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RESEARCH PAPER

Design development and experimental validation of an EBG matrix antenna for tracking application

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Today's increase of functions, improvement of performances, and cost reductions required on an agile electronically scanned antenna, drive researchers to develop an innovative antennas' concept in order to deal with the proposed challenge. In this context, this article describes and demonstrates an experimental prototype to show the reliability and efficiency of the electromagnetic band gap (EBG) matrix antenna theoretical aspect, for beam forming and beam steering applications. The originality of this work is the antenna itself which constitutes the subject of an accepted national and international patent. In fact, the proposed antenna is based on the equivalent radiating surface approach and used special EBG antennas called "pixels" to overcome some of the array approach defects. The antenna has demonstrated different electromagnetic behaviors, such as low mutual coupling, high gain preservation for high scanning angles values, etc.

Keywords: Agile antenna, Beam forming, Beam forming network, Beam steering, Electromagnetic, Electromagnetic Band Gap antenna, High scanning angles

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I. INTRODUCTION

Telecommunications, civil and military radars, radio frequency identification, and all the radiating systems are evolving towards the spatial agility that associates « range » and « coverage ». This evolution is natural since current applications still rely on mechanical antennas that do not offer the agility and the compactness that are required for future market needs, unlike active electronically scanned array (AESA). However, AESA design constraints are very critical since greater performances are required within less room or non-convenient places to fit the equipment [1], and this compactness leads to many problems, such as electromagnetic (EM) coupling, high side lobe levels, blind angles, low scanning angles, etc. Moreover, the main issue remains in the cost of such complex system where the market trend is to produce an innovative radiating system with low cost and excellent performances. Therefore, in the framework of tracking agile antennas applications (e.g. monitoring and guiding patients at hospitals), the challenge is to design and construct an efficient low cost antenna system in order to obtain an agile beam forming and steering. The proposed antenna working principle is based on the equivalent radiating surface approach and used a low profile electromagnetic band gap (EBG) antenna with the implementation of an elegant beam forming network (BFN), in order to form and electronically steer the radiation pattern.

In this article, the antenna theoretical aspect is presented briefly in Section II, since it was already published and detailed in [2, 3]. Moreover, the antenna design and the manufactured prototype will be discussed as well. Then, Section III will describe each part of the BFN with some experimental results. The experimental validation will enable us to achieve the aforesaid challenges with the implementation of a low cost feeding technique in order to obtain an optimal radiation pattern. Finally, Section IV presents the complete demonstrator (BFN + antenna) that was realized and measured to validate the theoretical concept of the antenna. Conclusions and perspectives are given in Section V.

II. OVERVIEW OF THE INNOVATIVE ANTENNA

A) Theoretical concept

The majority of high gain agile antenna designs are based on the array approach such as the phased arrays, the reflector antennas, etc. [1]. The aforementioned approach suffers from a lot of weaknesses versus the proposed approach, such as the design complexity and cost to achieve considerable performances. Moreover, the presence of mutual coupling and the grating lobes can significantly disturb the antenna functioning. Those

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limitations will tend to weaken the radiation performances of these agile antenna arrays. Therefore, a novel antenna called "EBG matrix antenna" was developed to encounter some of the mentioned weaknesses. The concept of the antenna constitutes the subject of an accepted Centre National de la Recherche Scientifique (C.N.R.S) patent [2].

The theoretical working principle of the matrix antenna is described in detail in [2, 3]. Briefly, it is based on the equivalent radiating surface approach to overcome some of the array approach defects. The concept of the matrix antenna relies on the creation of a radiating surface presenting EM fields (E_s, H_s) which can spatially vary in modulus and in phase to introduce agility on radiation patterns. The radiating surface is generated using small and jointed elementary radiating surfaces. These elementary surfaces are built by using special EM sources called "Pixels". The pixel should have particular EM properties in order to enhance the antenna efficiency. For this aim, the pixel's concept is inspired from the EBG antenna.

Therefore, the so-called matrix antenna is formed by an association of several joint and identical EBG pixels. Each EBG pixel is similar to a classical EBG antenna, acting as a resonant cavity formed between a ground plane and a frequency selective surface (FSS) placed above it in the *z*-direction (Fig. 1). The only difference is that the EBG pixel has a low profile height in comparison with the classical EBG antenna (EBG pixel height = $\lambda_0/12$, classical EBG antenna height = $\lambda_0/2$, $f_0 = 2.48$ GHz). This is due to the negative reflection phase value [4] of the FSS which makes the cavity height lower than $\lambda_0/10$. Therefore, the only advantage of this pixel versus the classical EBG antenna concern a very low height and a large radiation bandwidth (>70%). However, one can use a different type of FSS [5] with a different value of reflection coefficient and the structure principle will never change. The pixel principle is also valid for any frequency ranges.

In addition, a classical EBG antenna usually generates on its roof a circular radiating surface [3]. The original idea, in the EBG pixel, was to transform this circular radiating surface to a square radiating surface with a uniform electric field distribution. This was done by inserting four metallic walls inside the EBG cavity (Fig. 1). The presence of an evanescent mode existing into the EBG cavity, prohibiting any undesirable transverse resonance, permitted the metallic walls insertion. All these factors contributed to form a special EBG pixel with an original radiating surface which gives the matrix many EM advantages in comparison with an antenna array. We cite among them [3], the following:

- Low mutual coupling (below −20 dB for an inter-element spacing of $\lambda_0/2$)
- Better conservation of the gain regardless the high scanning angle values (above 65°)
- High inter-elements distance allowed ($d \geq \lambda_0$), where low scanning angles are obtained (±10°) and no significant effect for the grating lobes [6]
- Better radiating surface efficiency
- Low cost and compact antenna technology.

Table 1. The tender specifications of the matrix antenna prototype.

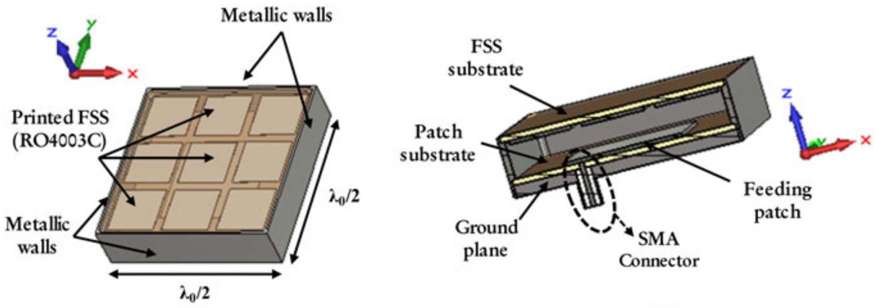
Specifications	
Working mode	Reception
Working frequency	2.48 GHz
Number of pixels	9, 1D arrangement
Inter-elements spacing	$0.5\lambda_0$
Gain (main lobe) without BFN losses	≥12 dB
Side lobe levels	≤−20 dB
Steering range	(−60°; +60°)

After a brief summary on the EBG pixel theoretical concept and its advantages, the design and the experimental prototype of an EBG matrix antenna will be discussed in the next sub-section.

B) EBG matrix antenna prototype

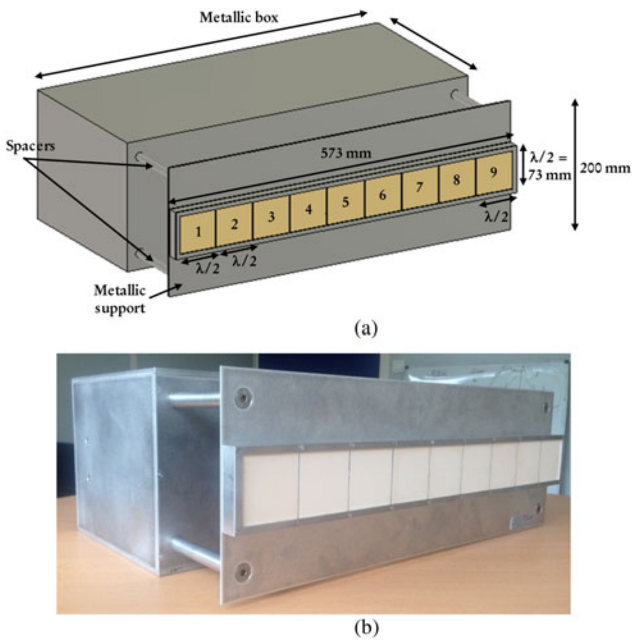
In the framework of a specific tracking application, it is important to determine the specifications of the EBG matrix antenna which will be designed and manufactured. All these specifications are critical in order to determine the BFN and its components. The EBG matrix antenna must have a sufficient gain ($Gain \geq 10$ dB) in order to detect the specified targets beyond 100 m (*the actual antenna systems that are used for monitoring and guiding patients at hospitals are limited to a dozens of meters maximum*). The desired gain enable us to fix the pixels number at 9. These pixels are associated along a single direction by adjacent walls, and they have an inter-element spacing of $0.5\lambda_0$. Moreover, the choice of the corresponding radiofrequency technology (*Wi-Fi*) permits to define the working frequency of the global system. The tender specifications are presented in Table 1.

The design and the experimental prototype of one-dimensional (1D) EBG matrix antenna are presented in Fig. 2. It is important to notice that the dimensions of the matrix antenna are ($573 \times 73 \times 19$ mm^3). Contrariwise, the global system is bulky, because the matrix prototype is placed on a metallic support presenting an extension of 200 mm along the *y*-direction. Moreover, the matrix prototype is fixed



(a) (b)

Fig. 1. EBG pixel design (a) perspective view, (b) inside view (cut-plane at the middle along (*oy*)).



(a)

(b)

Fig. 2. (a) Design of an EBG matrix antenna (9 × 1 pixels) modeled with CST Microwave software, (b) antenna manufactured prototype.

on a metallic box by the means of four metallic spacers. This metallic box should hold the BFN and should be used to fix the global system on the anechoic chamber support.

Figures 3 and 4 present respectively, the comparison between the measurement and the simulation, of the reflection coefficients and the mutual coupling for several pixels in the matrix. The pixels are matched to −10 dB over a bandwidth of 6% (2.45–2.6 GHz), as in Fig. 3. Moreover, one of the advantages of the matrix antenna is to limit each elementary radiating aperture at the pixel's dimensions in order to not disturb the neighboring pixels, as mentioned in [3]. Therefore, the first noticed observation is the weak mutual coupling between neighboring pixels. This was theoretically explained in [3] and will be experimentally demonstrated in this paper. Figure 4 shows the comparison between the simulated and measured mutual coupling of several pixels and their adjacent ones. The obtained results show a good agreement and the highest obtained level of mutual coupling is less than −19 dB.

III. DESIGN AND MANUFACTURING OF THE BFN

According to the aforementioned specifications in sub-section II B, the EBG matrix antenna should form a Gaussian beam having an important gain (≥12 dB) with low side lobe levels

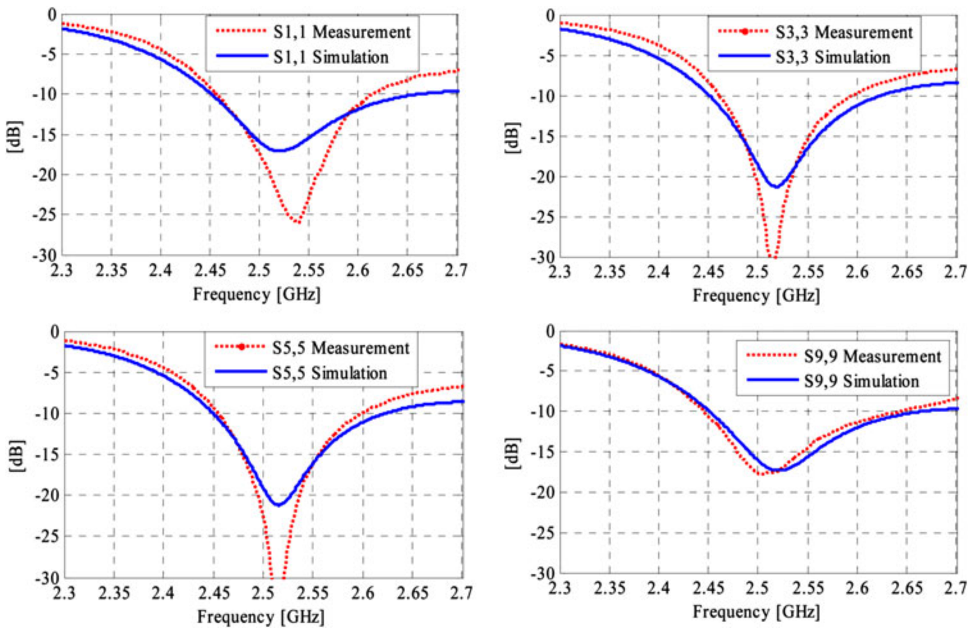


Fig. 3. Comparison between simulated and measured matching coefficients for several pixels (numbers 1, 3, 5, and 9).

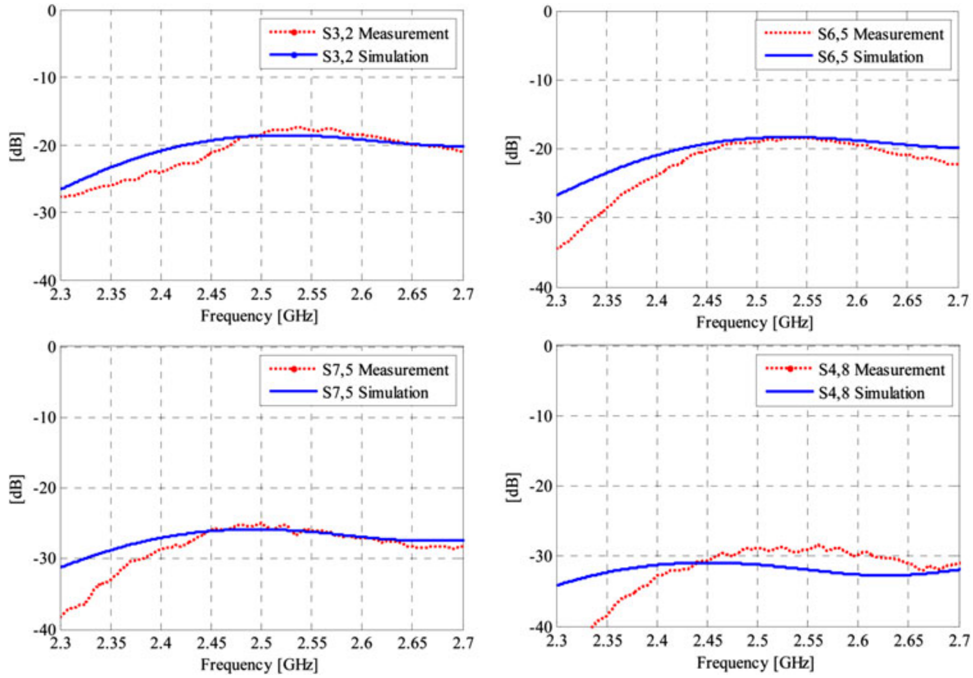
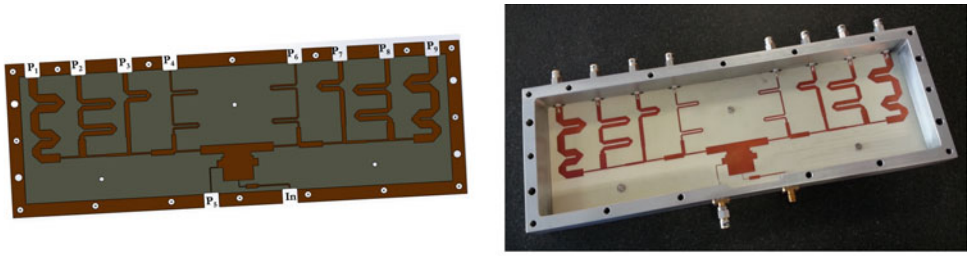


Fig. 4. Comparison between simulated and measured mutual coupling coefficients for several pixels.

Table 2. The excitation law in modulus and phase applied on input pixels, at 2.48 GHz.

Pixel number	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9
Modulus	0.22	0.43	0.67	0.92	1	0.92	0.67	0.43	0.22
Phase	0°	0°	0°	0°	0°	0°	0°	0°	0°
Ratio Pi/P_5	22%	43%	67%	92%	100%	92%	67%	43%	22



(a)

(b)

Fig. 5. Non-equi-modulus and equi-phase power divider 1–9 ways: (a) design, (b) manufactured prototype.

(≤ -20 dB). In addition, the formed beam should cover all the angles between $-50°$ and $+50°$ with 10° window step to monitor, detect, and identify the cooperative moving targets into an angular range of ($-60°$; $+60°$). In order to do this, the EBG matrix antenna will be connected to a BFN which will satisfy these requirements. The BFN is composed of a power divider, digital phase shifters and an electronic control board with a display screen in order to view the target position. Each part of the BFN is described below.

A) Power divider

Each component in the BFN will contribute to meet the datasheet requirements, as in sub-section II B. One of these requirements is to obtain low side lobe levels, i.e. below or equal to -20 dB. In order to achieve that, a magnitude law of excitation, which enables us to obtain an important gain with low side lobe levels, is used. The excitation law was developed at XLIM laboratory by using a synthesis algorithm which generates a cosine law which is described in Table 2. The main subject of this paragraph is to show that the used excitation law was provided by designing and manufacturing a non-equi-modulus and equi-phase power divider (1–9 ways).

The power divider has been designed and manufactured at 2.48 GHz using Momentum from Agilent Advanced System Design. Figure 5 presents the designed and manufactured power divider.

Figure 6 showed above, presents the power divider performances. Indeed, Fig. 6(a) presents the comparison between the measurement and the simulation of the power divider

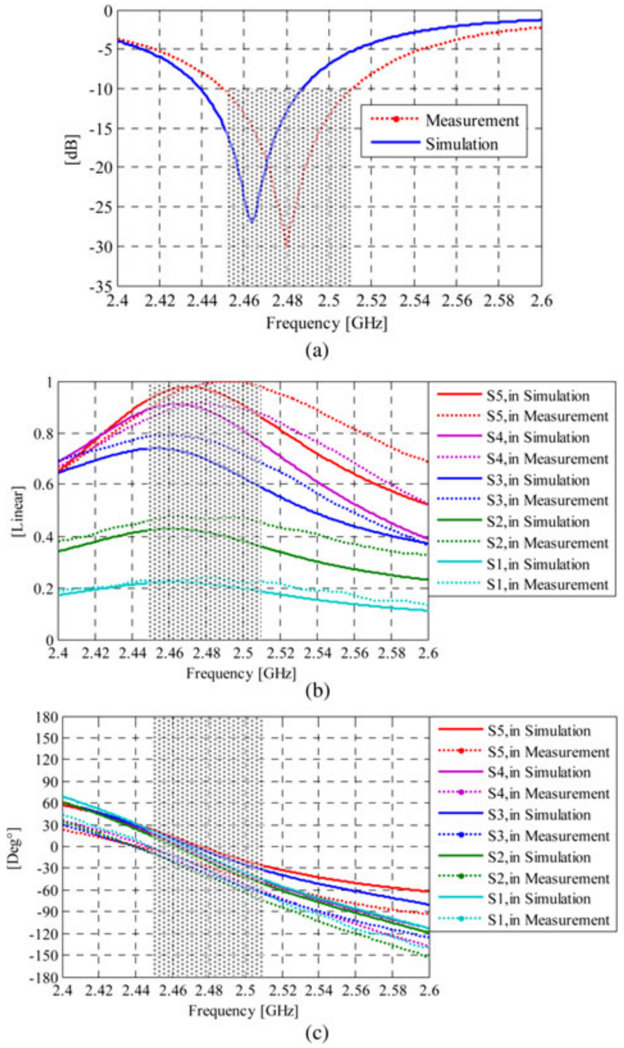


Fig. 6. Comparison of simulated and measured performances of the power divider: (a) matching coefficients, (b) modulus of transmission coefficients, and (c) phase of transmission coefficients.

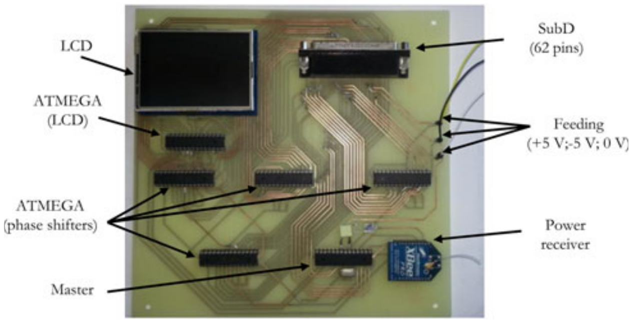
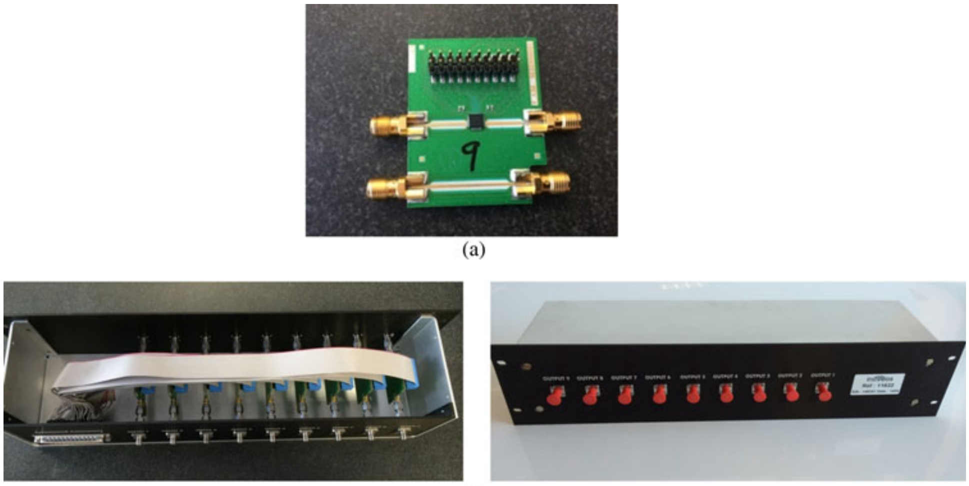


Fig. 8. Manufactured electronic control board.

input matching coefficient. The power divider is matched to −10 dB at 2.48 GHz and covers a bandwidth between (2.45 and 2.51 GHz). A slight frequency shift of 15 MHz is observed between the simulation and the measurement due to the uncertainties in the dielectric material characterizations and to the manufacturing defects. Figures 6(b) and 6(c) presents the comparison between the measurement and the simulation of the power divider transmission coefficients, in terms of modulus and phase. We can clearly see that the manufactured power divider is a non-equi modulus and equi phase satisfying the desired excitation law. The maximum relative error between the simulated magnitude and the measured one is about 0.04 dB. The phase error between simulation and measurement does not exceed 8°. These errors are very tolerable and enable us to feed each pixel with a specified magnitude and almost an equal phase (the phase can be corrected using the digital phase shifters) leading to obtain low side lobe levels. The next paragraph will describe the digital phase shifters.

B) Digital phase shifters

In order to scan the formed radiation beam between (-50° and $+50^\circ$), it is necessary to place efficient phase shifters between the power divider and the EBG matrix antenna. To carry out, nine commercial digital phase shifters from Macom Technology Solutions (MAPS-010164) were chosen because such phase shifters are ideally suited for use where high phase accuracy with minimum loss variation over the phase shift range is required. The MAPS-010164 is a GaAs pHEMT 6 bit digital phase shifter with an integrated



(b)

Fig. 7. (a) Commercial digital phase shifter, (b) metallic box containing nine embedded phase shifters.

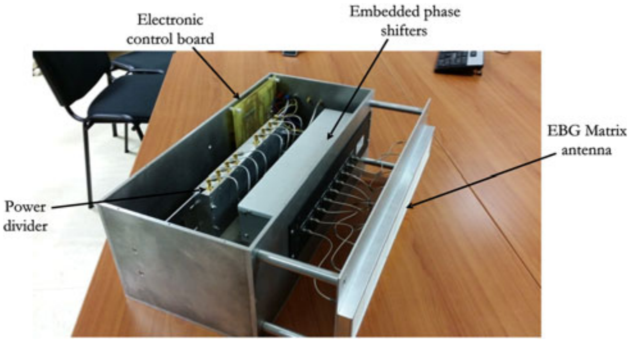


Fig. 9. Complete manufactured demonstrator: EBG Matrix antenna associated with the BFN.

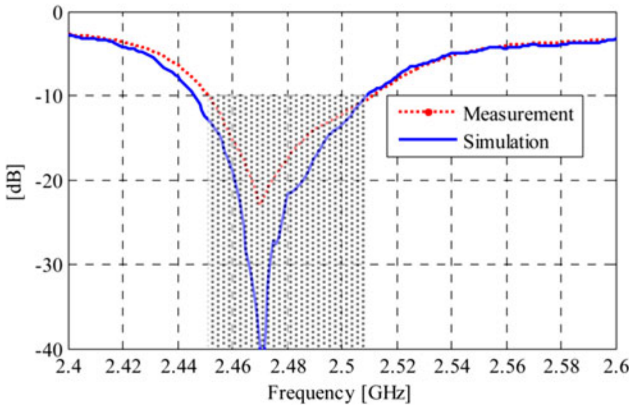


Fig. 10. Comparison simulation/measurement between the input matching coefficient of the complete demonstrator.

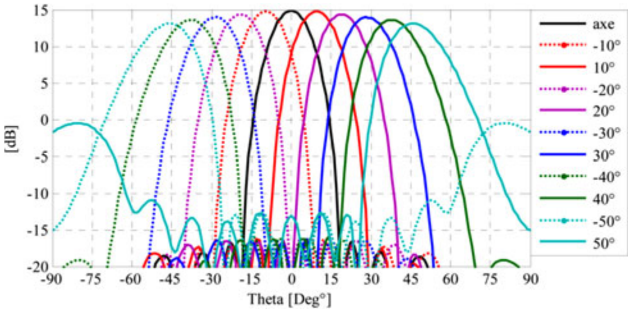


Fig. 12. Angular coverage scenario of 11 simulated radiation patterns obtained at 2.48 GHz, for the $\varphi = 0^\circ$ plane.

complementary metal-oxide semiconductor (CMOS) driver. Step size is 5.6° providing phase shift from 0° to 360°. They work between (2.3 and 3.8 GHz) and they have 3.2 dB insertion losses, ±0.6 dB attenuation variation and a Voltage Standing Wave Ratio of 1.3:1. The phase shifters have been integrated and assembled in a metallic box (Fig. 7) by INOVEOS. The next paragraph will present the electronic control board which handles the digital phase shifters.

C) Electronic control board

The control of the phase shifters and the generation of a correct phase at each pixel input corresponding to a steered direction are established by an electronic board. The board is composed of liquid crystal display (LCD), subD 62 pins, six integrated circuit (IC) "ATMEGA 328P" and a receiver (Fig. 8). The LCD is connected to "Arduino UNO R3" which is based on ATMEGA 328 P. An algorithm was implemented into the IC related to the LCD in order to control the phase shifting. The other ICs are connected to the phase shifters via the subD connector (62 pins) where one of the ICs play the role of a master IC which controls everything and retrieve the received signal from a power receiver. The power receiver was implemented to detect the received signal from the transmitter placed on a mobile target (for

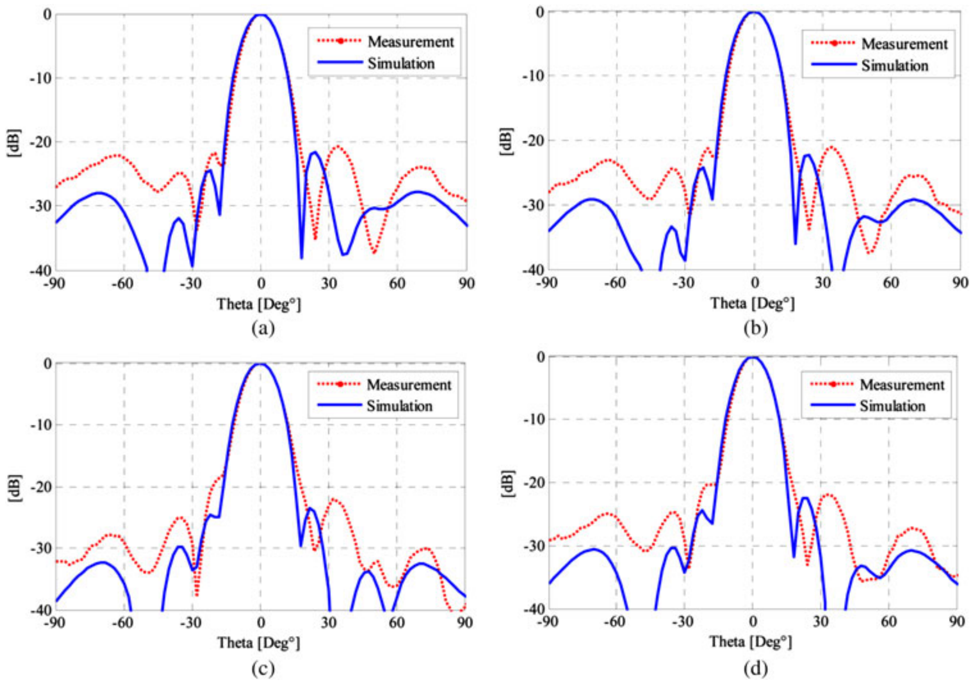


Fig. 11. Comparison simulation/measurement between the broadside radiation patterns for (a) 2.45, (b) 2.47, (c) 2.48, and (d) 2.5 GHz.

tracking application purposes). The electronic control board has been designed and assembled by CISTEME. The next section will present the complete demonstrator with some experimental validations.

IV. COMPLETE DEMONSTRATOR (MATRIX ANTENNA ASSOCIATED WITH THE BFN)

After describing the EBG matrix antenna and the various components of the BFN, Fig. 9 depicts the complete demonstrator. The first EM evaluations of such system were established in the anechoic chamber. However, in order to compare the measurements with the simulation in an efficient way, the BFN was measured separately and was integrated as a black box in CST Microwave Studio using the touchstone file with the measured data "S10p". Figure 10 presents the comparison between the simulated and the measured input matching coefficient. The results present a good agreement and exhibit a bandwidth between (2.45 and 2.51 GHz).

The evaluation of the EM radiation performances of the EBG matrix antenna in the presence of the BFN were carried out in two phases: broadside and steered patterns. Concerning the broadside direction, the comparison shows a good agreement, not only for the working frequency (2.48 GHz) but for other frequencies of the bandwidth (2.45–2.51 GHz), between the simulation and the measurement (Fig. 11). The main lobe is maintained and the side lobe levels are below −20 dB (consistent with the fixed specifications). Figure 11 shows the radiation patterns corresponding to 2.45, 2.47, 2.48, and 2.5 GHz, in the plane of $\varphi = 0°$.

Concerning the steered patterns, the choice of 10° step to cover an angular range between −60° and +60° was made in order to avoid creating gain reduction below −3 dB between adjacent patterns leading to obtain an accurate angular coverage. In order to be clearer, Fig. 12 illustrates a scenario of 11 simulated beams formed at 2.48 GHz and covering the desired angular range (−60°; +60°) with 10° step. The gaps between adjacent patterns do not exceed 1 dB, i.e. the angular coverage is maintained. To precede, the measurement of the steered patterns were made from −50° to +50° with 10° step. In this article, some of the steered direction will be shown. Figure 13 presents the comparison between measured steered patterns and simulated ones. A good agreement is observed, the same agreement is obtained as well for the remaining steered direction between (−50° and +50°). The steered lobes are maintained and the side lobe levels are below −20 dB as well. The shown comparison, Fig. 13, for the steered patterns was made at 2.48 GHz. However, the radiation performances, i.e. correct steering and low side lobe levels, are almost maintained over a frequency bandwidth (2.45–2.51 GHz). It is important to notice the occurrence of a "pixilation lobe" [3], which appeared at +80° for the −50° steered direction case (similar to a grating lobe in antenna arrays case), principally due to the inter-element spacing. The difference between the main axe gain and the pixilation lobe is less than −14 dB at the corresponding direction (−50°).

In this section, the complete demonstrator and in particular the EBG matrix antenna demonstrated its capabilities in beam forming (low side lobe levels) and beam steering (±50°). As a result, the complete demonstrator has fulfilled all the required specifications mentioned in section II B and validated the theoretical aspect of the EBG matrix antenna.

V. CONCLUSIONS

In this paper, the EBG matrix antenna theory was briefly described where the antenna concept constitutes the subject

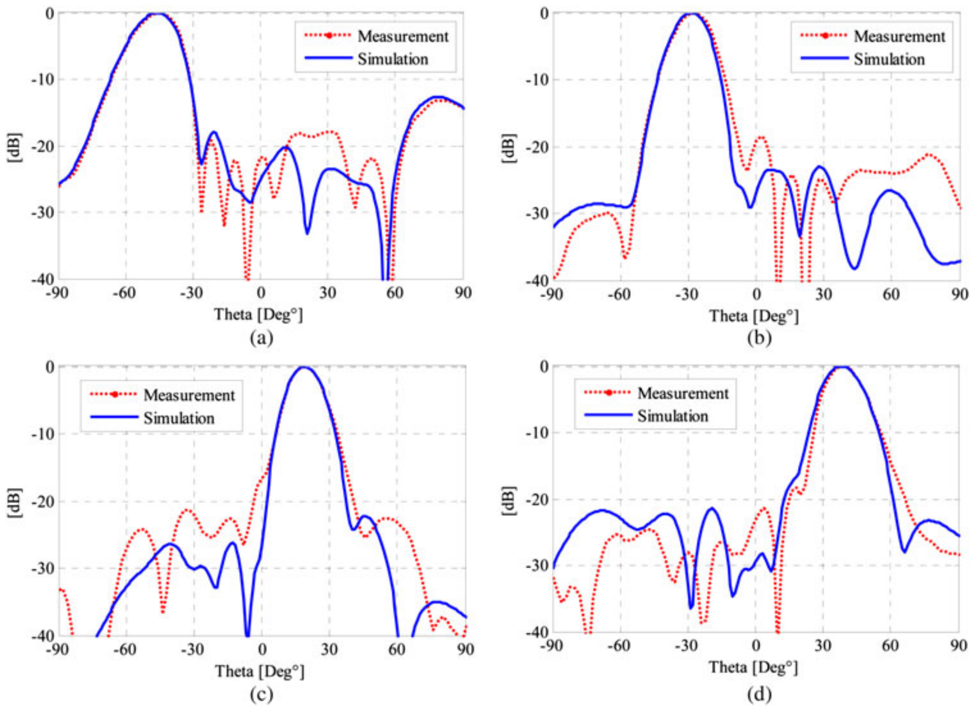


Fig. 13. Comparison simulation/measurement between the steered radiation patterns to (a) −50°, (b) −30°, (c) +20°, and (d) +40° at 2.48 GHz.

of an accepted C.N.R.S patent. Moreover, the EBG pixel, due to the original radiating aperture, gives the matrix (anonymous jointed pixels) many EM advantages, which was demonstrated theoretically, in comparison with an antenna array. For this purpose, an experimental demonstrator composed of the EBG matrix antenna and a BFN (electronic control board + digital phase shifters + power divider) was manufactured to validate the EBG matrix antenna beam forming and beam steering capabilities for a predefined tracking application. The EBG matrix antenna was described and all the component of the BFN as well. The EM performances, in particular the radiation patterns, were evaluated in the presence of the BFN. The measurement were done in anechoic chamber and showed a very good agreement in comparison with the simulation. The theoretical concept of the EBG matrix antenna was validated experimentally in terms of low mutual coupling between pixels and high steering angles, providing an elegant, efficient, and robust antenna system dedicated for agile antenna applications.

The short term perspective of this work is to realize outdoor measurements of the proposed demonstrator in the presence of a transmitter placed on a mobile target for tracking application purposes. The long term perspectives are to validate experimentally some of the EM advantages mentioned earlier, such as reduction of the grating lobes, better surface efficiency, and low mutual coupling by the means of different experimental prototypes.

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Mohamed Rammal received the degree in Telecommunications engineering from the Lebanese University– Beyrouth in 1988 and M.Sc. of High Frequency Electronics & Optoelectronics in 1990 and the Ph.D. degree in 1993 from Limoges University – France. Between 1993 and 1996, he joined THOMSON_CSF as engineer of research in the Communication Navigation and Identification CNI department. Since 1997, he was with the Department of GRIT at the Lebanese university (Institute of Technology). His present research interests include antenna arrays synthesis, smart antennas, and neural network Synthesis beamforming model for adaptive antenna arrays.