimental results for two structures with the dual behavior of their bands are also presented.

II. TRANSMISSION LINE MODEL AND FDTD METHOD

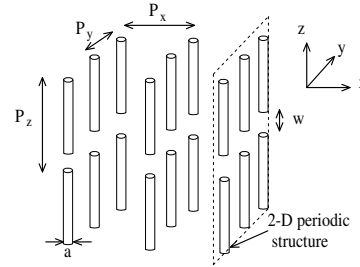


Fig. 1. Infinite 3-D periodic structure of discontinuous metallic wires in air.

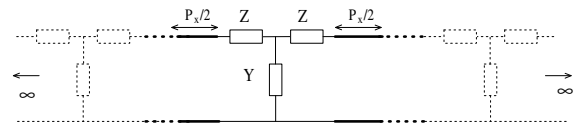


Fig. 2. Transmission line model of the periodic structure.

The infinite 3-D periodic structure of perfect metallic wires shown in Fig. 1 is considered. Its parameters are the periods P_x , P_y and P_z , the wire diameter a and the width w . The propagation of the transverse Electric field in x -direction is considered. To compute the propagation constant β_x , the transmission line model shown in Fig. 2 is used, where a 2-D periodic structure in y -direction (see Fig. 1) is modelled by a T-circuit. The propagation constant β_x of this transmission line is obtained from its well known dispersion equation, which is written [11]

$$\cos(\beta_x P_x) = (1 + ZY) \cos(kP_x) + j \left(Z + \frac{Y}{2} (1 + Z^2) \right) \sin(kP_x) \quad (1)$$

Manuscript received November 2004. This work was supported in part by the National Science Engineering Research Council of Canada (NSERC).

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where k is the free space wave number. The expressions for Y and Z are derived in terms of the complex reflection and transmission coefficients r and t of the 2-D periodic structure, at normal incidence. By converting the chain matrix of the T-circuit to the S matrix, r and t can be expressed in terms of Z and Y . After inverting these relations, Z and Y are written as functions of r and t

$$Y = \frac{(r - t - 1)(r + t - 1)}{2t} \quad (2)$$

$$Z = \frac{-r + t - 1}{r - t - 1} \quad (3)$$

In this work, r and t coefficients are computed rigorously with the FDTD method, where Floquet boundaries conditions and a thin mesh ($\Delta = \text{Period}/80$) are used. It should be noted that the T-circuit model gives more precise results than the simple circuit using only the admittance Y . Indeed, the impedance Z is negligible for thin wire, but it is not for thick wire. Only the fundamental mode is considered, then the limitations $P_y \leq P_x$, $P_x \leq \lambda$ and $P_z \leq \lambda$ are used.

III. RESULTS

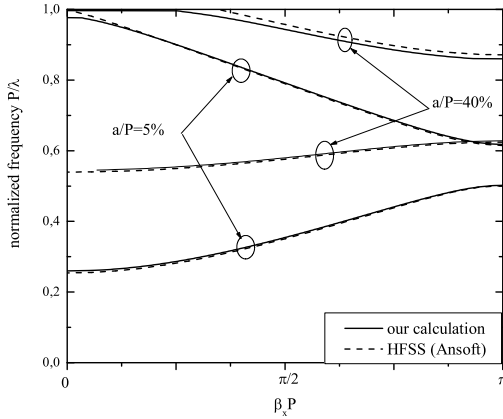


Fig. 3. Comparison of the dispersion diagrams calculated with the present method and obtained with a Finite Element method (HFSS-Ansoft), which considers all modes. A good agreement is observed between the results for both thin and thick wires. Fig. 4 shows the dispersion diagrams of structures with continuous ($P_x = P_y = P$, $a/P = 5\%$) and discontinuous ($P_z = P$, $w/P_z = 5\%$) wires. The dual behavior in the pass-band and stop-band of these structures is nearly obtained in the two first bands. The limits of the two first bands of these structures are now studied for different wire lengths and diameters. We consider $P_x = P_y = P$. We consider three values of the period in z -direction, $P_z = P$, $P_z = 2P$ and $P_z = P/2$.

To validate the method, Fig. 3 presents the computed propagation constants for a continuous wire medium ($w = 0$) compared with the results of a Finite Element method (HFSS-Ansoft), which considers all modes. A good agreement is observed between the results for both thin and thick wires. Fig. 4 shows the dispersion diagrams of structures with continuous ($P_x = P_y = P$, $a/P = 5\%$) and discontinuous ($P_z = P$, $w/P_z = 5\%$) wires. The dual behavior in the pass-band and stop-band of these structures is nearly obtained in the two first bands. The limits of the two first bands of these structures are now studied for different wire lengths and diameters. We consider $P_x = P_y = P$. We consider three values of the period in z -direction, $P_z = P$, $P_z = 2P$ and $P_z = P/2$.

Fig. 5 presents the limits of the two first bands for continuous and discontinuous cases versus the fill factor a/P , for different

widths w . To obtain a dual behavior in the first band, the lower limits of stop-band for discontinuous wires and pass-band for continuous wires must match. In addition, to obtain the dual behavior in the second band, the upper end of stop-band for discontinuous wires must match with the upper end of pass-band for continuous wires. To satisfy these conditions, for small diameter, the width must be near 5% of the period. When the diameter increases, the width should be increased.

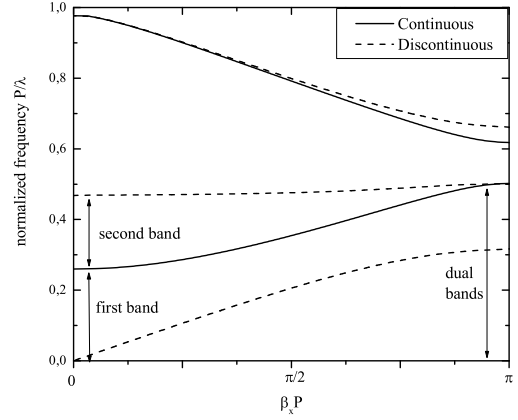


Fig. 4. Dispersion diagrams for structures with continuous wires ($a/P = 5\%$) and discontinuous wires ($P_z = P$, $w/P = 5\%$).

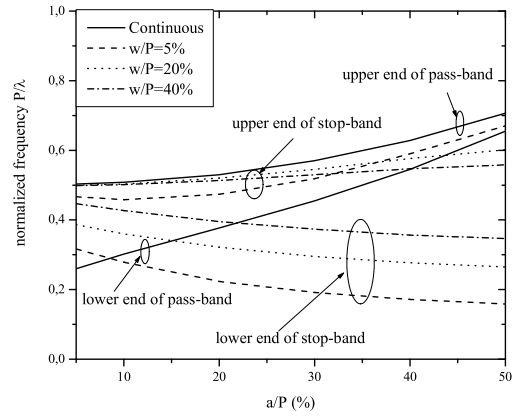


Fig. 5. Two first bands limits for structures with continuous and discontinuous wires ($P_z = P$) versus fill factor a/P , for different widths w/P .

Fig. 6 presents the same diagrams as that of Fig. 5 for the case $P_z = 2P$ (within the range $P/\lambda \leq 0.5$). From these curves, it can be seen that is difficult to obtain the dual behavior in both the first and second bands. To match the first bands, the width w must be very large ($w/P > 40\%$).

Fig. 7 presents the same diagrams as in Fig. 5 but for $P_z = P/2$. For this case, for thin wires, to match the first band limits, the width w must be very small ($w/P < 2.5\%$), whereas the second limits can be matched more easily.

The results presented in Figs. 5 to 7 are useful for the design

of two structures with the dual behavior in their bands.

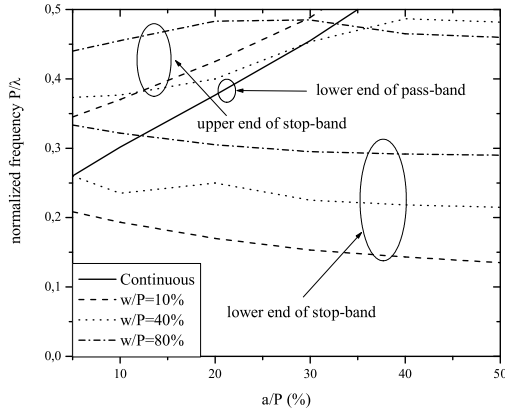


Fig. 6. Two first bands limits for structures with continuous and discontinuous wires ($P_z = 2P$) versus fill factor a/P , for different widths w/P .

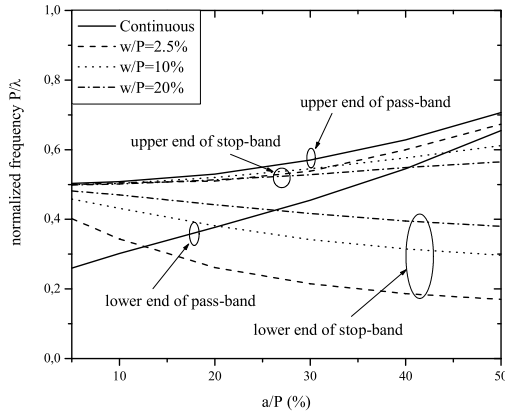


Fig. 7. Two first bands limits for structures with continuous and discontinuous wires ($P_z = P/2$) versus fill factor a/P , for different widths w/P .

To validate the proposed model, two structures with five rows in x -direction were fabricated (with wood supports) and their transmission coefficients were measured in an anechoic chamber using two horn antennas and a network analyzer. The fabricated structures have the finite dimensions $L_z = 280\text{mm}$ and $L_y = 600\text{mm}$ and the following parameters: $P_z = P = 40\text{mm}$, $a = w = 2\text{mm}$. The frequency range is 1GHz – 4.5GHz . The structures were at the distances 40m and 2mm from the transmitter and the receiver, respectively (at 2mm the evanescent waves are negligible, this distance has been chosen to avoid edge effects). A measurement without the structures was carried out for the normalization. For comparison, numerical simulations (FDTD) for the transmission coefficients were also carried out. Fig. 8 presents the simulated and measured transmission coefficients of the continuous and discontinuous wires structures, illustrating the dual bands. The simulated and experimental results are slightly different because of the finite dimensions of the fabricated structures.

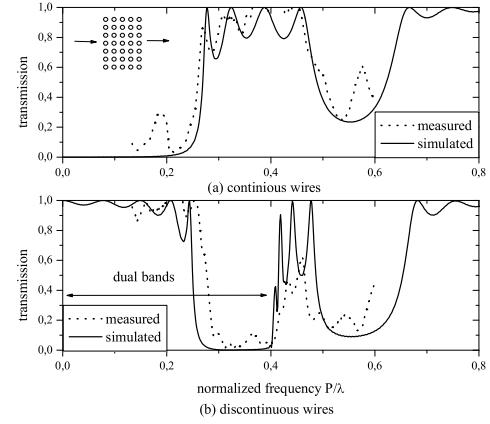


Fig. 8. Simulated (FDTD) and measured transmission coefficients for two structures with five rows of : (a) continuous wires ($a/P = 5\%$) and (b) discontinuous wires ($P_z = P$, $w/P = 5\%$).

IV. CONCLUSION

The band structure for normal propagation of crystal formed by discontinuous metallic wires has been analyzed for different wire diameters and lengths. To compute the propagation constant, the transmission line model and the T-circuit model have been used. The proposed approach has been validated with experimental results. The obtained results are useful for the design of two structures with the dual behavior of their band characteristics that can be used for controllable antennas applications.

REFERENCES

- [1] K. Sakoda, *Optical Properties of Photonic Crystal*, ser. Opt. Sci. Berlin, Germany: Springer, 2001, vol. 80.
- [2] F. Yang and Y. Rahmat-Samii, "Microstrip antennas integrated with electromagnetic bandgap (EBG) structures: a low mutual coupling design for array applications", *IEEE Trans. on Antennas and Propagation*, vol. 51, pp. 2936-2946, Oct. 2003.
- [3] M. Thevenot, C. Cheypre, A. Reineix and B. Jecko, "Directive Photonic Band-Gap Antennas", *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 2115-2122, Nov. 1999.
- [4] J.M. Lourtioz, A. De Lustrac, F. Gadot, S. Rowson, A. Chelnokov, T. Brillat, A. Ammouche, J. Danglot, O. Vanbesien, and D. Lippens, "Toward controllable photonic crystals for centimeter and millimeter wave devices", *Journal of Lightwave Technology*, vol. 17, pp. 2025-2031, Nov. 1999.
- [5] G. Poilasne, P. Pouliguen, K. Mahdjoubi, L. Desclos and C. Terret, "Active Metallic Photonic Band-Gap materials (MPBG): experimental results on beam shaper", *IEEE Trans. on Antennas and Propagation*, vol. 48, pp. 117-119, Jan. 2000.
- [6] C.R. Simovski, M. Qiu and S. He, "The average field approach for obtaining the band structure of crystals with conducting wire inclusions", *Journal of Electromag. Waves and Appl.*, vol. 14, pp.449-468, 2000.
- [7] C.T. Chan, Q.L. Yu, and K.M. Ho, "Order-N method spectral method for electromagnetic waves", *Phys. Rev. B, Condens. Matter*, vol. 51, pp. 16635-16642, 1995.
- [8] M. Silveirinha and C. A. Fernandes, "A Hybrid method for the efficient calculation of the band structure of 3D-metallic crystal", *IEEE Trans. Microw. Theory and Techn.*, vol. 52, pp. 889-902, March 2004.
- [9] S. Tretyakov, *Analytical modeling in applied electromagnetics*, Artech House, INC., Norwood, 2003.
- [10] C. A. Moses and N. Engheta, "Electromagnetic wave propagation in the wire medium: a complex medium with long thin inclusions", *Wave Motion*, vol. 34, pp. 301-317, Sept. 2001.
- [11] S. Silver, *Microwave Antenna Theory and Design*, McGraw-Hill Book Co., Inc., New York, N.Y., p. 315, 1949