Advances in EBG-resonator antenna research

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1. Introduction

Electromagnetic Band-Gap (EBG) materials can be successfully employed to improve the performances of antennas [1], [2]. When used as planar reflectors, as substrates, or as high-impedance ground-planes, they are able to eliminate the drawbacks of conducting ground-planes, to prevent the propagation of surface waves, also allowing a lowering of the antenna profile, and to improve the radiation efficiency. In EBG resonator antennas, instead, an EBG is employed as a superstrate on a primary radiator, backed with a ground plane, and its main effect is a considerable increase in the directivity [3]. It is also possible to obtain a highly-directive antenna by embedding a source in an EBG working near its band-gap edge, thanks to the limited angular propagation allowed.

In this work, we present new results and ideas on EBG resonator antennas. In particular, we refer to radiating structures constituted by a woodpile superstrate and a patch antenna. The woodpile is a three-dimensional EBG with a rather simple geometry, that may present complete 3D stop-bands. In EBG resonator antennas, the EBG cover has to be put at a distance equal to an integer multiple of half a wavelength from the source; as a result the forward radiation is remarkably enhanced by means of in-phase multiple reflections. EBG resonator antennas are a good alternative to aperture antennas, as parabolic antennas or lenses, or to antenna arrays, since they do not present some problems inherent to the usual directive systems, such as the size of the focal structures, or the limitations or complications induced by the feeding circuit of arrays.

In Section 2 we describe the antenna studied in this paper. Section 3 is devoted to experimental and numerical results; moreover suggestions for future investigations are given. Conclusions are drawn in Section 4.

2. EBG resonator antenna with woodpile superstrate

We design the superstrates of our EBG resonator antennas by using an in-house code implementing the Fourier Modal Method (FMM), a full-wave approach that solves the monochromatic plane-wave scattering problem by dielectric finite-thickness crossed gratings, as proposed in [4].

In this paper, the superstrate is always a woodpile, consisting of four periodic layers of alumina rods, with square section having side length w = 3.18 mm. The relative dielectric constant of the rods is $\varepsilon_{r,al}$ = 9.8. The spacing of each layer is d = 8 mm. Rods belonging to consecutive layers are orthogonal. In the third and fourth layers, the rods have the same orientation as in the first and second ones, respectively, but they are in offset by half of the horizontal spacing. The unit-cell of the structure is schematized in Fig. 1(a). When a monochromatic plane-wave, with electric/magnetic field parallel to the rods, impinges normally on this crystal, a band-gap centred on f = 12 GHz is observed, extending over almost 4 GHz (results are not reported here for the sake of brevity). A slight reduction in depth and width of this stop-band is observed if the off-plane behaviour of the woodpile is studied, however the structure reveals to be scarcely sensitive to variations of both incidence direction and field polarization.

Woodpile samples have been realized, see Fig. 1(b). The rod length is 25d = 20 cm, i.e., almost seven wavelengths at 10 GHz. The diameter tolerance of the rods is ±3%, the straightness is represented by a camber/length parameter 0.003, and the maximum twist is 2 degrees per 30.48 cm.

A microstrip antenna has also been realized, from a 0.76 mm thick Rogers/RT Duroid 5870 layer (relative permittivity 2.33), printed on both sides with 36-µm thick copper. With a PC-controlled milling table, on one side of the layer a 8 mm × 8.4 mm rectangular patch has been cut.

The antenna is fed from below by a coaxial probe (SMA connector): the feed point, where the probe is attached to the patch, is centred with respect to the shorter side of the patch, and it is 1.2 mm away from the centre of the longer side. The antenna resonates at 10.3 GHz. At this frequency, the magnitude of its return loss is $|S_{11}| = -11.69$ dB and its maximum gain is $G_p = 6.18$ dB.

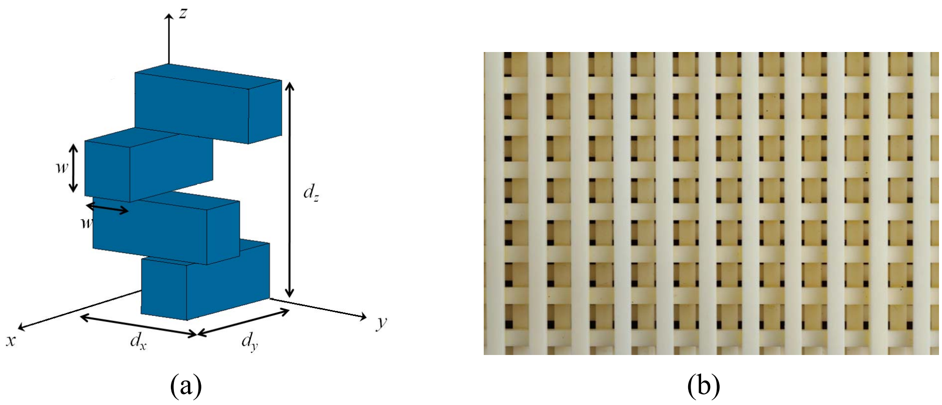

Fig. 1 – (a) Geometry of the woodpile unit-cell. (b) Picture of a woodpile prototype.

3. Results

In this Section, we present a selection of new numerical and experimental results on EBG resonator antennas with woodpile superstrate, and we discuss some new ideas. All our experiments have been performed in a 3.20 m × 3.20 m × 2.70 m shielded anechoic chamber, using a HP 8530 vector network analyzer. We have performed numerical simulations by using the software Ansys HFSS.

In order to understand the role of the periodic superstrate in the antenna directivity enhancement, it is important to study in depth the behaviour of Fabry-Perot cavities with EBG mirrors. In fact, according to the image theory, a configuration equivalent to a Fabry-Perot cavity is obtained, if it is halved with respect to its symmetry plane, with a perfectly-conducting surface. If the cavity mirrors are EBG structures and the ground plane of a patch antenna is employed in place of the perfectly-conducting surface, an EBG resonator antenna is built. An EBG cavity with equivalent length L_{eq} resonates when the following condition is satisfied [5]:

$$\frac{2\pi f_L L_{eq}}{c} + \Phi = m\pi \qquad (m = 0, \pm 1, \pm 2, ...)$$

where f_L is the resonance frequency, c is the light velocity in the medium between mirrors, and Φ is the phase of the mirror reflection coefficient.

In Fig. 2, the measured cavity transmission efficiency η_T is reported, as a function of frequency, for woodpile Fabry-Perot cavities with different lengths. The adopted setup consists of a couple of X-band pyramidal horn antennas, facing one another, with two identical woodpile samples in the middle, placed at a distance h from each other. The figure shows that a single periodicity interruption may cause several resonances: in fact, each curve presents various transmission peaks. In longer cavities, a higher number of resonances occurs within the same frequency range. All the structures considered in the figure resonate at 10.3 GHz, and it is noted that the relevant peak has a higher quality factor when the cavity is longer. The experimental curve for h = 90 mm was already presented in [3], where it was compared, with good agreement, with FMM results. Let us now consider more in depth this case. For such a cavity, three transmission peaks are observed in Fig. 2, centred on 8.80 GHz, 10.30 GHz, and 11.76 GHz. It can be deduced that the equivalent length of the cavity covers the whole air region plus about half thickness of both the mirrors ($L_{eq} = h+4w$). The same result is found if h = 60 or 119 mm cases are examined.

The equivalent length of the woodpile cavity is highly dependent on the electromagnetic field polarization with respect to the woodpile orientation. We measured cavities rotated of 90° with respect to the case of Fig. 2. We found that a resonance at 10.3 GHz, as in Fig. 2, is obtained, when

h = 26, 84, and 142 mm, with an equivalent cavity length covering the whole air region between mirrors, plus the thickness of three periodic layers of both the mirrors ($L_{eq} = h + 6w$).

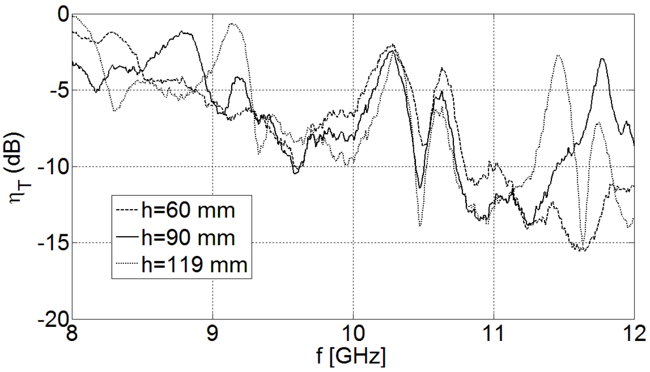

Fig. 2 – Transmission through the cavity vs. frequency (measured results): h = 60, 90, 119 mm.

Ultimately, it seems that the periodic arrangement of bars perpendicular to the electric field has a negligible effect on the transmission efficiency through the whole structure. This deduction is confirmed by the FMM results shown in Fig. 3, where η_T is plotted, as a function of frequency, when h = 90 mm and the behaviour of three different structures is compared: the solid line refers to a two-dimensional EBG cavity obtained from the whole woodpile cavity by removing the bars orthogonal to the electric field (consequently, only bars parallel to the electric field are present); the dotted line refers to a cavity obtained by removing the bars parallel to the electric field (so, the remaining bars are perpendicular to the electric field); the dashed line corresponds to the reference case of woodpile cavity and it has been reported for comparison. It can be appreciated that when only rods perpendicular to the electric field are present, the transmission through the structure is almost unitary; when only rods parallel to the electric field are present, the peaks are slightly shifted with respect to the woodpile case. These results suggest that orthogonal layers of a woodpile superstrate could appropriately be designed as two decoupled problems, in order to serve orthogonal radiators working at the same frequency, or at two different frequencies, and exploiting the same EBG cover. Development of this idea is currently under progress.

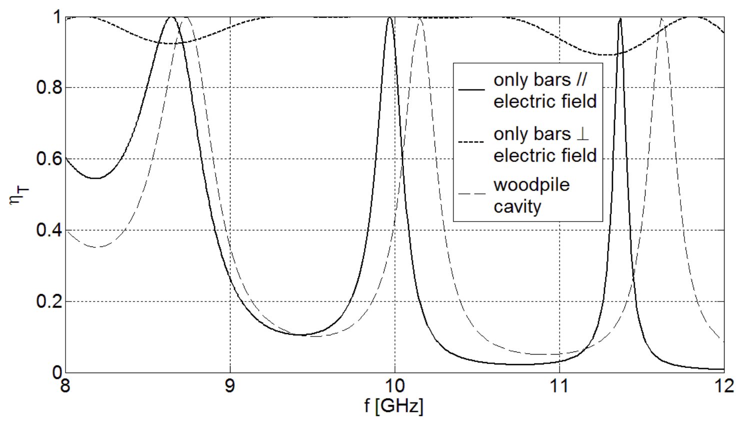

Fig. 3 – η_T vs. frequency (FMM results): h = 90 mm and only rods parallel (solid line) or orthogonal (dotted line) to the electric field are present; results for the whole woodpile cavity are also reported.

We presented preliminary experimental results on woodpile resonator antennas in [3]. Measurements that we can perform on such radiating systems include return loss, gain, radiation patterns in the E- and H- planes, half-power beam width, and side-lobe level. In [3], the maximum gain of the woodpile-covered patch antenna, G_{pw}, normalized to the maximum gain of the patch alone, G_p, was measured as a function of frequency for different values of the distance $h/2$ between patch and woodpile, and for different electric-field polarizations. We modelled our radiating system with HFSS, and performed some simulations in order to carry out comparisons with our experimental data. The results of the comparisons are satisfactory, as can be appreciated from the radiation patterns presented in Fig. 4, for an EBG resonator antenna with $h/2$=45 mm. For this antenna, the calculated gain-enhancement turns out to be 13.52 dB, higher than the measured one of about 10 dB.

It is interesting to perform a comparison between the gain enhancement obtained with the woodpile superstrate and the one that could be achieved with a uniform two-dimensional array of patches occupying the same geometrical area as the woodpile (i.e., 20×20 cm^2). We have calculated that with a 3×3 array, covering only a fraction of the available area, the gain enhancement is 13.56 dB. If an array with a high number of elements is simulated, occupying the whole woodpile area, a gain enhancement of 25.32 dB is achieved. The woodpile cover should therefore be considered as an alternative to an array, when a directive beam is needed, not in the sense that it can give a higher increase of the gain. One of the benefits of the EBG resonator antenna resides in the possibility of obtaining a high gain with a device that uses a single feed, without the complications and limitations of a multiple-source radiating system. Moreover, we think that by covering with our woodpile a patch resonating at a higher frequency, a better gain enhancement could be obtained. We think that even better results might be reached by designing a modified woodpile structure, for example with some bars displaced and optimized to achieve a more symmetric and directive radiation pattern and better matching. Another possibility to improve the gain enhancement, could be using a superstrate with a higher number of layers. These solutions are currently under investigation.

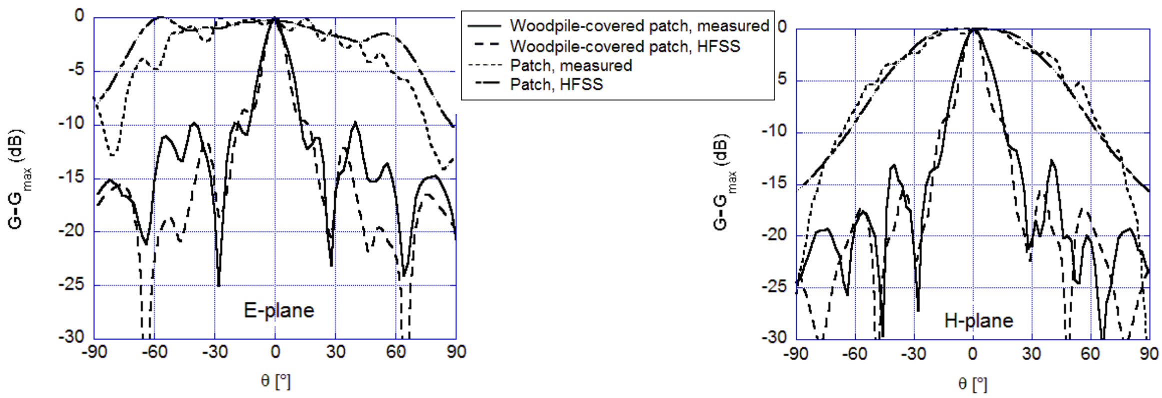

Fig. 4 – E- and H- plane radiation pattern (dB) of the woodpile-covered patch antenna, normalized to its maximum value; $h/2$ = 45 mm, experimental and HFSS results are compared.

4. Conclusions

This work is focused on EBG resonator antennas. A woodpile is used for directivity-enhancing of a linearly-polarized rectangular-patch antenna. New experimental and numerical results are reported and commented. Novel ideas are suggested, in order to further improve the performances of this kind of radiating systems.

References

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