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DESIGN AND FABRICATION OF ULTRA-WIDEBAND LEAKY WAVE METAMATERIAL ANTENNAS

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ABSTRACT

*This article is devoted to the design, analysis and fabrication of conventional and metamaterial leaky wave antennas. The effects of utilizing composite right/left handed structure on bandwidth, gain and beam steering are reflected. The structures with metamaterial cells conduct wider bandwidth of operation. Three different configurations of metamaterial unit cell structures are used. The mushroom ground structure is addressed as a cell which provides MTM features on Rogers 5880, traditional square patches and two reconfigurable rows sandwiched between the ground and the radiated arrays. The conventional antenna's dimensions are 50 mm *70 mm *6.36 mm and it is implemented using Rogers RT 5880 substrate, with a relative dielectric constant of (2.2), a thickness of (3.18) mm and a loss tangent of (0.002). The overall dimensions of the MTM antenna outline the same dimensions of the conventional antenna, but its thickness is varying. The antennas are simulated by the CST microwave studio, fabricated on Roger 5880 and measured using the network analyzer. The antenna conducts a gain of (9.8 dB) and a bandwidth between 7.2 GHz and 18.4 GHz. The structure adopted in this paper achieves a novelty of applying different reconfigurable structures of metamaterial unit cells. This type of antenna can be used as a radar sensor control in industrial production lines, while those with high gain could be used for target detection. There is a good agreement between the measured and simulated results*

KEYWORDS

MTMs, LWAs, UWB CRLH.

1. INTRODUCTION

Metamaterials (MTMs) are those structures that have unusual properties than materials which naturally exist; they gain their properties from the structures they are made of rather than the matter that composes them [1]. MTMs are macroscopic composites having man-made, three-dimensional, periodic structures with lattice constants smaller than the wavelength of the incident wave and are separated with distances smaller than this wavelength. These materials exhibit negative permittivity, negative permeability or both, leading to negative refractive index property due to the composition, shape and alignment of the periodic inclusions [1]–[3].

Implementing metamaterials allowed the proposal of numerous UWB structures to be analyzed, fulfilling the spectrum necessities to cover various applications [4]–[7]. A miniaturized UWB integrated antenna based on CRLH metamaterial transmission lines is proposed with techniques based on executing slits, designing rectangular and spiral inductances [4]. In addition, another miniature UWB antenna is suggested and based on (SCRLHTLs) and was implemented using F-shaped and T-shaped slits on the antenna's ground-plane and radiating arms, respectively [5]. Besides, sinusoidally modulated impedance surfaces composed of hexagonal unit cells are used for the implementation of leaky wave antennas. An SIW launcher with wide-band transition is used and a one-dimensional hologram is implemented [6].

Leaky Wave Antennas (LWAs) are travelling wave antennas with an electrically large radiating aperture. They are able to provide high gain without a complex feeding network [8]. Over the past decade, the composite right/left-handed (CRLH) configurations proved to be among the most

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attractive and powerful theory to design high-performance MTM devices and components, such as filters, power dividers/combiners and hybrid circuits [9]–[12]. Also, the CRLH technology has been applied to antenna design and various kinds of antennas have been proposed so far, such as frequency-scanned leaky wave antennas [13]. In this paper, both conventional and metamaterial-inspired broadband leaky wave antennas are proposed in order to illustrate the effect of utilizing CRLH structure on gain, bandwidth and beam steering characteristics.

2. ARRAY OF 2X2 ELEMENTS

2.1 Design

Figure 1 shows the geometry and dimensions of the proposed 2x2 array LWA. The antenna is printed on a Rogers RT/duroid 5880 substrate with a relative permittivity of 2.2 and a thickness of 3.18 mm. The overall dimension of the antenna is 50 mm x 70 mm x 6.36 mm.

The antenna consists of an array, a feed line and a ground plane. The array comprises four identical 5.2 x 5.2 mm^2 cells which are combined to realize Ultra-Wide Band (UWB). The array is fed capacitively beyond a small gap of 0.2 mm by a microstrip line. The width of the microstrip line is equal to 9.8 mm in order to achieve 50Ω characteristic impedance. Figure 1a (left) depicts the top layer of the array structure, while Figure 1b (right) illustrates the bottom layer of the ground. Figure 2 shows the fabricated version of the antenna structure. The methodology of the antenna design starts with an array of a few elements the frequency band of which depends on the dimensions of the patch constituting the array; then, the array elements are increased to improve the deficiency in the gain. On the other hand, the ground mushroom is supporting the antenna structure to improve the bandwidth.

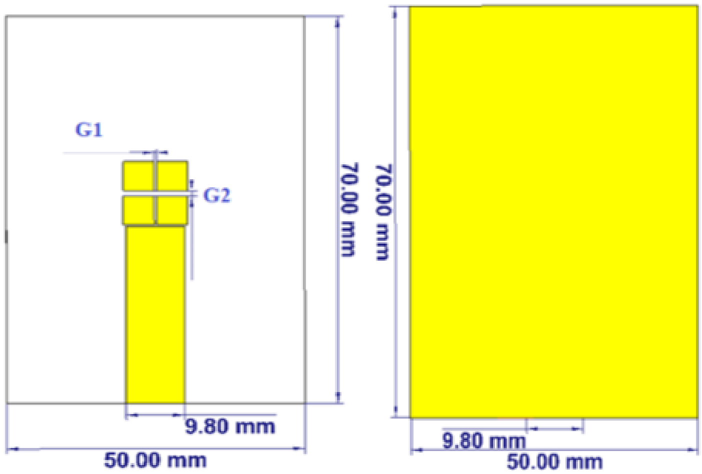

Figure 1. The structure of the proposed 2x2 array LWA; top view (left) and bottom view (right).

On the other hand, the structure of the proposed 2x2 array LWA with mushroom ground is discussed. The antenna comprises few layers. The top layer is similar to that presented in Figure 1, but the ground layer is replaced by a mushroom ground which consists of 3 layers, where the top layer consists of two columns of patches as shown in Figure 3a, while the second layer is a Rogers 5880 RT/duroid substrate with a relative permittivity of 2.2 and a thickness of 3.18 mm and the third (last) bottom layer is the ground layer whivh is connected to a column of vias [14] .The fabricated version of the antenna is depicted in Figure 4 with Figure 4a representing the top layer and Figure 4b showing the bottom one. The mushroom ground structure is addressed as a cell which provides MTM features [15].

To investigate the performance of the proposed antennas in terms of achieving wideband operations, the commercially available simulation software CST STUDIO SUITE ver.2017 was used for numerical analysis.

2.2 Results

The proposed antennas are simulated and measured. G1= 0.35 mm and G2= 1 mm for the proposed 2x2 array LWA were tuned to optimize the antenna performance. The simulated and measured return

Figure 2. Fabrication of the proposed 2x2 array LWA (top view (left) and bottom view (right)).

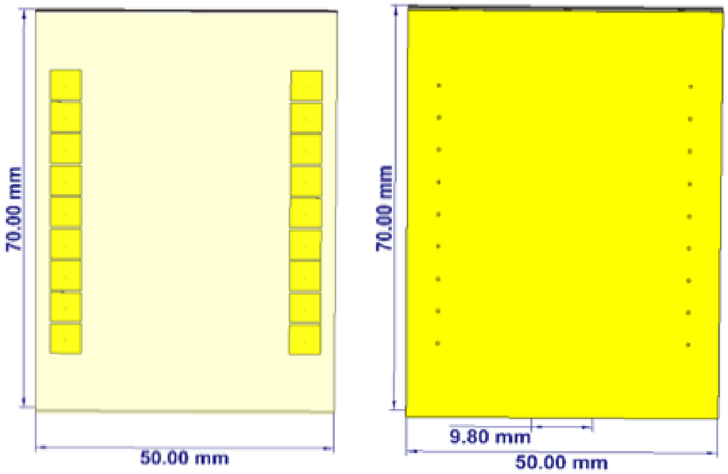

Figure 3. The mushroom ground structure (top view (left) and bottom view (right)).

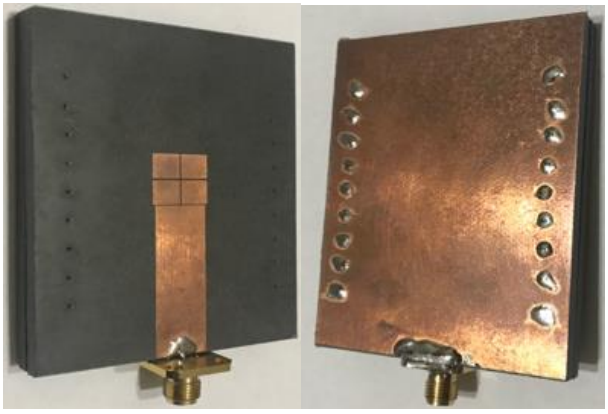

Figure 4. The fabricated 2x2 array LWA with mushroom ground (top view (left) and bottom view (right)).

loss is presented in Figure 5, from which it can be read that the antenna operates in a wide frequency range from 9.1 GHz to 14.6 GHz when -10 dB criterion is applied for bandwidth evaluation. Moreover, the simulated and measured return loss of the proposed 2x2 array LWA with mushroom ground has the optimized parameters G1 = 0.25mm and G2 = 0.4mm as illustrated in Figure 6.

It can be noticed that the antenna operates in a wider frequency range from 6.4 GHz to 16.8 GHz when -10 dB criterion is applied for bandwidth evaluation. There exists a good agreement between the measured and simulated results reflected in the figure. The antenna with mushroom ground has shown a notable improvement in bandwidth of operation. The gain of both the conventional structure and the structure with mushroom ground is displayed in Figure 7, which shows further improvement in gain.

The proposed antenna with mushroom ground also conducts clear steering capability as reflected in Figure 8.

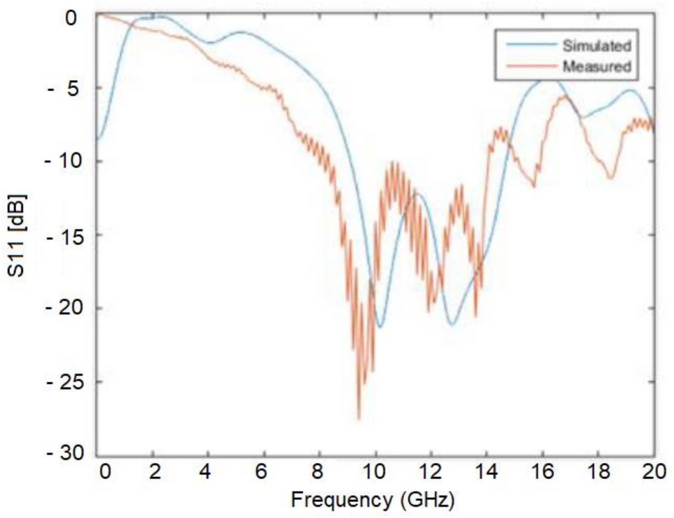

Figure 5. Return loss of the proposed 2x2 array LWA.

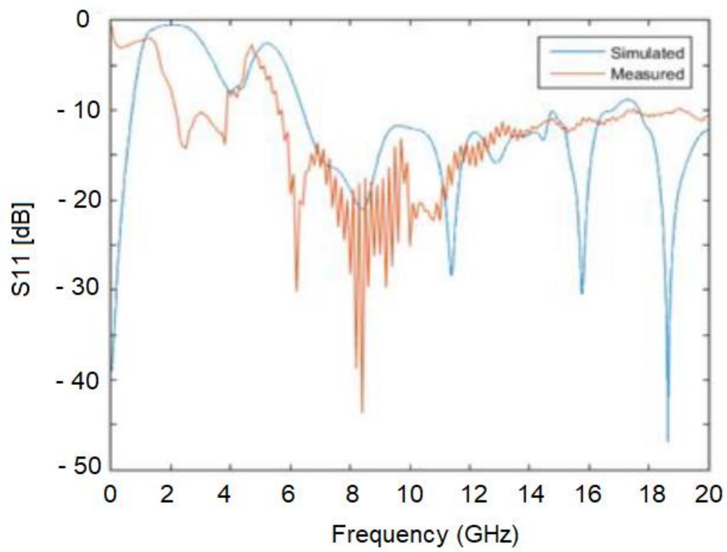

Figure 6. Return loss of the proposed mushroom grounded LWA.

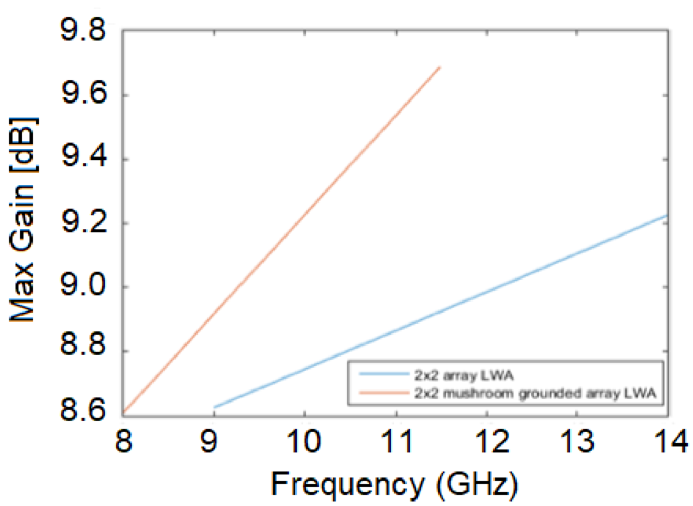

Figure 7. Maximum gain over frequency for 2x2 array LWA and 2x2 mushroom grounded LWA.

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3. ARRAY OF 9X11 ELEMENTS

In order to enhance the gain of the two models proposed in section 2 while maintaining the UWB, two other models were designed and simulated using the same simulation software CST STUDIO SUITE ver.2017. One of them is conventional, while the other has one column of vias connecting ground to the array depending on via location.

3.1 Design

Figure 9 presents the geometry and dimensions of the proposed 9x11 array LWA. The overall dimensions of the antenna are 50 mm x 70 mm x 3.18 mm. The antenna is printed on a Rogers RT/duroid 5880 substrate.

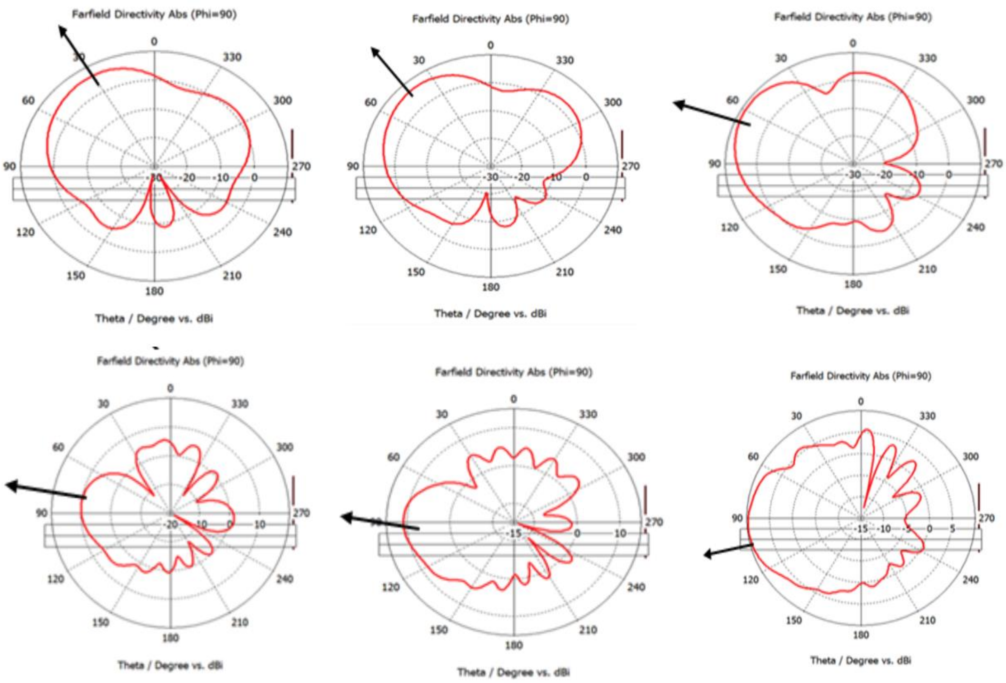

Figure 8. Radiation patterns in E-plane of the proposed mushroom grounded LWA at frequencies from 6.5 GHz to 16.1 GHz.

The Rogers RT/duroid 5880 substrate has a relative permittivity of 2.2 and a thickness of 3.18 mm. The antenna comprises an array, a feed line and a ground plane. The array consists of 9x11 identical 5.2 x 5.2 mm^2 cells. The array is fed capacitively beyond a small gap of 0.1 mm by a microstrip line of 9.8 mm width in order to achieve 50Ω characteristic impedance.

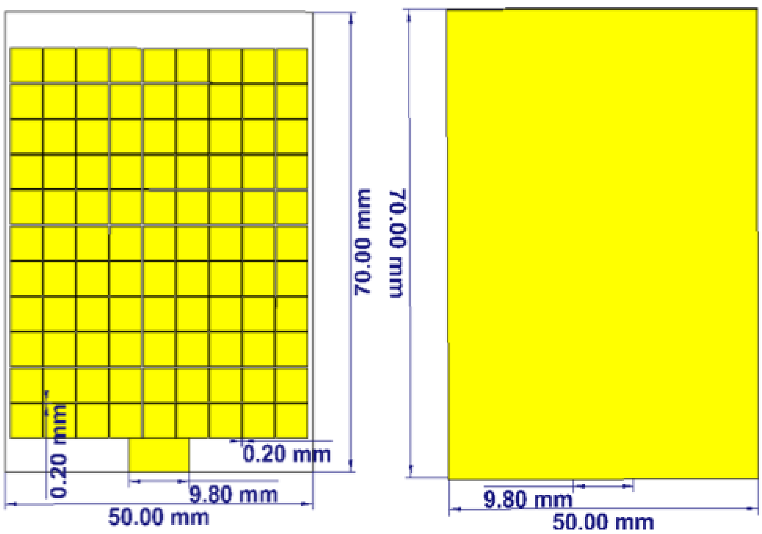

Figure 9. The structure of the proposed 9x11 array LWA (top view (left) and bottom view (right)).

In order to optimize the bandwidth of the antenna, tuning is carried out by moving the column of vias illustrated in Figure 10 either to the left or to the right as both directions give identical results.

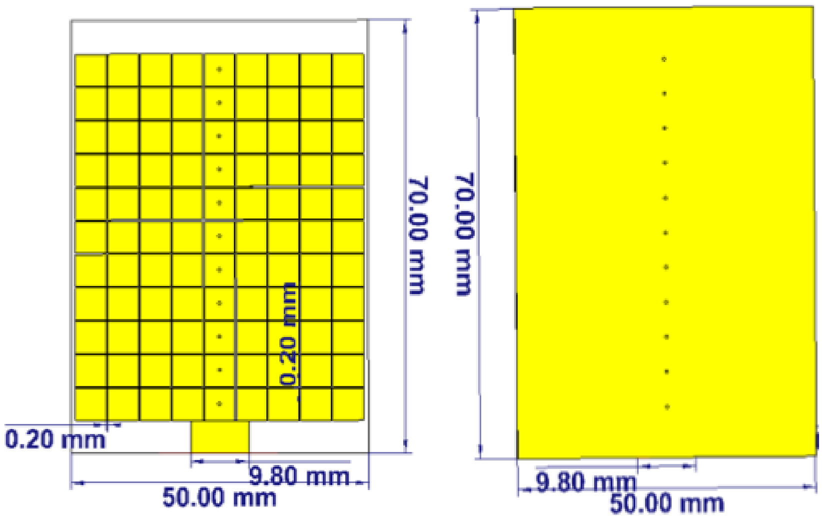

Figure 10. Structure of via-tuned 9x11 array LWA (top view (left) and bottom view (right)).

3.2 Results

The simulated return loss of the proposed 9x11 array LWA is depicted in Figure 11, which shows a UWB ranging from 8.7 GHz to 18.2 GHz. Figure 12 depicts the return loss of via-tuned LWAs.

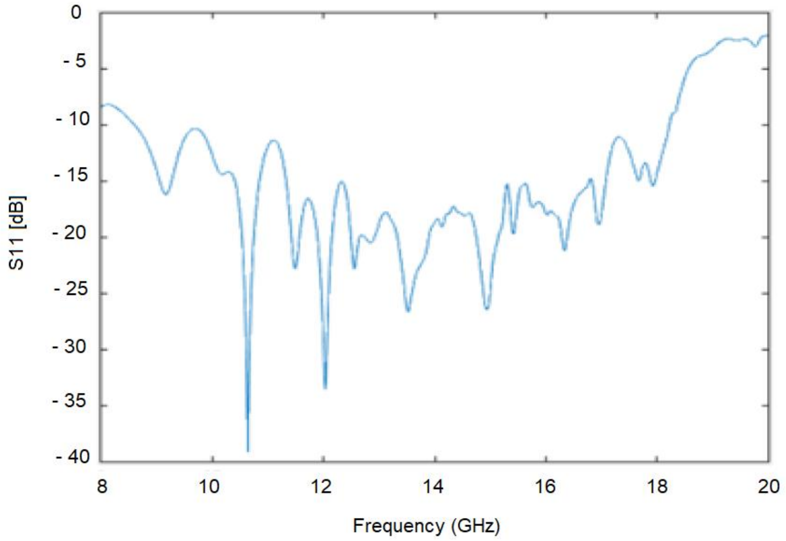

Figure 11. Return loss of the proposed 9x11 array LWA.

Figure 12 shows the return loss of each model with respect to via location. The antenna with the 1st shift shows the widest bandwidth, despite having a short discrepancy at 17.4-17.6 GHz which is then eliminated through gap tuning. The return loss of the 1st shift is depicted in Figure 13 achieving wider bandwidth ranging between 7.2 GHz and 18.4 GHz. Figure 14 displays gain over frequency for the proposed 9x11 array LWA ranging from 8.9 to 11.9, while the via-tuned model has a gain range of 4.8 to 9.8, indicating a drop in gain values after via tuning. The gain drop can be interpreted by that the column of grounded vias is acting as either an absorber or a reflecting metamaterial, where the power is either absorbed on the ground mushroom or reflected back to the source which conducts more losses in the radiated power. This can be proved as the effect of the metamaterial when the column of vias depicted in Figure 10 can be repeated all over the structure from right to left as depicted in Figure 15. The return loss of this modified structure is shown in Figure 16, where the antenna's return loss is above (-10 dB), which proves that the mushroom MMT structure represents a good medium for mismatching between the antenna structure and the source.

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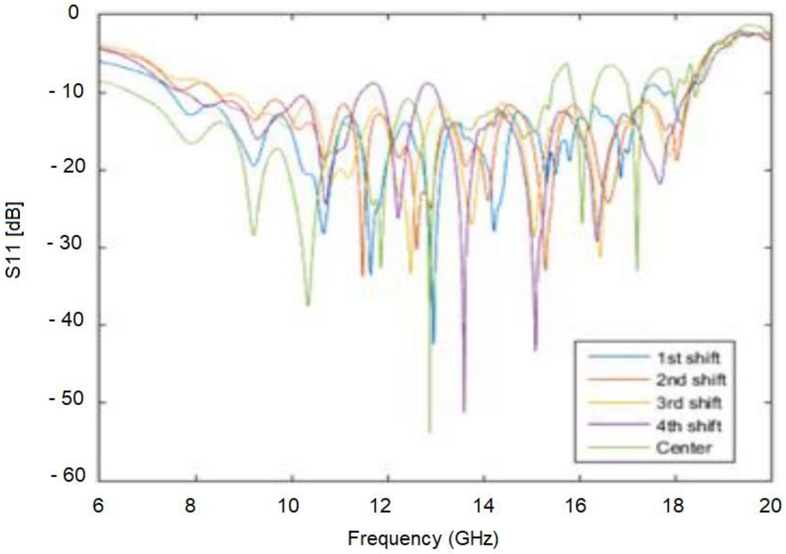

Figure 12. Return loss of the proposed 9x11 with via tuning.

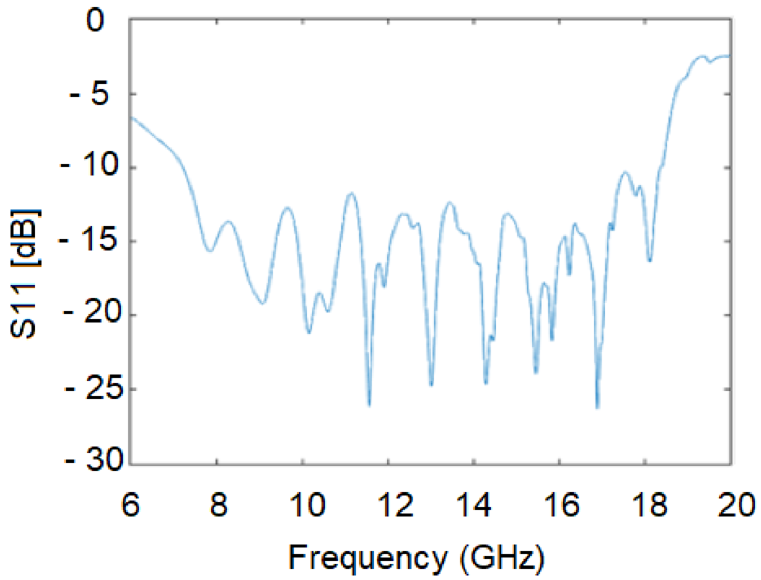

Figure 13. Return loss of the gap-tuned 9x11 array LWA.

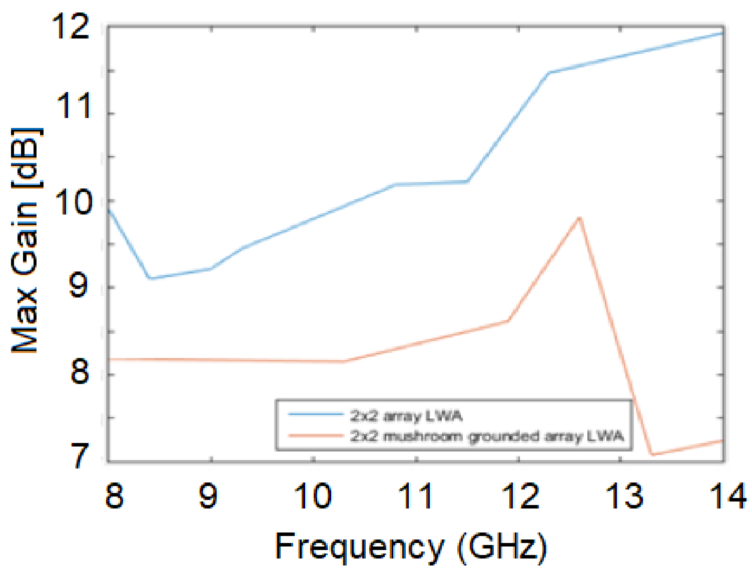

Figure 14. Maximum gain over frequency of 9x11 array LWA.

The proposed 9x11 LWA with via tuning maintained the beam steering capability as reflected in Figure 15. Figure 16 presents another structure, where via tuning was used. The via column used in Figure 10 is placed on the whole 9x11 array structure to form a wave absorber.

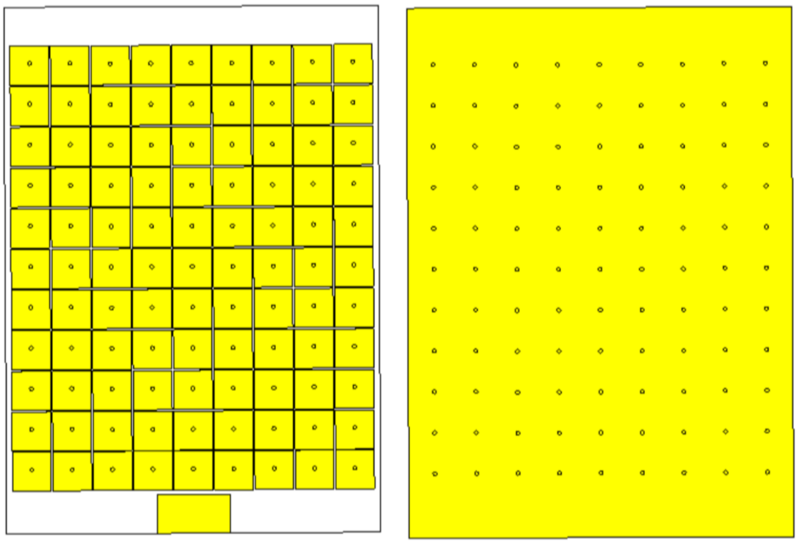

Figure 15. Structure of 9x11 absorber with via tuning A.

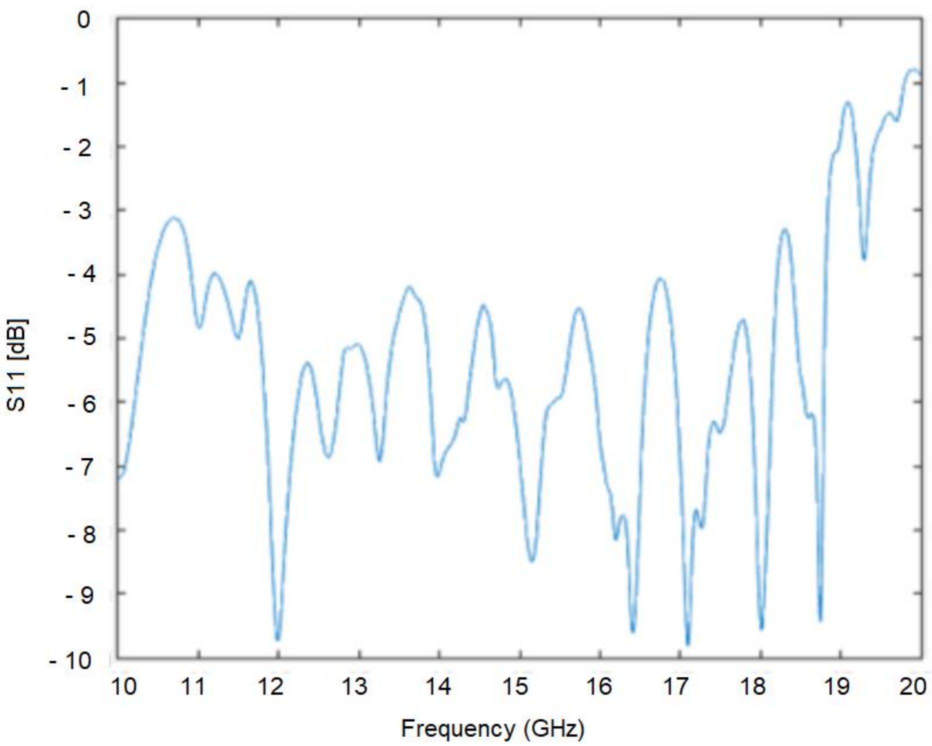

Figure 16. Return loss of the 9x11 absorber array LWA.

Figure 17 shows the return loss of the structure in the frequency range from 10 GHz to 20 GHz. It can be observed that the curve is shifted above -10 dB and up to -1 dB when operating near 19 GHz.

One notices the novel results of beam steering of the proposed array with via tuning over the whole structure as shown in Figure 17, while in this simulation the radiated field fulfils the boundary conditions or the dielectric substrate. Once the boundary conditions are satisfied on the conducting elements, this means that the current is accurately outline over these conducting elements, of course taking the coupling between the array elements into consideration.

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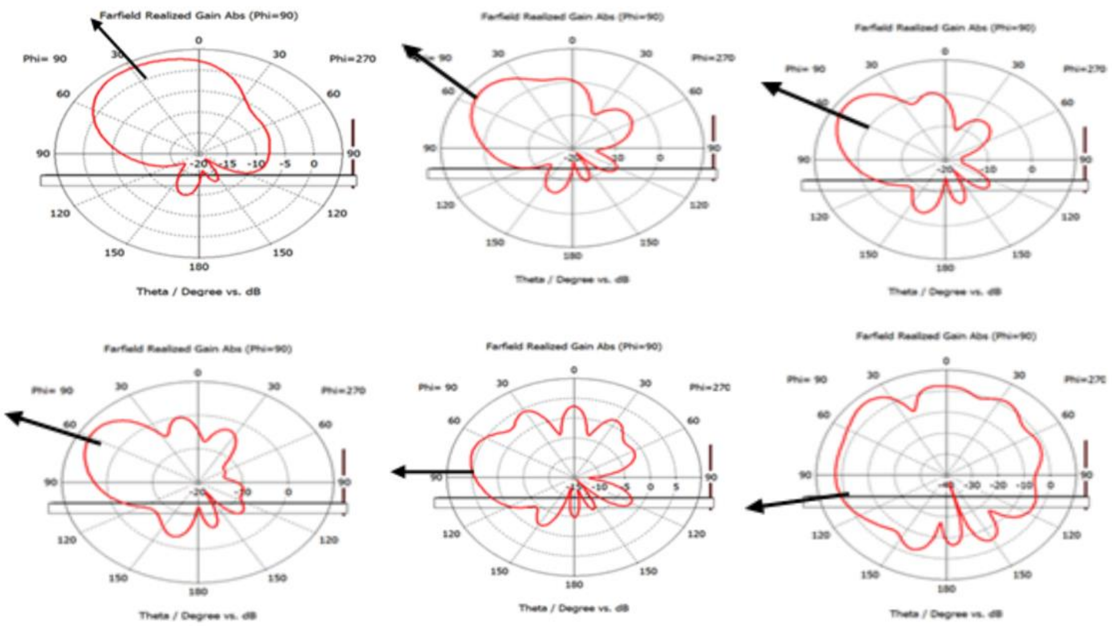

Figure 17. Radiation patterns of via-tuned 9x11 array LWA for frequencies from 6 GHz to 11.9 GHz.

4. Discussion

In this section, a comparison between the different leaky wave antennas proposed and suggested in this paper will take place. The following table represents different parameters, such as bandwidth and gain, in addition to the various arrays suggested.

	2x2 Array		9x11 Array	
	Traditional	Mushroom Ground	Traditional	Via Tuning
Bandwidth (GHz)	9.1 – 14.6	6.4 – 16.8	8.7 – 18.2	7.2 – 18.4
Average Gain	8.6 dB – 9.2 dB	8.6 dB – 9.7 dB	8.9 dB – 11.2 dB	4.8 dB – 9.8 dB

This type of antenna is considered as a leaky wave antenna with aperture constituted by an array of patched radiating elements. Supporting the MTM in unit cells achieves more resonance than patch resonance and array resonance. Basically, each type of MTM unit cell is designed separately by determining its resonance frequency, then optimizing the whole structure on CST can emphasize the total operating band, depending on how near the resonance frequency of each identical element in each structure is.

It's very important to point out that there are some similar works that have been made in literature for antenna arrays including MTM structure, [4]–[7]. In [4], a miniaturized UWB integrated antenna is proposed based on CRLH metamaterial transmission lines and according to the results it can fit communication devices. A bandwidth of 10.8 GHz, a measured frequency bandwidth from 500 MHz to 11.3 GHz and a maximum gain of 6.5 dBi at 8 GHz are achieved.

The miniature UWB antenna proposed in [5] is implemented using F-shaped and T-shaped slits, operating between 0.65 GHz and 9.2 GHz. The maximum gain measured is 3.5 dBi at 4.5 GHz.

Holography sinusoidally modulated impedance surfaces were used to design an LWA in the 13-18 GHz frequency band. The unit cells are composed of hexagonal unit cells which are suitable for any polarization of incident waves. Its performance in the desired band makes it suitable for FMCW radar systems [6].

5. CONCLUSION

This paper illustrates the design and implementation of both conventional and MTM LWAs. By optimizing the gaps laid between patch cells, a large bandwidth was attained. Tuning through vias was also introduced in order to get a wider bandwidth, as shown in section 3. Poor directivity of antennas gives a great benefit to avoid serious distortion of wide-spectrum pulses transmitted/received in a specific direction. Thus, these highly efficient and broadband leaky wave antennas are very attractive and useful for radar systems and future broadband wireless communications.

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ملخص البحث:

هـذا البحـث مخصـص لتصـميم وتحليـل وتصـنيع هوائيـات تقليديـة وهوائيـات تسـتند الـى المـواد الفائقـة والموجـات الراشـحة. وتـنعكس فـي الهوائيـات التـي يقترحهـا هـذا البحـث آثـار اسـتخدام البنيـة المركبـة يمين/يسـار علـى كـل مـن عـرض النطـاق التـرددي والكسـب وقيـادة الشـعاع. وتجـدر الإشـارة الـى أن اسـتخدام المـواد الفائقـة مـن شـأنه أن يـؤدي الـى الحصـول علـى هوائيـات ذات نطـاق تـرددي أعـرض. فـي هـذا البحـث، يـتم اسـتخدام ثلاثـة أشـكال مختلفـة مـن التركيبـات القائمـة علـى اسـتخدام خلايـا مـن المـواد الفائقـة. ويـتم تنـاول البِنيـة الأرضـية المسـماة بِنيـة "الفطـر" كخليـة تعطـي خصـائص المـواد الفائقـة علـى رُقـع مربعـة تقليديـة (روجـرز 5880) وباسـتخدام صـفين قـابلين لإعـادة التشـكيل موضـوعين بين الطبقة الأرضية ومصفوفات الإشعاع.

بلغـت أبعـاد الهـوائي التقليـدي (50*70*6.36 ملـم)، وهـو مركـب علـى طبقـة أسـاس مـن طـراز (روجـرز 5880) ذات ثابـت عـزل كهربـائي مقـداره (2.2) وسـمك مقـداره (3.18) ملـم وانحـراف فقـد مقـداره (0.002). أمـا الأبعـاد الإجماليـة لهـوائي المـواد الفائقة فهي مشابهة لأبعاد الهوائي التقليدي، لكن بسُمك متغير.

تمـت محاكـاة الهوائيـات المقترحـة فـي هـذا البحـث باسـتخدام سـتوديو الميكروويـف (CST)، علـى طبقـة الأسـاس المـذكورة آنفـاً، وبحيـث أجريـت القياسـات باسـتخدام محلّـل الشـبكات. وبلـغ كسـب الهـوائي (9.8) ديسـبل، بينمـا تـراوح النطـاق التـرددي بـين (7.2) جيجـاهيرتز و (18.4) جيجـاهيرتز. وتسـمح البِنيـة المسـتخدمة فـي هـذه الدراسـة بتطبيـق تشكيلات مختلفة من خلايا المواد الفائقة، وهو ما يُعد من جوانب تميز هذه الدراسة.

والجـدير بالـذكر أن هـذا النـوع مـن الهوائيـات الـذي تـم بحثـه فـي هـذه الدراسـة يمكـن اسـتخدامه فـي الـتحكم بمجسّـات الـرادار فـي خطـوط الإنتـاج الصـناعية، بينمـا يمكـن اسـتخدام الهوائيـات مـن هـذا النـوع ذات الكسـب العـالي فـي كشـف الأهـداف. وكـان هنـاك اتفـاق جيـد بـين نتـائج القيـاس ونتـائج المحاكـاة بالنسـبة للهوائيـات المصـممة فـي هـذا البحث.