A Novel Reconfigurable EBG Structure and Its Potential Use as Liquid Sensor

S. Jun, B. Sanz-Izquierdo and E.A Parker
School of Engineering and Digital Arts, The University of Kent CT2 7NT, Canterbury, Kent, UK
b.sanz@kent.ac.uk

***Abstract*— A novel reconfigurable antenna using a modified electromagnetic band gap (EBG) structure is introduced. The EBG is made of an array of square patches with a series of cuts and grooves in the dielectric material between the patches. These grooves allow for the deposition of liquids that can be used to change the resonant frequency of the antenna. The variation in the dielectric permittivity of the liquids produces a change in the reflected phase of the EBG. This change in phase is detected using a planar antenna placed at a short distance from the EBG structure. The change in phase in the EBG produces a change in the reflection coefficient of the antenna. This relationship is shown to be linear for lossless liquids. The reconfigurable structure could also be used as a sensor or detector. In order to assess the use as a sensor, Butan-1-ol, propan-2-ol, ethanol and methanol have been tested. The reflection coefficients and the radiation patterns were measured. Simulations were carried out simulated and measured results.**

Keywords— Electromagnetic bandgap, dielectric permittivity, antenna.

.

I. Introduction

Electromagnetic band gap (EBG) is able to resonate at a longer wavelength than the size of their unit cell. They were invented more than two decades ago [1] and have been a popular topic in the antenna and microwave research area ever since. The EBG structures can be used as high impedance surface to improve antenna matching [1] and to produce low profile antenna with high gain [2]. They can also be used to isolated the radiation of the antenna when close to the human body [3] and for telemedicine [4],

Reconfigurable EBG structures have been accomplished using a variety of techniques such as diodes and RF microelectromechanical systems (MEMS) switches [5] – [10]. Frequency [5], [6] and polarization agility [7], [8] are possible through variation of the EBG characteristics. Both frequency and polarization tuning have also been achieved in the same structure [9]. Moreover, mechanical movement of the elements have been demonstrated to produce phase variations across the EBG array [10].

The sensitivity of antennas to its surrounding environment has recently been employed to developed novel RF sensor and detectors [11] - [15]. For example, the changes in dielectric constant of the substrate as a function of temperature has been used as a sensor though measuring the reflection coefficient of a microstrip patch antenna [11], Similar technique has been structures consist of an array of periodic elements that are used in [12] with a reconfigurable slot patch antenna. There, the structure was filled with distilled water to increase the sensitivity to changes in environmental temperature.

Sensing the dielectric permittivity of liquids have been proposed using the reconfigurable characteristics of RF structures [13] - [16]. In [13], a low cost chipless dielectric permittivity sensor has been developed using a planar substrate integrated waveguide (SIW) structure connected to antennas. Liquid reconfigurable Metamaterials and its potential used as sensors are described in [17] - [19]. In [17], it was demonstrated that the resonant frequency of a frequency selective surface (FSS) can be changed using a liquid substrate. A split-ring resonator FSS array was theoretically proposed for thin-film sensing of liquids in [18]. A complementary split ring resonator in combination with a microchannel has been employed as a highly-sensitive dielectric sensor in a two-port device in [19].

In this paper, a frequency agile EBG-antenna structure using liquids is presented. A planar EBG structure consisting of square unit cell elements is modified by cutting trenches between the elements. using a high precision milling machine. These trenches are filled with liquids of a variety of permittivities. The theoretical concept of electrically lossless liquids is first assessed. The change in dielectric permittivity produces a change in the reflection phase of the EBG structure. Once this is demonstrated, a modified circular slot antenna with a coplanar waveguide (CPW) feed line is mounted above the center of the EBG array. By varying the dielectric permittivities of the liquids in the trenches, the resonant frequency of the antenna is tuned. The created trenches are then filled with liquids of different dielectric permittivities and losses and the results are studied both theoretically as well as experimentally. All designs have been optimized using the finite integration technique (FIT) techniques included in CST Microwave Studio™.

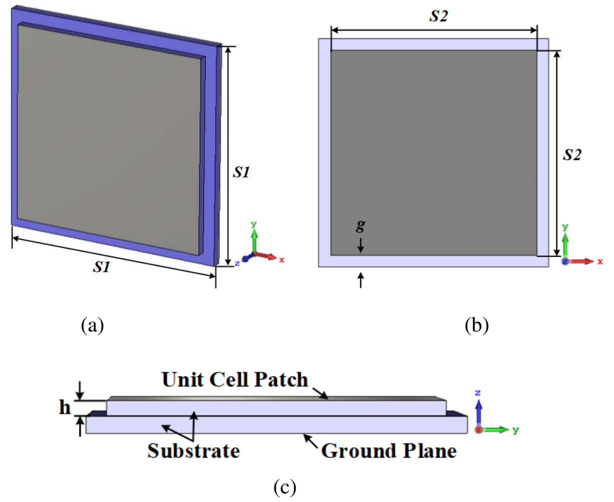


Fig. 1. Geometry of the unit cell element with trenches: a) perspective view, (b) top view, (c) side view.

TABLE I
DIMENSIONS OF UNIT CELL GEOMETRY [mm]

S1	*H*	*S2*	*g*
37.4	1	33.4	2

II. EBG Reconfigurable Structure

A. Unit cell design

The unit cell consisting of square patches with trenches between the patches can be seen in Fig. 1. Trenches are created by taking away the substrate surrounding the square patch. A resonant frequency of 2.45 GHz can be obtained by adjusting the patch size of the unit cell element. The main dimensions of the unit cell is provided in Table I. The patch on the front is 33.45 mm square and the unit cell and ground plane at the back are 37.45 mm square. The substrate employed is an RT/duroid 5870 with dielectric constant of $\varepsilon_r = 2.33$, loss tangent of $tan\ \delta = 0.0005$ and thickness of 3.175 mm.

Fig. 2 presents the resonance frequency and wavelength response of the structure with the trenches filled with various liquids. The dielectric constant was changed from 1 to 15 while the loss tangent was 0. The depth of the trenches was set to 1 mm. The change in permittivity led to a linear change in operating wavelength, which is ideal for reconfigurable and sensing applications.

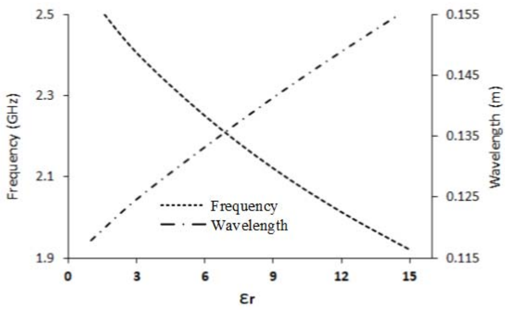


Fig. 2. Sensitivity of the resonance frequency to dielectric constant (ε_r) of liquids in the trenches.

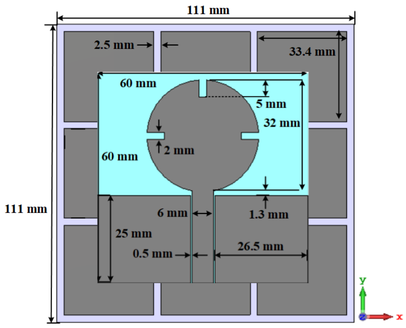
III. EBG Liquid Reconfigurable antenna

A. Antenna on planar EBG structure

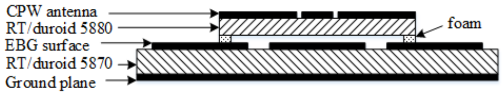
A CPW antenna on a planar EBG structure is first tested in this section. The configuration of this antenna with corresponding dimensions is shown in Fig. 3. The antenna is made up of a modified circular radiator with slots and is fed by a CPW feed line. The substrate is an RT/duroid 5880 with $\varepsilon_r = 2.20,\ tan\ \delta = 0.0004$ and thickness 1.575 mm. The total dimensions of the antenna is 60 mm x 60 mm. The antenna is located on the center of the planar EBG structure. A 3x3 array of unit cell elements make EBG. This was calculated to be the smallest array able to provide the required resonant frequency and antenna matching (S_{11} < -10dB). The optimum separation between the antenna and the EBG structure was found to be 5 mm.

Fig. 4 shows the fabricated structure. A 50 ohm SMA connector is attached to the feed line. Non-conductive polystyrene foams ($\varepsilon_r \approx 1$) with thickness of 5 mm were attached behind the corners of the antenna and topside of the EBG structure to keep the distance between the antenna and the EBG. Fig. 5 presents the reflection coefficient of the antenna, with and without the EBG structure. An Anritsu 37397C vector network analyzer was used for the measurement. The measured frequency range of the antenna alone has a bandwidth at the -10dB points of about 52%. On the other hand, the antenna on the planar EBG structure has a -10dB bandwidth of 14%. The null is deep at 2.45 GHz with -36.5 dB.

The measured normalized radiation patterns at 2.45 GHz in the *xz* and *yz* planes is shown in Fig. 6. In free space, the antenna has omnidirectional radiation patterns. It becomes more directional on the EBG structure,. The front-to-back ratio of the radiation pattern increases by about 20 dB. The gain is enhanced by 6.8 dB as compared with that of the antenna alone.



(a)



(b)

Fig. 3. EBG structure with antenna (a) Top view (b) Side view of CPW antenna on planar EBG structure.

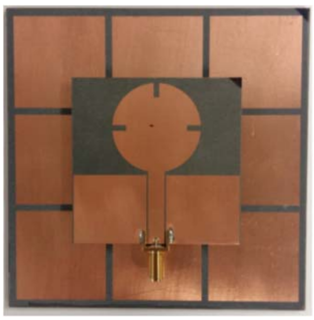


Fig. 4. Photograph of the fabricated planar EBG antenna structure.

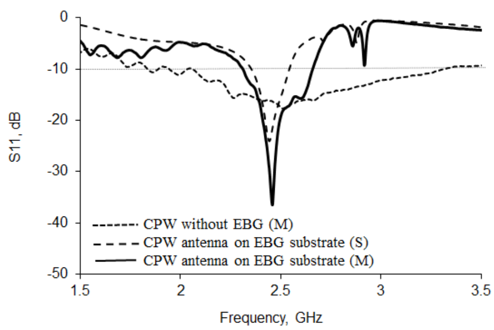
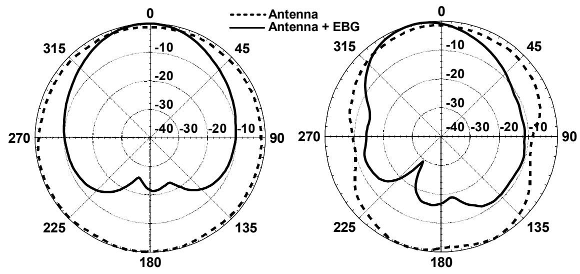


Fig. 5. Reflection coefficient (S_{11}) of the planar EBG antenna structure (S: Simulation, M: Measurement).

B. Liquids reconfigurable EBG antenna

The trenches (Fig.1.) were created in the EBG structure and the antenna was placed on the top. The empty trenches may be filled with liquids as illustrates Fig.7. To assess the frequency tuning characteristics, the structure was simulated when the trenches were filled with liquids of various dielectric constants.



(a) (b)

Fig. 6. Measured radiation pattern of the CPW antenna in free space and on planar EBG structure at 2.45 GHz (a) *xz* plane (b) *yz* plane.

The dielectric permittivities were changed from 1 to 15, and the loss tangent was fixed to 0. The resonant frequency shifted down when the dielectric constant increased (Fig. 8(a)). These compare well with those for the EBG (Fig.2). A Less than 2% deviation was found from the corresponding resonant frequencies of the unit cell.

The loss tangent of the trenches was then varied from 0 to 0.9, while keeping the dielectric constant at 2. The bandwidths (-10dB) were wider and the nulls were shallower when the loss tangent was increased (Fig. 8(b)).

Fig. 9 presents the change in resonance frequency and wavelength to various trench dielectric constants. The response is mostly linear.

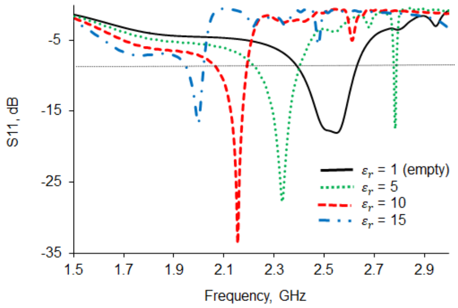
To assess the sensing properties of the structure, four sample liquids: butan-1-ol, propan-2-ol, ethanol and methanol were tested. Their dielectric properties were selected from the report [20]. At 20^0C and 2.5 GHz they are: $\varepsilon_r = 3.57$ and $tan\ \delta = 0.47$ for Butan-1-ol, $\varepsilon_r = 3.80$ and $tan\ \delta = 0.64$ for Propan-2-ol, $\varepsilon_r = 6.57$ and $tan\ \delta = 0.96$ for ethanol, and $\varepsilon_r = 21.3$ and $tan\ \delta = 0.65$ for methanol.

The simulated reflection coefficients when the trenches were filled with the four liquids is shown in Fig. 10 s. In the simulations, the trenches not filled with any liquid (empty) were assumed to have $\varepsilon_r = 1$ and $tan\ \delta = 0$. The resonant frequencies for these liquids are lower than that of the empty trench. The higher the loss tangent the larger the resonant bandwidth.

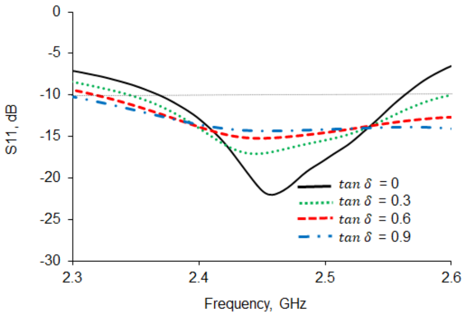
C. Fabrication and Measurement

Fig. 11 shows the fabricated EBG structure with trenches. The trenches on the substrate were cut out and the depth adjusted using a high precision milling machine with a 2.5 mm cutter. The dimensions of the trenches were 2.5 mm x 105.4 mm and depth 1mm. The antenna was placed on the EBG structure at a distance of 5 mm, fixed by rectangular non-conductive polystyrene formers on the edges of antenna substrate.

Fig. 7. The EBG antenna structure with trenches filled with liquids.



(a)



(b)

Fig. 8. Simulated dependence of reflection coefficient (S_{11}) of the EBG-antenna (a) dielectric constant (ε_r) and (b) loss tangent ($tan\ \delta$) of the trenches ($\varepsilon_r = 2$).

In order to seal the liquids in the trenches, a thin adhesive masking tape (Tesa® 51408 Orange Masking Tape) of thickness of 60µm was used. The four liquids (butan-1-ol, propan-2-ol, ethanol and methanol) were inserted into the trenches using a disposable syringe.

Fig. 12 shows the S_{11} of the antenna for the four liquids. The various liquids clearly provide frequency tuning capability for the antenna. The profile of S_{11} curves is noticeably different in term of null depth and bandwidth as well as null frequency for different materials. As expected, the resonant frequencies decrease as ε_r increases. The differences between the simulations (Fig.10) and measurements may be due to potential differences in the dielectric permittivities and loss tangent, errors in the fabrication process, and deviations in the quality, quantity and temperature of the liquids.

The measured normalized antenna radiation patterns for two liquids (propan-2-ol, and ethanol) is presented in Fig. 13. The EBG structure improves the directivity in all cases. However, there are measured losses and expected loss in efficiency.

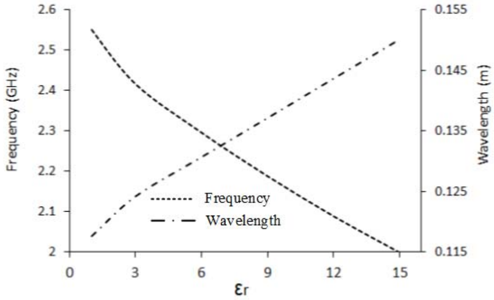


Fig. 9. Sensitivity of the CPW antenna on the EBG structure: simulated dependence of the resonant frequency and wavelength on trench dielectric constant.

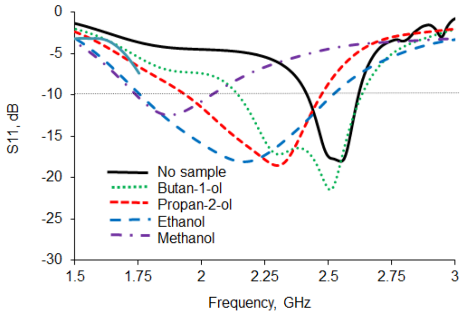


Fig.10. Simulated reflection coefficient (S_{11}) of the EBG-antenna with trenches filled with different sample liquids.

IV. Discussion and Conclusion

A novel reconfigurable EBG technique suitable for sensing applications has been demonstrated. The reconfigurable behavior of the EBG is obtained by creating trenches between the unit cells and filling them up with liquids of different permittivities. The changes in permittivity produce a change in the resonant frequency of the EBG structure. A CPW antenna placed at the center of the EBG structure can provide information of liquids with different permittivities. This can be used as a sensor. This first concept a sensor has shown good sensitivity and linear behavior for lossless materials. Liquids with higher loss tangent, however, can reduce the sensitivity of the sensor. This might be improve using a different type of EBG element such as the narrowband convoluted designs [21].

Acknowledgment

This work was funded by a UK EPSRC High Value Manufacturing Fellowship (REF: EP/L017121/1) and a Royal Academy of Engineering Industrial Secondment scheme (REF: ISS1617/48). The author would like to thank Simon Jakes for help with the fabrication of the antennas.

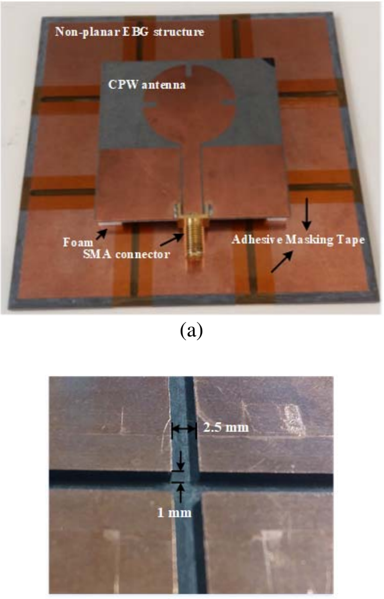


Fig. 11. Photographs of (a) the fabricated antenna on the trenched EBG structure, (b) detail of the trenches

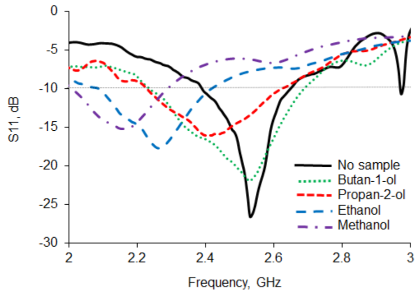


Fig.12. Measured reflection coefficient (S_{11}) of the EBG-antenna with trenches filled with liquids.

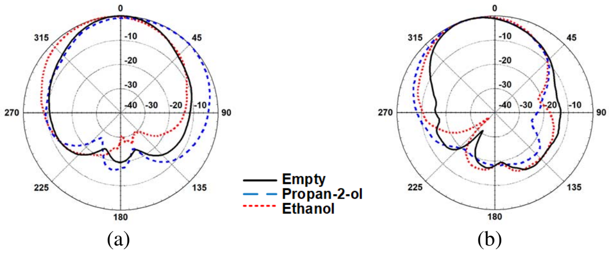


Fig.17. Measured radiation patterns of the EBG-antenna structure with trenches filled with empty, propan-2-ol, and ethanol at 2.53 GHz, 2.40 GHz, and 2.26 GHz (a) *xz* plane (b) *yz* plane.

REFERENCES

[1] D. Sievenpiper, L. Zhang, R. F. Broas, N. G. Alexopolous, and E. Yablonovitch, "High-impedance electromagnetic surfaces with a forbidden frequency band", *IEEE Trans. Microw. Theory Tech..*, vol. 47, no. 11, pp. 2059–2074, Nov. 1999.

[2] A. P. Feresidis, G. Goussetis, S. Wang, and J. C. Vardaxoglou, "Artificial magnetic conductor surfaces and their application to low-profile high gain planar antennas", *IEEE Trans. Antennas Propag.*, vol. 53, no. 1, pp. 209–215, Jan. 2005.

[3] S. Zhu and R. Langley, "Dual-Band Wearable Textile Antenna on an EBG Substrate", *IEEE Trans. Antennas Propag.*, vol. 57, pp. 926-935, Apr. 2009.

[4] H. R. Raad, A. I. Abbosh, H. M. Al-Rizzo, and D. G. Rucker, "Flexible and Compact AMC Based Antenna for Telemedicine Applications", *IEEE Trans. Antennas Propag.,* vol. 61, pp. 524-531, Feb. 2013.

[5] H. J. Lee, K. L. Ford, and R. J. Langley, "Dual band tunable EBG", *Electron. Lett.*, vol. 44, no. 6, pp. 392–393, Mar. 2008.

[6] B. Schoenlinner, A. Abbaspour-Tamijani, L. C. Kempel, and G. M. Rebeiz, "Switchable low-loss RF MEMS Ka-band frequency-selective surface", *IEEE Trans. Microw. Theory Tech.,* vol. 52, pp. 2474-2481, Nov. 2004.

[7] F. Yang and Y. Rahmat-Samii, "Polarization-dependent electromagnetic bandgap surfaces: Characterization, designs, and applications", in *IEEE Int. Symp. Dig. Antennas Propag.*, Jun. 2003, pp. 339–342.

[8] W. Yang, W. Che, H. Jin, W. Feng, and Q. Xue, "A Polarization-Reconfigurable Dipole Antenna Using Polarization Rotation AMC Structure", *IEEE Trans. Antennas Propag.,* vol. 63, pp. 5305-5315, Dec. 2015.

[9] B. Liang, B. Sanz-Izquierdo, E. A. Parker, and J. C. Batchelor, "A Frequency and Polarization Reconfigurable Circularly Polarized Antenna Using Active EBG Structure for Satellite Navigation", *IEEE Trans. Antennas Propag.,* vol. 63, pp. 33-40, Jan. 2015.

[10] D. Sievenpiper, J. Schaffner, J. J. Lee, and S. Livingston, "A steerable leaky-wave antenna using a tunable impedance ground plane", *IEEE Antennas Wireless Propag. Lett.,* vol. 1, pp. 179-182, Oct. 2002.

[11] J. W. Sanders, J. Yao, and H. Huang, "Microstrip patch antenna temperature sensor", *IEEE Sensors J.*, vol. 15, no. 9, pp. 5312–5319, Sep. 2015.

[12] F. Yang, Q. Qiao, J. Virtanen, A. Z. Elsherbeni, L. Ukkonen, and L. Sydänheimo, "Reconfigurable sensing antenna: A slotted patch design with temperature sensation", *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 632–635, Jun. 2012.

[13] H. Lobato-Morales, A. Corona-Chávez, J. L. Olvera-Cervantes, R. A. Chávez-Pérez, and L. José, "Wireless Sensing of Complex Dielectric Permittivity of Liquids Based on the RFID", *IEEE Trans. Microw. Theory Tech.,* vol. 62, pp. 2160-2167, Sep. 2014.

[14] A. C. d. Lima, E. A. Parker, and R. J. Langley, "Tunable frequency selective surface using liquid substrates", *Electron Lett.*, vol. 30, pp. 281-282, Feb. 1994.

[15] M. Labidi, J. B. Tahar, and F. Choubani, "Meta-materials applications in thin- film sensing and sensing liquids properties", *Opt. Exp.*, vol. 19, no. S4, pp. A733–A739, May 2011.

[16] A. Ebrahimi, W. Withayachumnankul, S. Al-Sarawi, and D. Abbott, "High-sensitivity metamaterial-inspired sensor for microfluidic dielectric characterization", *IEEE Sensors J.*, vol. 14, no. 5, pp. 1345–1351, May 2014.

[17] A. C. d. Lima, E. A. Parker, and R. J. Langley, "Tunable frequency selective surface using liquid substrates", *Electron Lett.*, vol. 30, pp. 281-282, Feb. 1994.

[18] M. Labidi, J. B. Tahar, and F. Choubani, "Meta-materials applications in thin- film sensing and sensing liquids properties", *Opt. Exp.*, vol. 19, no. S4, pp. A733–A739, May 2011.

[19] A. Ebrahimi, W. Withayachumnankul, S. Al-Sarawi, and D. Abbott, "High-sensitivity metamaterial-inspired sensor for microfluidic dielectric characterization", *IEEE Sensors J.*, vol. 14, no. 5, pp. 1345–1351, May 2014.

[20] A. P. Gregory and R. N. Clarke, "Tables of the complex permittivity of dielectric reference liquids up to 5 GHz", *CETM*, Teddington, U.K., Nat. Phys. Rep. 33, Jan. 2012.

[21] S. Tse, B. Sanz Izquierdo, J.C. Batchelor and R.J. Langley, "Convoluted elements for electromagnetic band gap structures", in *IEEE Int. Symp. Dig. Antennas Propag.*, Jun. 2004, pp. 819-822.