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DESIGN BROADBAND REFLECTARRAY USING E-SHAPED SLOT CIRCULAR MICROSTRIP ANTENNA

Abdulkareem S. Abdullah, Ramzy S. Ali, Musa H. Wali
Department of Electrical Engineering, College of Engineering, University of Basrah, Iraq
Emails: drasabdallah@ieee.org; ramzy.salim@uobasrah.edu.iq; msda7498@gmail.com

ABSTRACT: - In this work, a circular E-shaped slot microstrip patch element is investigated to design a reflectarray. The E-shaped slot dimensions are varied to study, reflection properties of the patch antenna. It is discovered that the reflection properties and phase range of the proposed element can be optimized using the E-shaped slot's dimensions. The element's resonance and full parametric analysis were checked using a modern microwave software tool was involved to simulate. A 340^{o} phase range is achieved easily;it is enough to design a small-size reflectarrays.

1. INTRODUCTION

In 1963, reflectarray antenna was discovered by Berry et al. to provide a better replacement to the parabolic reflector and phased array [1]. In spite of it has both features, it is not practically efficient to implement it using truncated waveguides. Later with the introduction of microstrip reflectarray in 1991 [2], this dilemma was neutralized. Flat plate, thin structure, and low assembling costs are some of its advantages. A microstrip reflectarray consists of microstrip resonators printed on a grounded substrate [3].A good resonator should provide low reflection loss, large reflection phase range, and slow phase change. Extra reflection phase can be achieved by varying of element size [4], or for linear polarization the microstrip patch is loaded with a phase-delay stub [5].

Microstrip patch is the first planar unit cell investigated for designing different kind of reflectarrays due to its simplicity. Phase shifts that required for designing reflectarrays are provided by slots loading the Patch elements [6]. The simplicity of this method comes from the fact that the separation distances between adjacent elements are constant [6]. A 270^{o} phase range can be easily achieved by making a square slot centered on the rectangular patch [6], yet it is not enough for building a large-size reflectarray and because of the gained phase range is less than360^{o}.

A phase range greater than 360o is achievable by using triple-patch loaded with slot [7], but it has many parameters to be optimized. The multilayer microstrip patch structure is another way to produce reflection phase shift for reflectarray design [8]. A330^{o} phase range was achieved using multilayer element with variable slot lengths on the ground plane; it is not a good choice for a reflectarray element because the slope of the Phase-curve changes too fast. An annular slot and a C-patch can be joined to design a broad-range reflectarray [9]. Unfortunately, such a multilayer structure may not be easy to tune. Different broad-range arrangements, for example, ring, circular patch [10], and fractal-shaped unit components also been showed in [11]. Integrating a planar amplifier array with a passive microstrip component was another option to design a reflectarray [12]. On the other hand, the utilization of dynamic components in the design can present higher losses which thusly badly influence the radiation efficiency of a reflectarray.

The aim of this work is to propose and analyze an E-shaped slot microstrip circular patch for reflectarray design, as well as investigating the effect of changing the slot dimensions of the reflection properties of the unit cell. It has been discovered that those dimensions of the E-slot could be used to optimize both the reflection loss and the phase range of the unit cell. Simulations were carried out using a novice microwave software tool, and supported by experimental results, which uses the MS4642A Vector Network Analyzer (VNA). In order to verify this work, the resonance will be analyzed and comprehensive parametric study will be done.

2. Unit Cell Structure

Figure 1 demonstrates the layout of the suggested unit component constructed of a disk microstrip patch with an E-slot scratched in its middle, resonates at the frequency of 6 GHz. It is fabricated on a FR-4 substrate with relative permittivity (εr = 4.3), tangential loss (tan δ = 0.025), and thickness (t = 1.524 mm. The radius of the circular patch is R = 7.5 mm as shown in Figure 1 (a), the E-slot is constructed by joining three y-directed slots and a one x-directed slot with their widths given by W1 = W2= 1.6 mm. Now, varying the lengths (L1, L2) of both slots might change phase shift. A fabricated prototype unit is shown in Figure 1 (b). To explore the proposed element, a waveguide method is used. A waveguide with the following details (a = 34.85 mm, b = 15.8 mm, h =154 mm), operate in C-band (5.8 GHz - 8.2 GHz), is used for measurement. Figure 2 (a) shows the simulation model and Figure 2 (b) illustrates the measurement configuration. As it is seen the prototype is laid inside a rectangular sleeve etched on a metal plate, with the element face toward the waveguide hole. The electromagnetic wave is traveling from the feeding point to the waveguide adaptor, guided through the waveguide section, finally arrives at the model, which is laid at the other side. The wave appears from the wave port is polarized via the X-axis, as the simulation model exhibit in Figure 2 (a). There are two ways to simulate the reflectarray unit cell the waveguide method and the Floquet method. Figure 2 (a) demonstrates the boundaries for the waveguide method. As shown in the Figure, the prototype unit cell is fixed in the waveguide front, and exiting a 6 GHz y-directed wave at the other end, a.k.a. wave port. The waveguide allows the wave to travel towards the experimental unit, and all the side walls defined as perfect electrical conductors (PEC). The incident wave angle (α) is a function of the utilized frequency (f) and the waveguide cutoff frequency (fc), which is calculated using the following formula $\alpha = 90^o - \cos^{-1}\sqrt{1-\left(\frac{f_c}{f}\right)^2}$[13]. This angle is calculated to be = 14.8° for the operating frequency of f = 6 GHz. The main advantage of the waveguide method is that measurement can be easily performed on this unit element using a section of the waveguide. However, the dimensions of the unit cell are restricted by the cross section size of the waveguide (a x b), hence this method is inapplicable to investigate unit cells larger than the size of the waveguide.

The boundary conditions of the Floquet method, where two of its walls are marked as perfect electrical conductors (PEC) and the other two are marked as perfect magnetic conductors (PMC). Those boundaries make the unit cell act as an infinite array of elements in two dimensions, and taking into consideration the mutual coupling effect between all the adjacent elements [14].

The Floquet method is used to investigate the unit cells whatever were its size. It's better to use Floquet method to design the unit cell because of its flexibility when choosing the frequency of operation and the illumination angle (α), l1 and l2 can be any values as well. One of the biggest drawbacks of the Floquet method is that we cannot apply it experimentally to a single unit cell. In this paper, using C-band waveguide with dimension a x b x h (34.85mm x 15.8mm x 154 mm), and covering the frequency range (5.8 GHz - 8.2 GHz) for experimental verification, shown in Figure 2 (b).

A coaxial-to-waveguide adaptor is used to connect the waveguide section to the port cable of a vector network analyzer (MS4642A, 300 kHz - 20 GHz), which act as a microwave source. The ATM rectangular horn (5 GHz - 8 GHz) can be used to feed the full-range reflectarray designed using this unit element. Even so, feeding horn is not needed in this case since it only involves a unit element. The calibration procedure will now be described. First, the standard one-port OPEN-SHORT-LOAD calibration is performed on the output end of the port cable. In this case, the other end of the cable is connected to the vector network analyzer's output port. The calibrated cable is then connected to the coaxial connector of the coaxial-to-waveguide adaptor. The reason behind the use of the shorting plate in the experiment is to transfer the reference plane to the input adapter, which is an analogue to the simulation setup. This was mainly done by compensating additional length until the reflection phase is close to 180° in a particular frequency range, which simply implies that the reference plane is now aligned along the shorting plate. In closing, the verges of prototype element are cut to make it suitable for the rectangular trench size.

3. Results and Discussion

Figure 3 shows the simulated and measured reflection losses and reflection phases (Phase-curves) of the prototype element when varying the slot lengths (L1, L2) progressively. In Figure 3 (a), -1.3 dB at slot length 7 mm and -1.2 dB at slot length 6.5 mm are the peaks of for the simulated and measured reflection losses simultaneously, it's obvious that the proposed element dissipates tiny amount of power for all sizes of the slots.

The measured and simulated Phase-curves are shown in Figure 3 (b). A reasonable phase range of 334° is easily accomplished, which is suitable for designing a small-size reflectarray. Figure 4 shows credible agreement between simulation and measurement results of the frequency responses for the matter of L1 = L2 = 9 mm in the frequency range 5.5 GHz - 6.5 GHz. A good settlement is found between the measured and simulated results, which are directly proportional to the frequency. Minor inevitable impedance mismatch causes a peak measured reflection loss (-0.34 dB) as shown in Figure 4 (a), In Figure 4 (b), minor acceptable contradiction (~2%) is noticed between the simulated and measured reflection phases.

Analytical evaluation is used to characterize the influence of patch and slot dimensions on the loss and phase of the reflected wave. Begin by investigating the role of the slot widths (W1, W2). The lengths of the azimuthal (L1) and vertical (L2) slots are changed from 3 mm to 10 mm respectively. Figure 5 (a) shows that the reflection losses of three cases of the slot widths (W1 = W2 = 0.5 mm, 1.5 mm, and 3.5mm) are about - 1.5 dB in worst case. Figure 5 (b) depicts the reflection phase and it is observed that the phase ranges for the three cases are 328° (0.5 mm), 334° (1.5 mm), and 330° (3.5 mm), obviously the phase range is almost the same for the three cases. It was also found from simulations that varying the slot length L1 or L2 separately barely affects the unit cell reflection characteristics. Only when changing the slot lengths (L1 and L2) together, the phase range and reflection loss will be affected.

Now to accommodate the reflection characteristic, changing one of the slot widths along with L1 and L2 is varied at the same time. Figure 6 illustrates the case that several horizontal slot widths (W1= 0.5, 1.5, and 3.5) while the width of the vertical slot fixed at (W2= 1.5). It is clear that for all slot lengths the reflection loss is under -1.5 dB. As shown in Figure 6(b), the reflection phase range is slightly improved from 326° to 336° when the horizontal slot width (W1) is increased from 0.5mm to 3.5 mm. Although a phase range of 336° is achievable in the case of W1 = 3.5 mm, it has a faster changing rate (305°/mm) of Phase-curve when compared to the cases of W1 = 0.5mm (273°/mm) andW1 = 1.5mm (267°/mm).

The same results as showed in Figure 6 are getting when fixing the horizontal slot width to (W1= 1.5 mm), along with varying the vertical slot for W2= 0.5, 1.5, and 3.5 mm. Figure 7 illustrate the fluctuation in reflection loss and phase respectively by fixing W1= W2= 1.5 mm and changing the slot lengths L1=L2 in the range of 3 mm – 10 mm when changing the circular radius R. With reference to Figure 7 (b), the reflection phase range of the Phase-curve decrease from 336° to 318°, as the circular element radius R is changed in the range 7 - 8 mm. Evidently that reducing the unit cell radius is cause the increase in the phase range of patch element, except that both of reflection loss and the Phase-curve slope will increase. Hence, a compromise in the reflectarray design should be made to get a wider reflection phase range besides keeping the Phase-carve gradually fades.

To simulate the effects of the adjacent elements on the reflection characteristics of a unit element when it is placed in the array structure, the Floquet method is illustrated in [16] to emulate the unit cell reflection characteristics, shown in Figure 8. This simulation model duplicates the unit element infinitely in the x- and y-directions by taking account of their mutual coupling. In the Floquet simulation model, the unit cell is made to be square (L X L), implying that every two of the circular patches have a center-to-center separation distance of L.

With the use of this model, the reflection coefficients for the cases of L= 0.5λ, 0.75λ, and λ are simulated for the slotted circular patch with the dimension of R = 7.5 mm and W1 = W2 = 1.5 mm, as depicted in Figure 9. Again, those slot lengths (L1, L2) are changed together in the range (3 - 10 mm). It can be observed in Figure 9 (a) that larger separation distance induces higher reflection loss. A maximum reflection loss of ~-8.9 dB is obtained for the case of λ. With reference to Figure 9 (b), a larger separation distance between the neighboring elements contributes to a broader phase range, but at the cost of having steeper phase curve.

The phase range and gradient of the Phase-curve increase from 319.1^o to 354.66^o and from 207.36^o/mm to 1310^o/mm, respectively, when the separation distance is varied from 0.5λ to λ. Although the Floquet method does not pose any constraints on the unit cell size and it can be used to simulate reflection coefficient with respect to the phase-changing parameter for an incoming wave with any frequency and incident angle, the simulated results are not able to be experimentally verified at the cell level.

4. Conclusions

This work involves comprehensive analysis of An E-shaped slot circular microstrip patch for broadband reflectarray antenna design. Inspecting a circular microstrip patch with E-slot scratched in the middle of it to study the influence of the slot in the reflectarray behavior. 328.68o phase range can be realized. This effort established that the phase fluctuation can be controlled by changing the width of the slot (W). Comparing The E-shaped slot circular patch with the square patch it has been found that both have the same footprint, but E-shaped slot circular element have a wider phase range than the square element. Also, it has been proven that decreasing the separation distance between the adjacent elements improves the slope of the phase carve, but at the cost of reducing the phase range. There was a good agreement between experimental and simulated results. It is not possible to check experimentally the simulated results for a single element.

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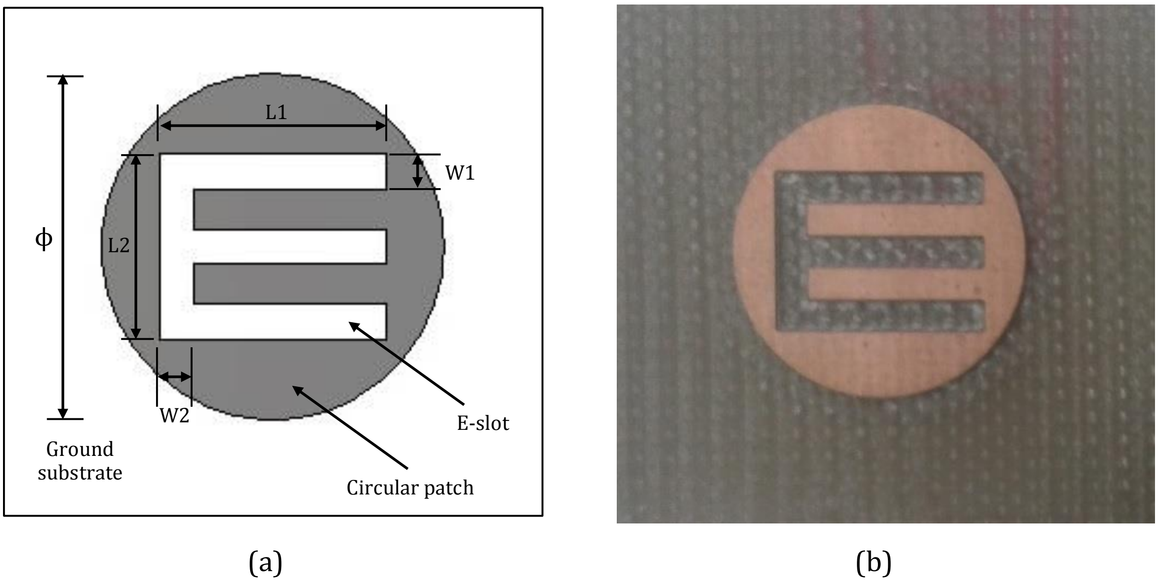
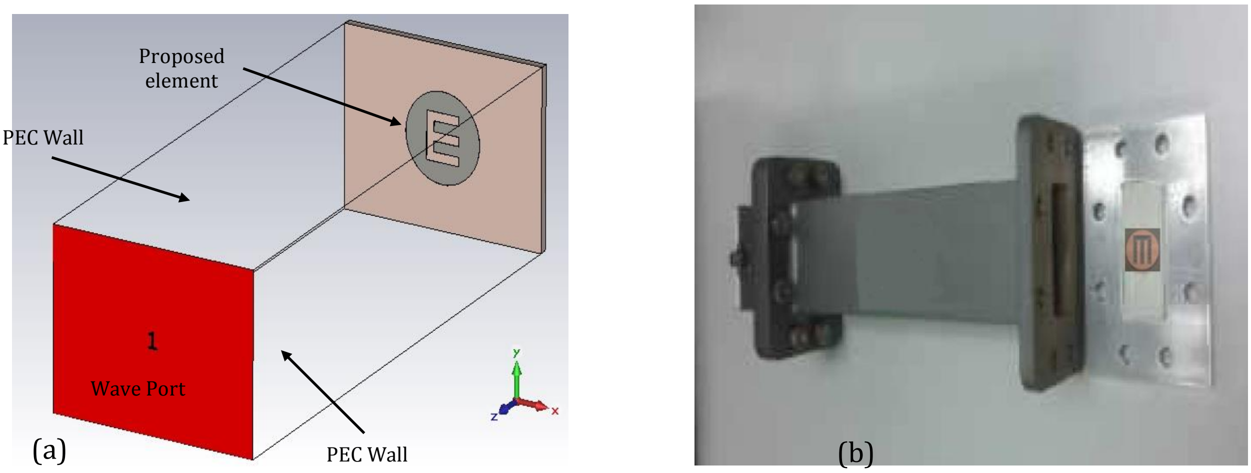


(a) (b)

Figure(1): (a) Graphical of the suggested disk patch with E-slot at the middle.
(b) Picture of the manufactured prototype.



Figure(2): (a) Simulation setup for the suggested E-slotted patch element.
(b) Picture of the measurement setup.

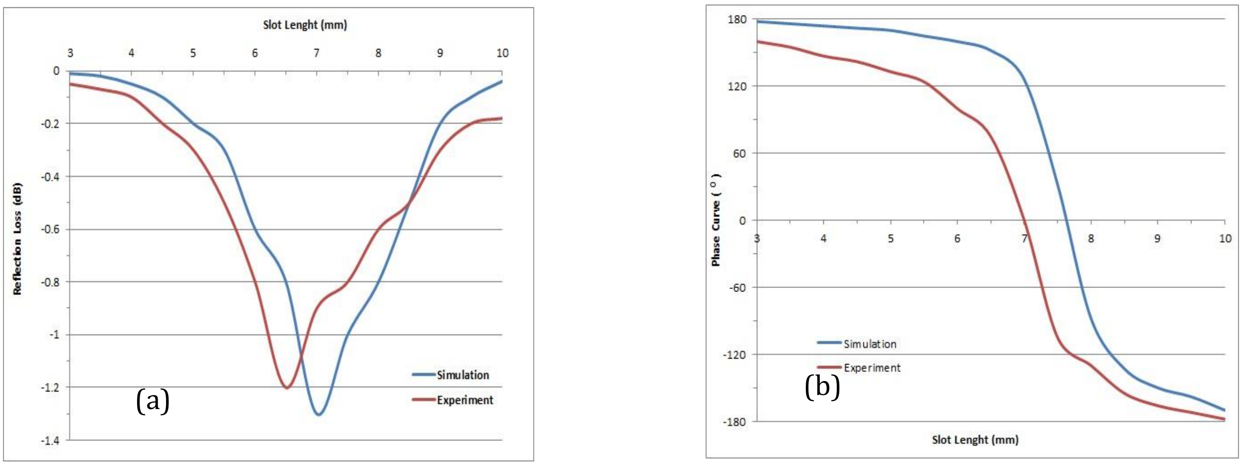


Figure (3): Simulated and measured (a) reflection losses, (b) phase curves of the suggested E-slotted circular patch element.

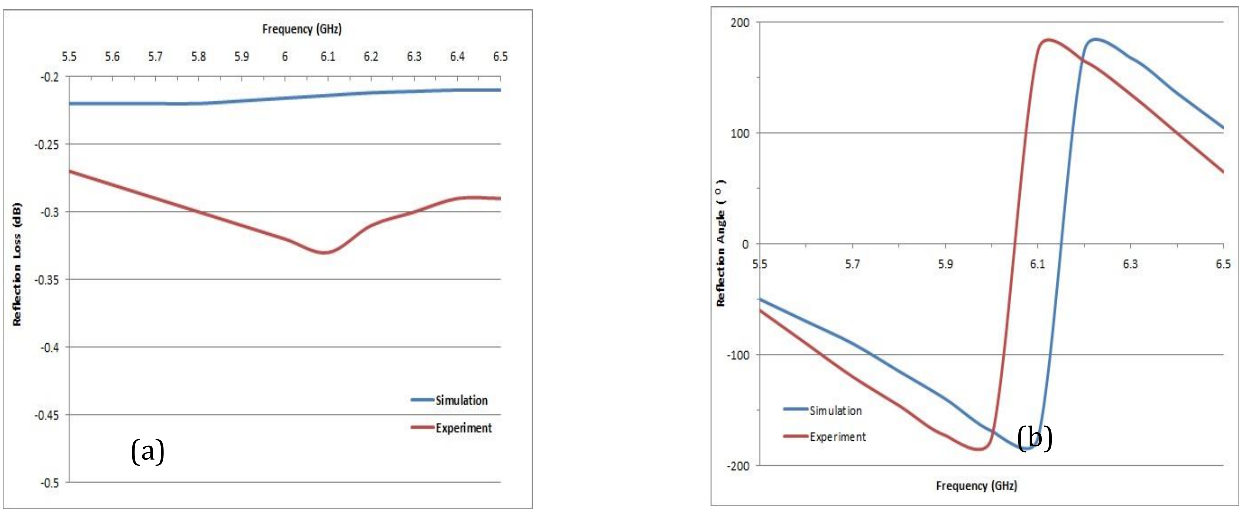


Figure (4). Simulated and measured (a) reflection losses, (b) reflection angles vs. frequency for L1 = L2 = 9 mm for the proposed element.

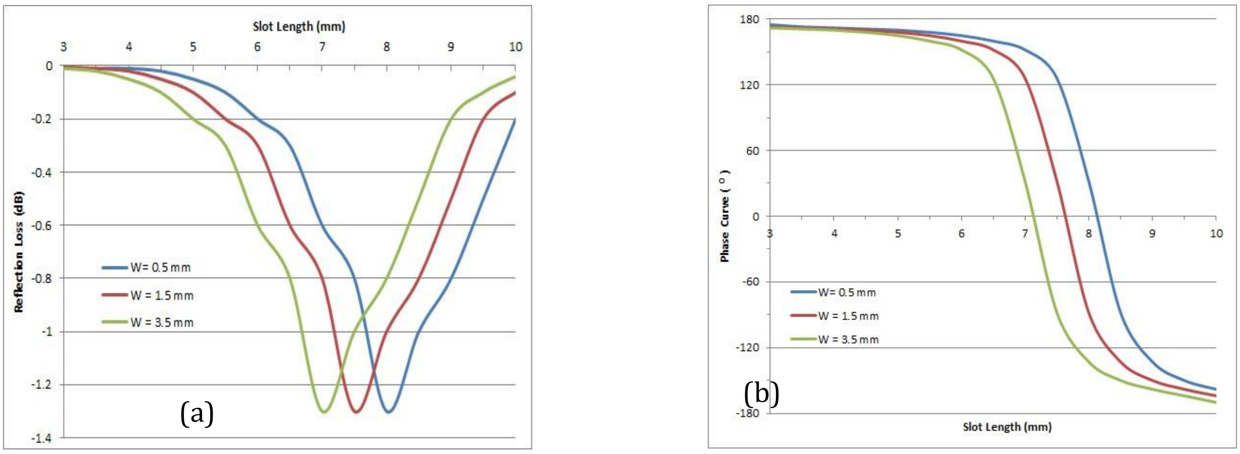


Figure (5): Influence of the slot widths (W1 = W2) on the (a) reflection loss, (b) phase - curve of the unit cell.

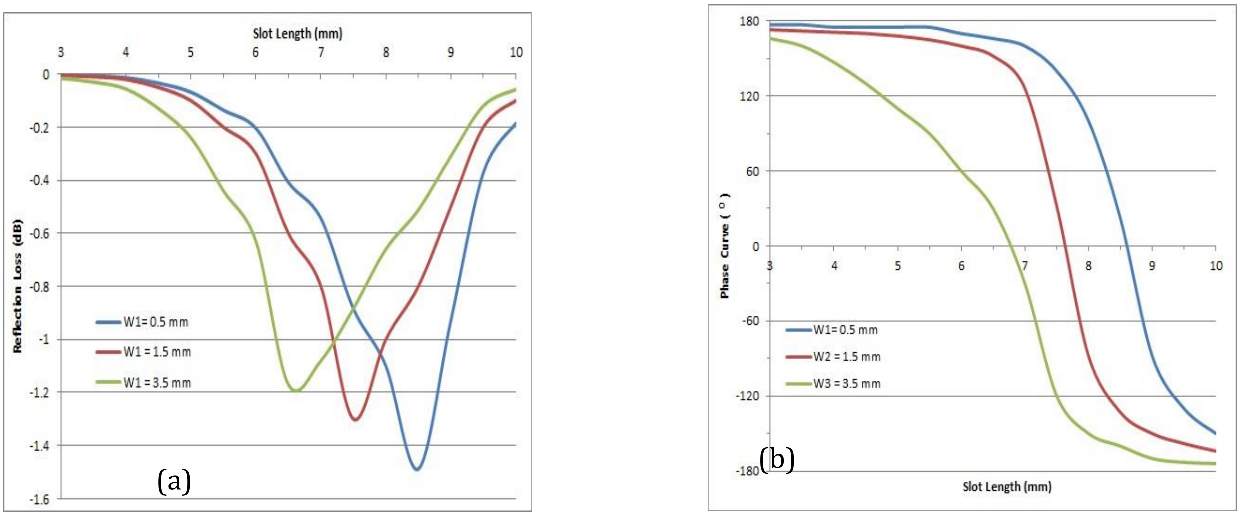


Figure (6): Influence of the horizontal slot width W1 on the (a) reflection loss, (b) phase - curve of the unit cell.

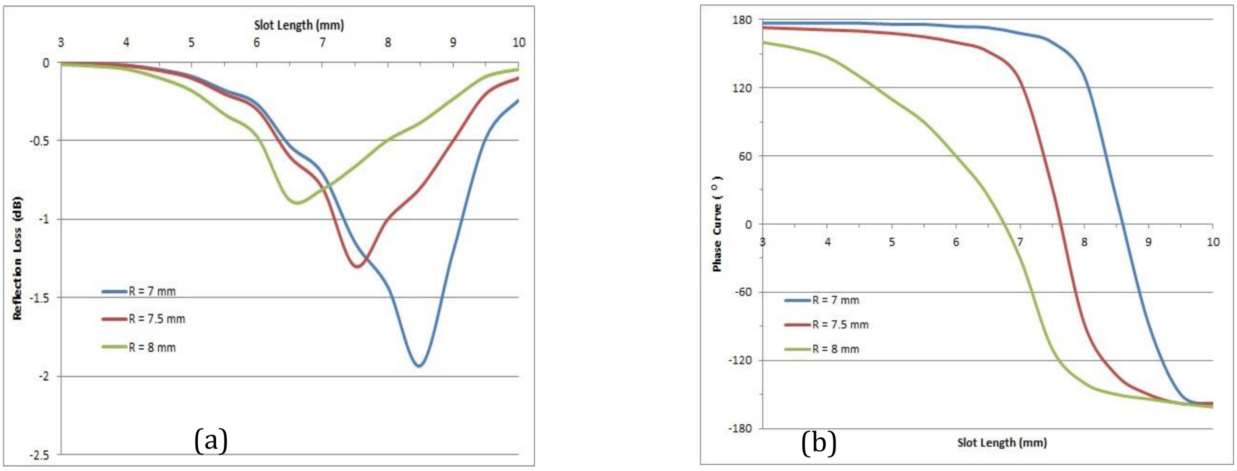


Figure (7): Influence of element radius (R) on the (a) reflection loss, (b) phase - curve of the unit cell.

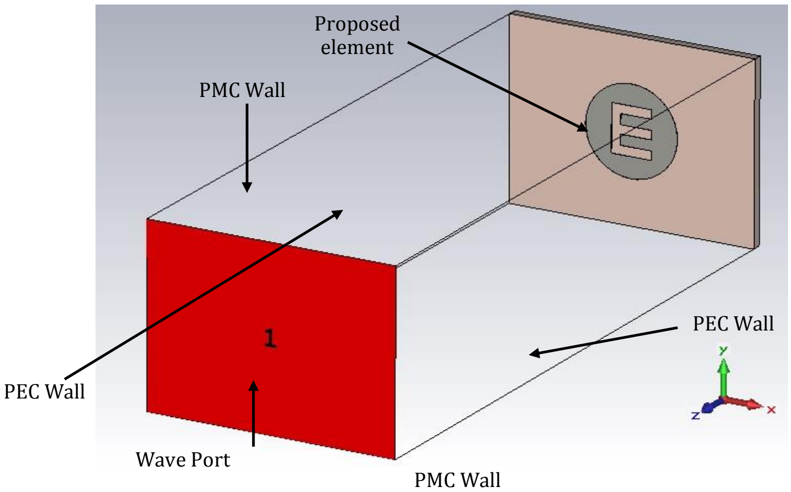


Figure (8): Floquet model setup for the suggested E-slotted patch.

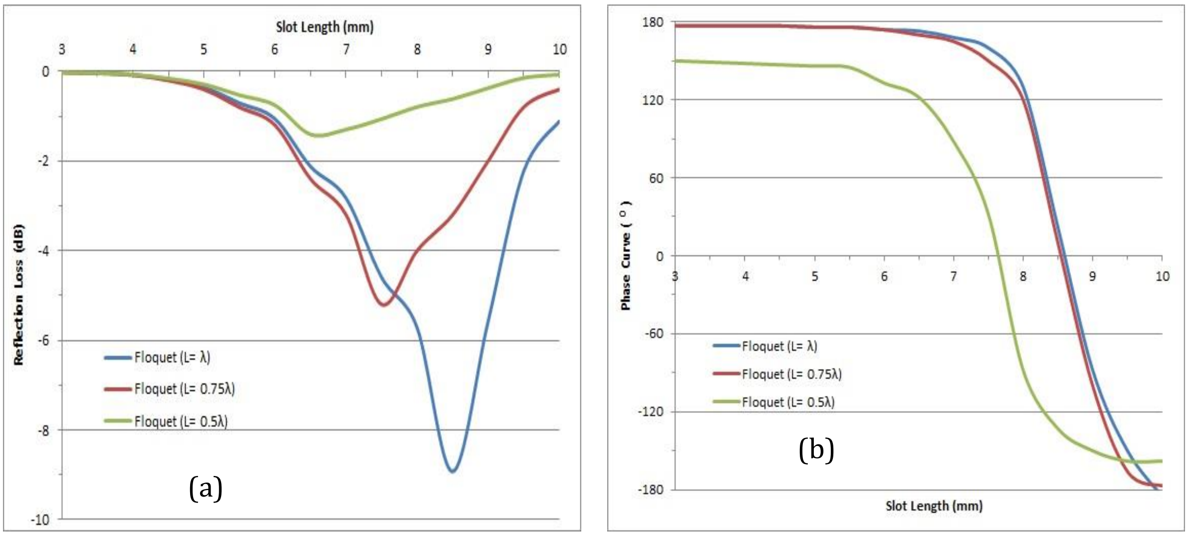


Figure (9): Influence of the separation distance between any two adjacent elements on the (a) reflection loss, (b) phase curve of the unit cell element.

تصميم هوائي Reflectarray عريض الحزمة باستخدام عنصر دائري مع فتحة على شكل-E

أ.م.د.عبد الكريم سوادي عبدالله ,أ.م.د.رمزي سالم علي , م. موسى هادي والي
قسم الهندسة الكهربائية / كلية الهندسة / جامعة البصرة

الخلاصة

في هذا العمل، سوف يتم اختبار عنصر مغير التصحيح على شكل دائري يحتوي شق على شكل–E لغرض تصميم reflectarray. تم تغير أبعاد الفتحة على شكل–E لغرض دراسة خصائص الانعكاس للهوائي المصمم. تبين أن خصائص الانعكاس ومدى الطور للموجة المنعكسة من العناصر المقترحة يمكن أن يكون الأمثل باستخدام أبعاد فتحة على شكل –E. تم فحص عنصر في حالة الرنين وتحليل كامل باستخدام أداة برمجية حديثة لتحليل الموجات لغرض المحاكاة. تحقق مجموعة طور (340^{o}) درجة بسهولة، وهو ما يكفي لتصميم (reflectarrays) بحجم صغير.