Z. Li, J. Volakis, P. Papalambros, "Performance Enhancement of Bandgap Printed Antennas Using Finite Element Method and Size/Topology Optimization Methods" Millenium Conference on Antennas and Propagation (AP2000), Davos, Switzerland, Digest pp. 456-457, April 2000

Performance Enhancement of Bandgap Printed Antennas Using Finite Element Method and Size/Topology Optimization Methods

Zhifang Li(1), John L. Volakis(1), Panos Y. Papalambros(2)

Radiation Laboratory, EECS Department, University of Michigan
Ann Arbor, MI 48109-2122, USA
Email: zhifang@eecs.umich.edu, volakis@eecs.umich.edu

Optimal Design Laboratory, MEAM Department, University of Michigan
Ann Arbor, MI 48109-2125, USA
Email: pyp@engin.umich.edu

INTRODUCTION

Photonic bandgap (PBG) antennas consist of printed elements on perforated (usually periodic) substrates and have shown improved performance over uniform substrates. More specifically, PBGs can increase gain and bandwidth and reduce loss. However, design approaches for these antennas have yet to be developed and furthermore there is great interest for a better understanding of bandgap structures and more generally for frequency selective volumes.

This paper considers an optimization method for the design of bandgap substrates associated with the radiation of printed antenna. A goal is to develop optimal values for the length/width of the circular/rectangular perforations. This will be achieved by employing size optimization.

Performance enhancement can further be achieved by applying topology optimization methods such as the density and homogenization design methods in conjunction with antenna simulators based on the finite element and sequential quadratic programming method or genetic algorithms. These methods could be combined to find the size and shape of holes and/or the material distribution of the hole region for optimal performance. Theoretically, there is no restriction on the topology of the substrate, and these holes might be of arbitrary shape and with any possible periodicity or topology.

In this paper, theories on topology optimization for optimal material distribution will be introduced and a numerical example for a simplified optimization problem on bandgap patch antennas will be given.

TOPOLOGY OPTIMIZATION TECHNIQUES

An antenna optimization problem is to obtain the optimal configuration which satisfies the prescribed performance subject to some limitations and constraints. Numerical analysis (such as finite element method) can be combined with optimization methods to carry out such kind of problems [1]. Many optimization techniques, such as genetic algorithms and linear/quadratic programming methods, have been developed to solve specific kinds of problems. For PBG antennas, the desired goal is to compute the material distribution in the dielectric substrate. Therefore, topology optimization methods are necessary to perform this task.

In the topology optimization methods, the design domain is discretized into finite elements and each finite element is viewed as one or more microstructures, as shown in Fig. 1. A microstructure can be expressed as void, porous, or solid depending on the hole size of the microstructure. On the basis of the homogenization design method (HDM) [2], the homogenized value of the material constant for each finite element is first computed on the basis of its microstructures in each iteration. In contrast, when employing the density method, the material constants of the microstructures need not be homogenized. These topology optimization methods allow for completely arbitrary and novel designs. They have already been very successful in structural optimization problems in automotive and magnetostatics designs [3]. In this paper, we will present a PBG patch antenna design in a simplified design domain. That is, each finite element consists of only one microstructure with circular hole, and all holes in the design domain have identical size and spacing. This reduces the design problem from topology optimization to size optimization.

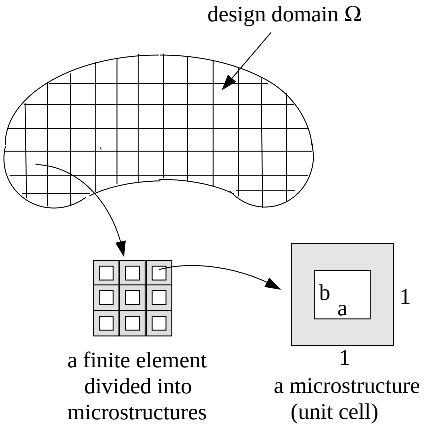

Fig. 1. Microstructures in a design domain.

BANDWIDTH ENHANCEMENT DESIGN

Microstrip antennas on high dielectric-constant substrates can have smaller antenna size than those on low dielectric-constant substrates, but there is a sacrifice of low efficiency and narrow bandwidth. Several methods have been proposed to solve this problem, one of which, as shown in Fig. 2, is to use closely spaced holes underneath and around the microstrip antenna, thus lowering the effective dielectric constant. Several patch antennas have been fabricated based on micromaching techniques and bandwidth improvement for these antennas has been observed [4].

In this paper, a finite element boundary-integral (FE-BI) method [5] is used to model such a cavity backed patch antenna with perforated substrate. The synthesized dielectric constant ε_{rsynth} for the PBG region is proportional to the volume of the removed substrate, and the high-index material surrounding the PBG has a dielectric constant ε_r. Therefore, the substrate inside the cavity can be viewed as having a uniform ε_{rsynth} for the PBG region and a value of ε_r for the region surrounding the PBG portion of the substrate.

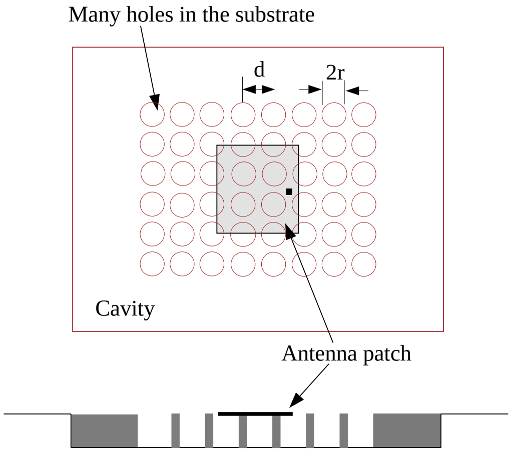

Fig. 2. Geometry of the composite substrate with many holes: top and side view.

Numerical Examples

The objective of our design is to find the optimal size of the hole in PBG region to maximize the bandwidth of the PBG antenna, while maintaining the resonant frequency in the vicinity of 12.0-13.0 GHz. Therefore, when a certain percent of the substrate volume is removed, the synthesized permittivity could be computed, and the length and width of the patch needs to be adjusted accordingly in order to maintain the resonant frequency. There is also a need to constraint the dielectric volume size, i.e. the maximum percent of volume that is allowed to be removed. During the design process, the thickness of the substrate is kept at $h = 0.0635$ cm and the dielectric surrounding the PBG region has a fixed $\varepsilon_r = 10.8$, the hole spacing is set at $d = 0.07$ cm, and other parameters such as patch size and hole diameter are subject to change during each iteration.

If the volume constraint is 80%, i.e. at most that much of the volume is allowed to be removed from the substrate, a printed antenna with $L = 0.7$ cm and $W = 0.9$ cm residing in a cavity of 2.7 cm by 3.3 cm is obtained. The hole region is 1.3 cm by 1.7 cm. Each hole has a diameter of $2r = 0.06$ cm and spacing of $d = 0.07$ cm. The resulting ε_{rsynth} is about 2.3 [4]. This antenna has a resonant frequency of 12.42 GHz from the FEM simulation.

If we increase the volume constraint to 100%, the optimization process results in a suspended patch residing over an air region of 1.6 cm by 1.8 cm. The patch has a size of $L = 1.0$ cm and $W = 1.2$ cm residing in a cavity of 3.0 cm by 3.6 cm. In both the above two cases, the optimized patch has the maximally allowed volume removed, which means that the optimization results in boundary optima. This is reasonable because for periodic PBG substrates, the more is volume removed, the larger the bandwidth.

To compare the performance of the optimized patches, we modeled two other cavity backed patch configurations with uniform substrate. The dimensions of the four antennas are shown in Table 1. All of them are designed to have a resonant frequency close to 13.0 GHz. The patches are fed with a single probe feed which is adjusted to make the impedance matched to approximately 100 Ω.

Table 1: Dimensions of the three patch antennas

Patch	Homogeneous $\varepsilon_r = 2.2$	Homogeneous $\varepsilon_r = 10.8$	PBG substrate 80% removed	PBG substrate 100% removed
L (cm)	0.74	0.33	0.7	1.0
W (cm)	0.91	0.47	0.9	1.2
thickness (cm)	0.0635	0.0635	0.0635	0.0635
cavity (cm^2)	2.22 x 2.73	0.99 x 1.41	2.7 x 3.3	3.0 x 3.6
resonant freq. (GHz)	12.18	11.75	12.42	13.04

The calculated reflection coefficients for the above three antennas are shown in Fig. 3. It is seen that the two ‘regular’ patches with $\varepsilon_r = 2.2$ and $\varepsilon_r = 10.8$ have a typical -10 dB bandwidth of 2.95% and 1.19%, respectively, with the former wider than the latter as expected. The bandwidth of the patch with $\varepsilon_{rsynth} = 2.3$ substrate increases to 3.53%, a 200% increase over the -10 dB bandwidth of the regular patch with $\varepsilon_r = 10.8$. And the bandwidth of the suspended patch has a slightly wider bandwidth of 3.69%.

The above examples are optimal for pure periodic PBG structures. In the meeting, optimized results on aperiodic substrates and structures with multiple layers of different periodicities will be presented. The shape of the metal patch will also be optimized subject to radiation criteria on bandwidth, beamwidth, etc.

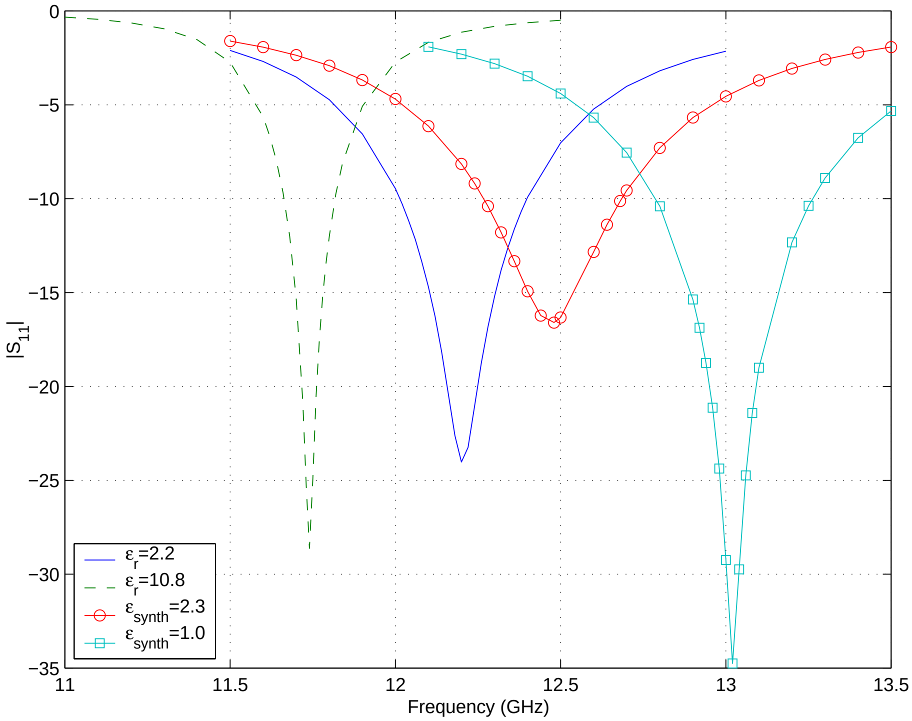

Fig. 3. Computed reflection coefficient for the three antennas in Table 1.

CONCLUSION

A topology method for the material distribution problem of PBG patch antennas is introduced, and a simplified numerical example is presented to demonstrate that perforated dielectric substrate produce a significant bandwidth increase.

REFERENCES

[1] Zhifang Li, P.Y. Papalambros, and J.L. Volakis, "Designing broadband patch antennas using the sequential quadratic programming method," *IEEE Trans. Antennas Propagat.*, vol. 45, no. 11, pp. 1689-1692, November 1997.

[2] M.P. Bendsoe and N. Kikuchi, "Generating optimal topologies in structural design using a homogenization method," *Comput. Methods. Appl. Mech. Eng.*, vol. 30, no. 6, pp. 4296-4298, 1994.

[3] J. Yoo, N. Kikuchi and J.L. Volakis, "Structural optimization in magnetic fields using the homogenization design method," *IEEE Transactions on Magnetics*, in printing.

[4] G.P. Gauthier, A. Courtay, and G.M. Rebeiz, "Microstrip antennas on synthesized low dielectric-constant substrates,", *IEEE Trans. Antennas Propagat.*, vol. 45, no.8, pp.1310-1314, August 1997.

[5] J. Jin and J.L. Volakis, "A hybrid finite element method for scattering and radiation by microstrip patch antennas and arrays residing in a cavity," *IEEE Trans. Antennas Propagat.*, vol. 39, no. 11, pp. 1598-1604, November 1991.