Reducing the Mutual Coupling of Cylindrical Circular Microstrip Antennas (CCMAs) Array Using EBG Structure

Nabeel Abbas Areebi ⓘ

Department of Physics, College of Education, University of Al-Qadisiyah, Al-Qadisiyah, Iraq.
E-mail address: nabeel.alsaadawi@qu.edu.iq

Abstract:

A theoretical study to design a conformal microstrip antennas was introduced in this work. Conformal microstrip antennas define antennas which can be conformed to a certain shape or to any curved surface. It is used in high-speed trains, aircraft, defense and navigation systems, landing gear and various communications systems, as well as in body wearable. Conformal antennas have some advantages such as a wider-angle coverage compared to flat antennas and low radar cross-sectional (RCS) and they are suitable for using in Radome. The main disadvantage of these antennas is the narrow bandwidth. The FDTD method is extremely useful in simulating complicated structures because it allows for direct integration of Maxwell's equations depending on time. The 1x2 cylindrical circular microstrip antennas array is designed and simulated vertically via Finite Difference Time Domain (FDTD) method where can directive antenna be achieved through antennas array design. Mutual coupling between the antennas in the array and the different separation between them were studied. The circular patch is excited by a probe feed method for several reasons including providing less spurious radiation from the probe current, in addition to the simplicity in theoretical engineering installation and practical manufacturing. It is well known that the values of the coupling are decreased as the distance separation increased. Cylindrical circular microstrip antenna with resonant frequency operating is 3.5GHz for TM_{01} mode, several parameters like return loss, band width, and input impedance are calculated. Also, for isolated coupling, mutual coupling coefficients, directivity gain, for different separations between the centers of the two adjacent circular patches in terms the wave length operating are calculated. Moreover, the electromagnetic band gap EBG structure is used for reducing the mutual coupling created by the surface waves in order to enhance the antenna's performance in an array has become smaller than before. The proposed EBG is a three triangular-shape equal sides metallic structure, utilizing the inter-element spacing in an array. The less value of S_{12} is -69dB for the spacing between the two centers of patches is 102.84mm. BW percentage increased to 34.3% and the directivity is enhanced also. Additionally, simulations were done using MATLAB 2017b.

Keywords: Array Antennas, Conformal microstrip antennas, EBG structure, FDTD method, Mutual coupling.

Introduction:

Recently, communications have developed widely and the microstrip antennas array played a curial role in this developing due to its multitasking possibilities which made it have many advantages in several applications. One of them, in high-performance spacecraft, is satellite and missile applications [1].

As known, a conformal antenna is defined as an antenna that can be compatible with a specific shape or on any curved surface by just changing the shape of the antenna ground plane. Additionally, the patch can be rolled on the base without getting any unacceptable changes in its radiation characteristics and does not cause an additional drawback [2].

The conformal antennas are divided into a singly curved (such as cylindrical antennas) and doubly curved (such as spherical antennas), depending on how many curvatures the geometry has. Generally, conformal antennas have some

advantages such as special angular coverage, wideband and lower radar cross-section(RCS) [3].

The directive gain of the single element has a low value and provides a relatively wide radiation pattern. Some applications demand the design of antennas with high directive gain characteristics. The directive antenna can be achieved by antennas array design. Important parameters must be calculated at stages of the conformal microstrip arrays design such as the effect of the mutual coupling between the elements [4]. Conformal microstrip arrays are used widely in a miscellaneous application [5] such as satellite arrays, antennas of an aircraft, and wearable networks [6]. The configuration of a directional cylindrical circular microstrip antenna CCMA array requires that the identical elements of CCMAs can be placed with an adjacent spacing between the elements. However, the closeness of the elements causes a mutual coupling between the elements due to the electromagnetic EM interaction between the elements which influenced the radiating properties. When the mutual coupling has a significant value then it affects the performance of the array including directivity, return loss and bandwidth, with a little negative effect on both near and far field patterns and the radiation efficiency. In other words, the current in each element changed depending on the amount of the mutual coupling between the elements. Thus, it is necessary to take into account the effect of mutual coupling while analyzing the arrays [7].

The radiation of the surface wave increases as the dielectric constant and substrate thickness increases [8], hence, this radiation may be controlled by various methods such as restricting the substrate size or adding a photonic band gap modal .The surface waves can be suppressed by utilizing the electromagnetic band gap EBG structures which reduce the mutual coupling and enhance the performance of antenna [8].An EBG structure can be defined as the fabricated periodic objects that prevent the propagation of EM waves with a certain band of frequency over the incident angles and for all polarization cases [9].The main challenge of tactical communication systems is the accessibility of relevant information on the particular operating environment required for the determination of the waveform's ideal use. The propagation model focuses mainly on broadcasting and wireless communication with a high directivity antenna [10].The current work has played a vital role in enhancing CCMA's performance. In other words, the EBG structure is used for reducing the mutual coupling created by the surface waves in order to enhance the antenna's performance in an array has

become smaller than before by reducing the mutual coupling between the array elements. Also, for isolated coupling, mutual coupling coefficients, directivity gain, for different separations between the centers of the adjacent circular patches in terms the wave length operating will be calculated .The inter-element spacing in an array can be utilized to put the proposed EBG.

Several EBG structures are used for mutual coupling reducing and bandwidth enhancement such as EBG structure with T- shaped slot (EBGT) and EBG structure with Opposite L-shape slot Loading T- shaped slot (EBGTL) in order to reduction the mutual coupling between radiating elements in such array($S_{12} = -32.19dB, BW = 4.76\%$ and the directivity 7.7 dB [7]. A rectangular-shape metallic structure with four periodic inverted H-shape slots, as a EBG structure is proposed by the researcher [8]. The mutual coupling coefficients between the elements of the array $S_{12} = -52.7dB$ and BW= 2.99% while directivity about 14.9 dB .

Cylindrical Circular Microstrip Antennas (CCMAs)

Antennas on singly surface curved are the easiest conformal antennas. It is the most obvious in non-planar geometry. Especially, the cylindrical antennas are commonly used in conformal antenna applications such as aerospace, communication systems and in many experimental radars[3]. Our study is concentrated on cylindrical conformal microstrip antenna with a circle patch or which is known cylindrical circular microstrip antenna (CCMA) [11].

The basic structure of CCMA is shown in Fig.1. The excitation was chosen by a probe feed method for several reasons including providing less spurious radiation from the probe current, in addition, to the simplicity in theoretical engineering installation and practical manufacturing. The coaxial feed consists of two conductors, the outer conductor is connected with the ground plane while the inner conductor extends through the dielectric substrate reaching to the patch. The essential feature of this type of feeding methods is that the feed can be placed at any required position within the patch aimed to obtain the impedance matching [8]. The ground plane of the CCMA is a metal cylinder of radius (a). The dielectric substrate is of dielectric constant ε_r and having thickness h extends around the body of the ground plane. The circular metal patch is etched on the surface of the substrate [12].

The ground plane has been assumed infinite along z-axis. The resonant frequency of the circular patch $f_{m,n,l}$ for TM_{mn} mode as a function of an

effective radius r_{eff} and effective dielectric constant ε_{eff} is given by [3]:

$$f_{010} = \frac{3.8318\,c}{2\pi\,r_{eff}\sqrt{\varepsilon_{eff}}} \qquad 1$$

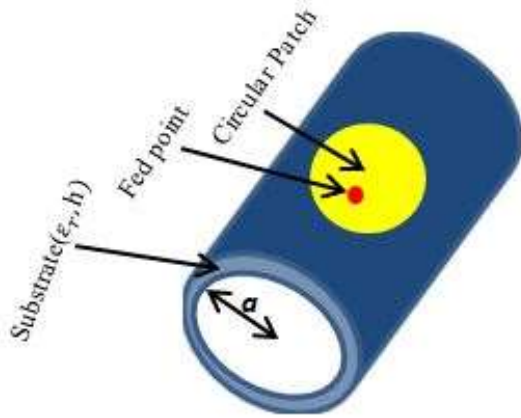where $m = 0, n = 1, l = 0$ and c is the speed of light.

Figure 1. Geometry of Cylindrical Circular Microstrip Antenna.

An antenna bandwidth is defined as

$$BW = 200 * \frac{(f_u - f_L)}{(f_u + f_L)}\% \qquad 2$$

where f_u: upper frequency. f_L: lower frequency.

FDTD method

Simulation model of FDTD method in time-domain is obtained by solving Maxwell curl equations [12]. FDTD method provides us with an understanding of the propagation of the electromagnetic waves in microstrip antennas. This method is to solve Maxwell's time-dependent equations in the time domain by converting it into finite difference equations. Simulation steps of FDTD method are starts by representing the physical structure depending on material type (conductor, dielectric or boundaries).

The second step is applied Gaussian pulse to simulate all the sources. Then, all the fields (electric and magnetic) are calculated at any increments of time. These fields are recalculated again after each increment until they decay to zero into the system. Finally, the frequency information is extracted by Fourier transformation. Yee supposed that FDTD space are cells of an $\Delta x \Delta y \Delta z$-volume and the components of electric and magnetic fields in 3D space are distributed as shown in Fig. 2. Every E-field component is surrounded by four H-field components and every H-field component is surrounded by four E-field components [12].
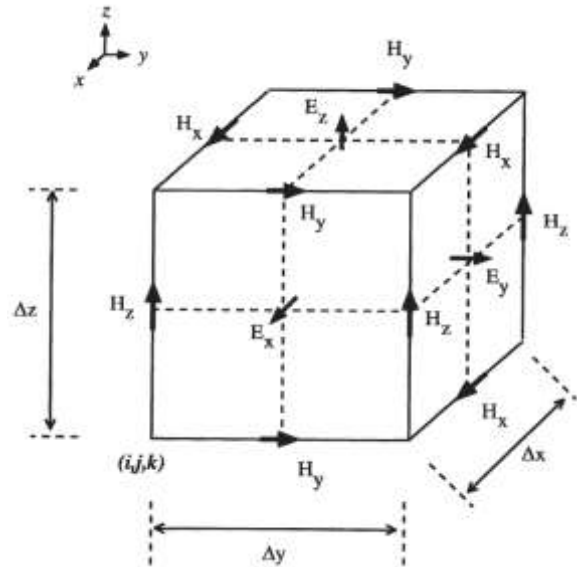

Figure 2. Yee's cell FDTD in 3D.

Basic Formulation of FDTD

Maxwell's time-dependent equation is used because of the wave front of the input signal is a function of time , and any computed results from a FDTD simulation are in the time domain, where the relationship between the input and output is available. When the FDTD simulation is completed , then, the input and output time functions will be transformed to the frequency domain by using Fourier transform Based on the system of central difference, Maxwell's curl equations can be replaced by a set of finite difference equations. The curl operator is yield to six-coupled scalar equations which equivalent to Maxwell's curl equations in a 3D rectangular coordinate system. These equations can be written as:

$$\frac{\partial H_x}{\partial t} = \frac{1}{\mu}\left(\frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y} - \rho' H_x\right) \qquad 3$$

$$\frac{\partial H_y}{\partial t} = \frac{1}{\mu}\left(\frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z} - \rho' H_y\right) \qquad 4$$

$$\frac{\partial H_z}{\partial t} = \frac{1}{\mu}\left(\frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x} - \rho' H_z\right) \qquad 5$$

$$\frac{\partial E_x}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} - \sigma E_x\right) \qquad 6$$

$$\frac{\partial E_y}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} - \sigma E_y\right) \qquad 7$$

$$\frac{\partial E_z}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} - \sigma E_z\right) \qquad 8$$

where ε represents the electric permittivity in Farad per meter, μ is the magnetic permeability in Henry per meter , σ represents the electrical conductivity and ρ' is the magnetic conductivity.

The FDTD simulation space is bounded, and these radiated or scattered fields will be

reflected back into the simulation space when they arrived at the boundary of FDTD space.

The perfect matched layer (PML) technique is presented by Berenger [13], who proposed an absorbing layer designed to absorb EM waves without any reflections [14]. The excitation of the system can be done by Gausses pulse

$$p(t) = e^{-\left(\frac{t-t_0}{\tau}\right)^2} \qquad 9$$

where τ is a damping factor has to value depends on the frequency range of the problem, t_0 is the time delay[15]. The far-field components can be getting by using the equivalence principle and through a near-field to far-field transformation.

Design of cylindrical circular microstrip antenna (CCMA)

The CCMA is fed by the coaxial probe technique, it is excited with the dominant mode TM_{01}. The dimensions of the patch are determined in terms of its resonant frequency formula (eq.1). The cylindrical antenna has a radius (a=10 cm). It is used in the civilian and military fields [10], especially, for unmanned aerial vehicle which need a broadband antenna. In our study, for a circular patch with its pure shape, the standard operating resonant frequency is 3.5 GHz. The proposed antenna is very suitable for the wireless local area network WLAN applications. WLAN operates at the frequency spectrum 3-10 GHz .In addition, this antenna is used in civilian and military fields, specially, for unmanned aerial vehicle, which need broadband antennas.

The proposed antenna contains RO 3003 material as a dielectric layer with the dielectric constant $\varepsilon_r = 3$ and thickness of the substrate is (h=1.5 mm). From Eq. 1 with resonant frequency $f_r = 3.5 GHz$, so the radius of patch obtained is equal $r_{eff} = 30.19$ mm. The simulated results of CCMA with the optimum dimensions are shown in Fig. 3.
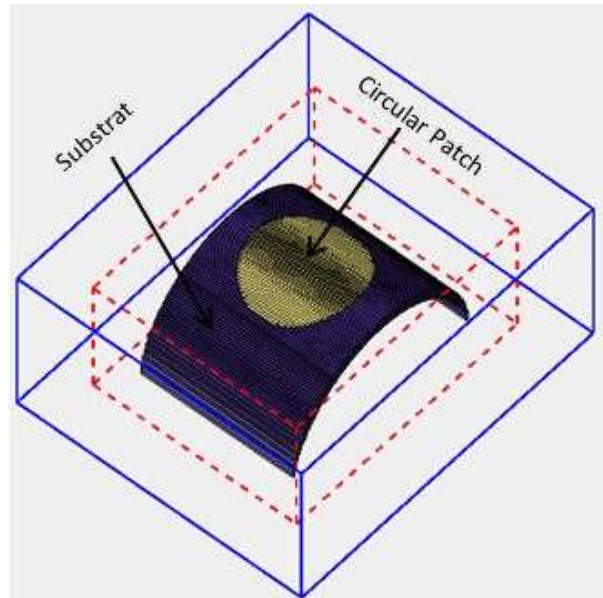

Figure 3. CCMA calculated by FDTD method.

Results and Discussion:
Input impedance Z_{in} and resonant frequency f_r

Simulation results of the real part (resistance) and imaginary part (reactance) of the input impedance are plotted in Fig. 4. At the moment where the reactance value is zero, the resonant frequency is $f_r = 3.5 GHz$ and the input impedance is $Z_{in} = 50\Omega$.
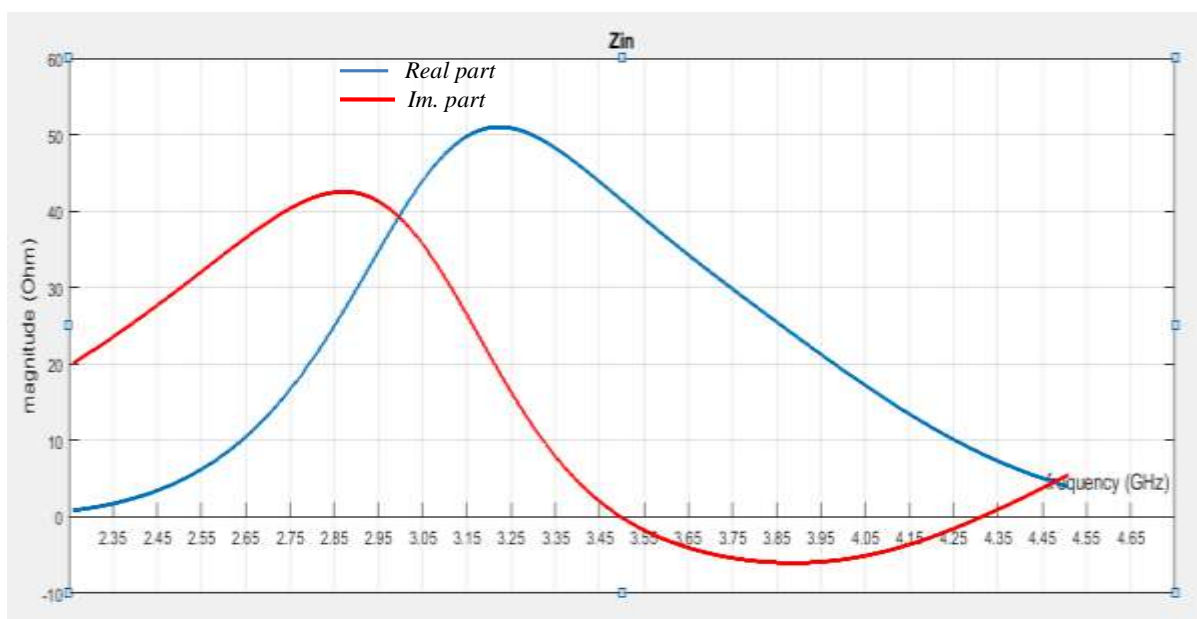

Figure 4. Input impedance versus frequency calculated by FDTD method.

Return loss(RL) and bandwidth

Fig. 5 shows that the calculated value of return loss is (-23.95dB) and the resonant frequency is $f_r = 3.5$GHz. Bandwidth of the microstrip antenna is calculated from Eq. 2. It is calculated from the frequency range at two sides of return loss at -10dB. The percentage of bandwidth is 12.34%.
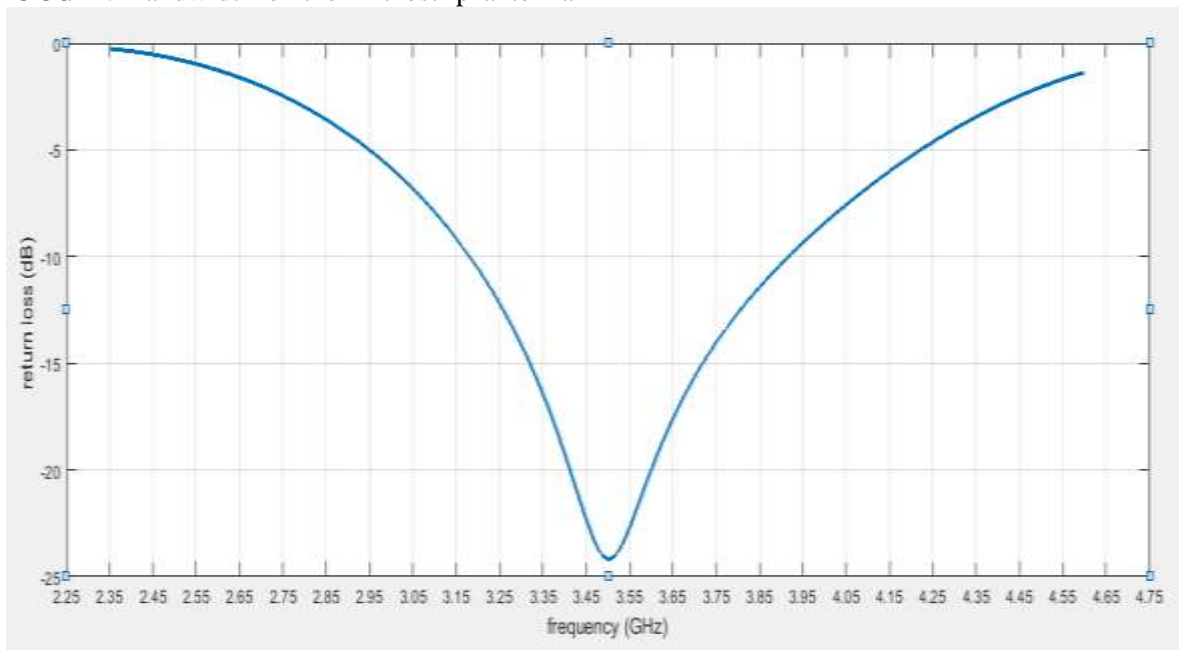

Figure 5. Return loss versus frequency calculated by FDTD method.

Design of 1x2 CCMAs Array

The proposed 1x2 array is designed and simulated by FDTD method. Return loss coefficients, mutual coupling coefficients, and resonant frequency are calculated and plotted for different separations between the elements. In addition, the directive gain is calculated.

Fig. 6 shows the simulated results for two identical CCMAs. The two patches have the same size and fed individually by a coaxial probe with TM_{01} mode. The separation between the centers of the two adjacent patches is 0.9λ where λ=85.7mm is the wavelength corresponds to the resonance frequency operating.

The analysis here is for isolated coupling which is defined as the mutual coupling between two elements only. The beginning was by study the effect of the separation (d) between the centers of two adjacent patches on the performance of the antennas array. The spacing (d) is selected to be in the range $0.9λ - 1.4λ$. The mutual coupling coefficients were calculated as a function of this spacing (d).

Values of the return loss coefficients, mutual coupling coefficients, and resonant frequency are shown in Figs. 7 and 8. Fig. 7 shows the values of the return loss for four different spacing (d), while, Fig. 8 shows the values of the mutual coupling. Table 1 shows the effect of the mutual coupling on the parameters of antenna for different separations (d).
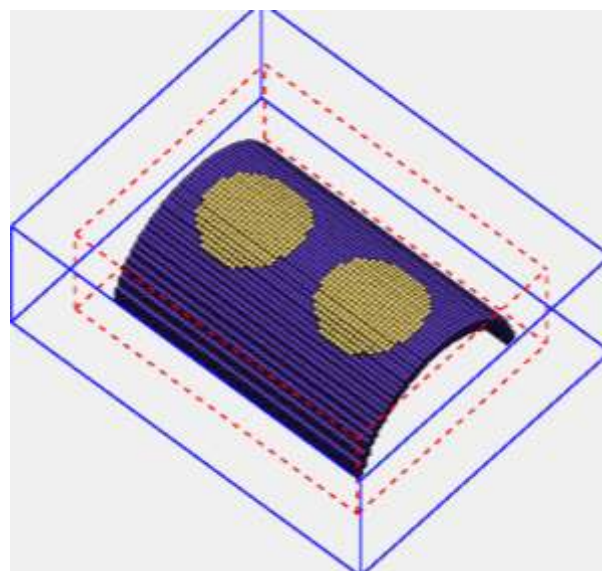
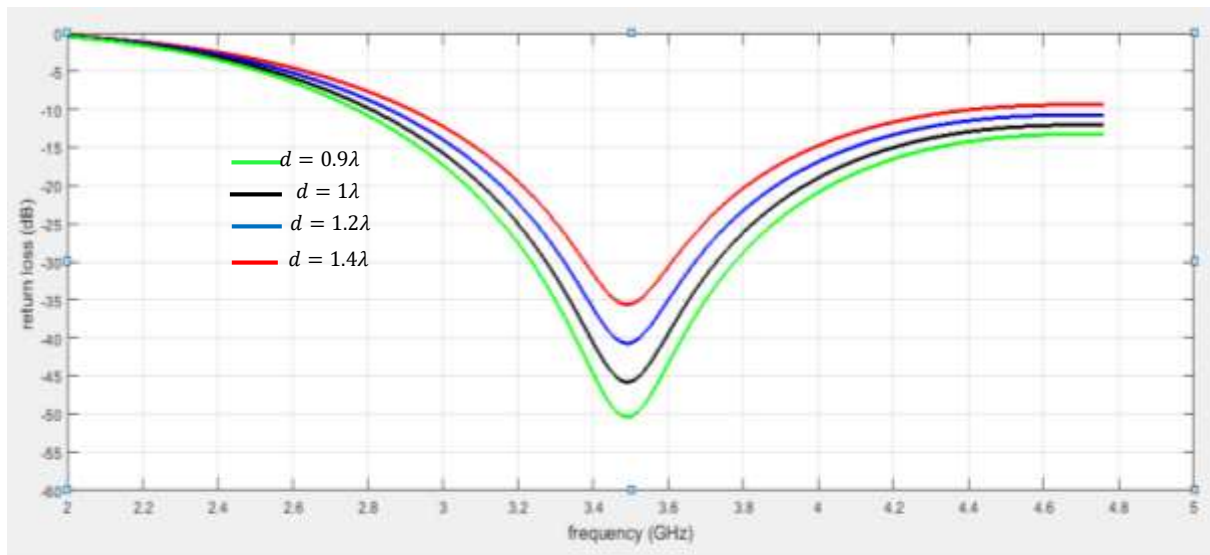

Figure 6. 1x2 array of identical CCMAs with.d $=$ 0.9λ.

Figure 7. Return lossS_{11} for different separations (d).
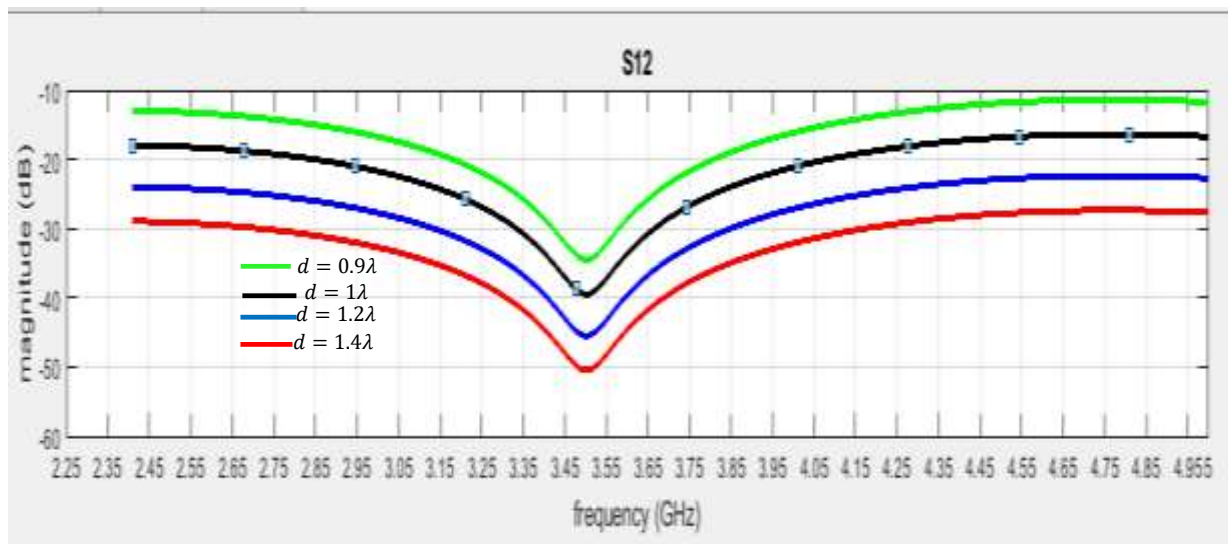

Figure 8. Mutual coupling coefficientS_{12} for different separations (d).

Table 1. Effect of the mutual coupling on the parameters of antenna for different separations.

Spacing (d)	S11 (dB)	S12 (dB)	Directivity (dB)	Resonant Frequency (GHz)
0.9λ	-50	-35	12.5	3.5
1λ	-46	-40	13.2	3.5
1.2λ	-41	-46	13.9	3.5
1.4λ	-36	-52	12.88	3.5

From the above results, it is shown that there is no change in the value of resonant frequency as a result of the design of the array. The return loss coefficient S_{11} increased as the interspacing between the centers of two adjacent patches increased, whereas, the mutual coupling coefficient S_{12} decreased. A better array directivity obtained at d = 1.2λ and $S_{11} = -41$dB. The resonant frequency was not significantly affected by the separation variation**.**

Design of 1x2 CCMAs Array with EBG structure

Several techniques are used for reducing mutual coupling. In this work, the electromagnetic band gap structure is employed to solve this coupling problem. Electromagnetic band gap (**EBG**) structure defined as an artificial structure reduces the propagation of the surface waves and its generated currents at special band and frequency for all the incident angles.

The proposed EBG is a three triangular-shape equal sides metallic structure. FDTD method is used to design and simulate EBG structure with side length is 4mm as shown in Fig.9. These dimensions are determined by using the trying and error method.

Values of the return loss coefficients, mutual coupling coefficients, and resonant frequency are shown in Figs. 10 and 11. These values are calculated for four different spacing (d). These Figs. show that the return lossS_{11} with EBG structure is increased compared with the S_{11} of the cases without EBG structure, whereas, the mutual coupling coefficient $S_{12}$is decreased. The less value of S_{12} is -69dB for the spacing between the two centers of patches is 102.84mm. S_{12} coefficient less than -32.19dB or -52.7dB for both 7,8, respectively. It can be clear that BW percentage increased to 34.3% compare with earliest studies. Directivity is enhanced also. The effect of EBG structure on the parameters of antenna for different separations is shown in Table 2. The current results can be compared with the earliest studies 7,8 as depicted in Table. 3. The resonant frequency didn't change because of the size both of the two circular patch or ground plane didn't change also due to not using a slots or partial miniaturization, respectively.
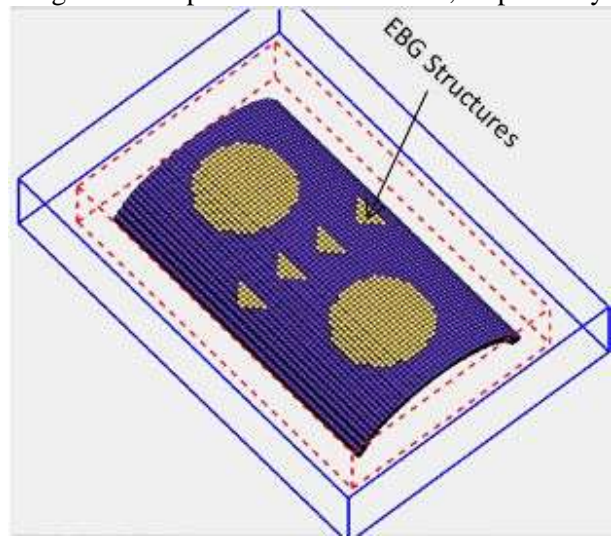

Figure 9. Results simulated of two identical CCMAs with EBG structure . $d = 0.9\lambda$
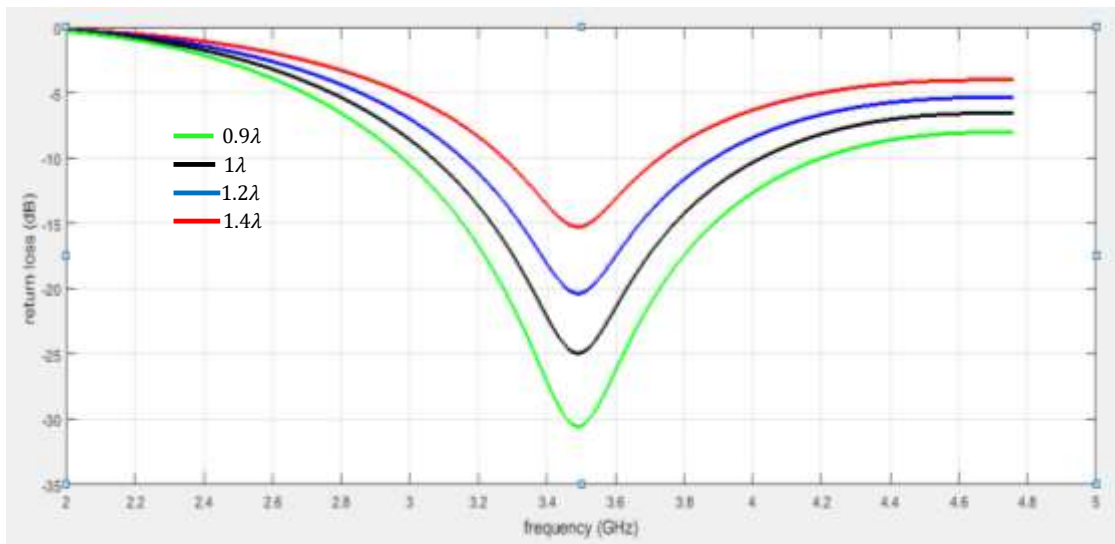

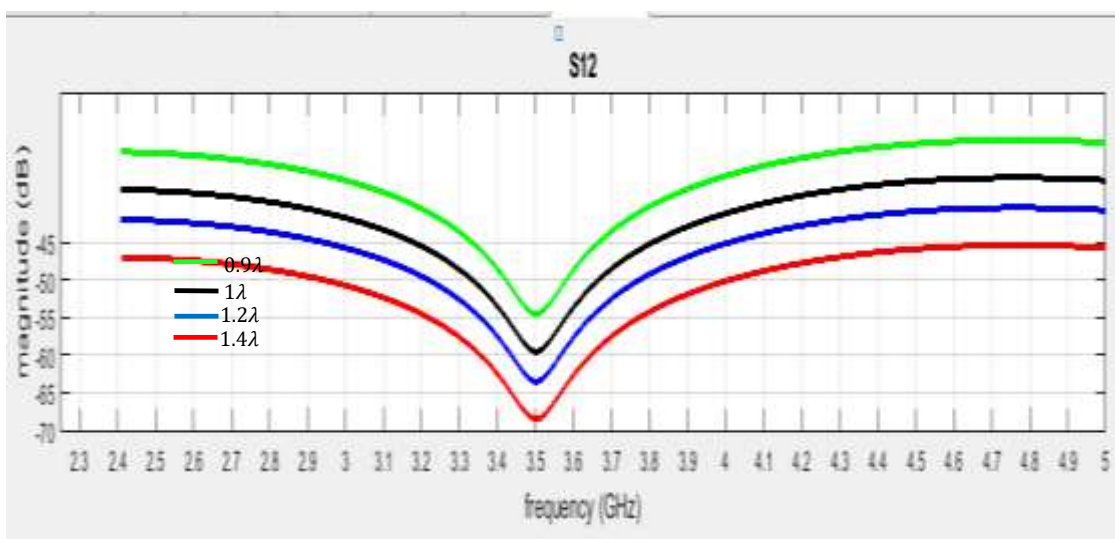**Figure 10. Return lossS_{11} for different separations (d).**

Figure 11. Mutual coupling coefficientS_{12} for different separations (d).

Table 2. Effect of EBG structure on the parameters of antenna for different separations.

Spacing(d)	S11(dB)	S12(dB)	Directivity(dB)	Resonant Frequency(GHz)
0.9λ	-31	-55	14.55	3.5
1λ	-25	-60	15.67	3.5
1.2λ	-21	-64	16.89	3.5
1.4λ	-15	-69	14.04	3.5

Table 3. Compare the parameters of antenna with the earliest studies

S12 (dB)	S12 (dB)7.	S12 (dB)8.	Directivity (dB)	Directivity (dB)7.	Directivity (dB)8.	Bandwidth%	Bandwidth% 7.	Bandwidth% 8
-55	-32.91	-35.8	14.55	7.7	12.9	14.28	4.76	2.73
-60	-33.96	-39.44	15.67	7.77	12.1	20.76	4.83	2.99
-64	-33.35	-42.64	16.89	7.82	14.99	26.72	4.81	2.82
-69	-32.95	-52.7	14.04	7.8	11.95	34.3	4.76	2.71

Conclusion:

To conclude, the FDTD method has been used to design and simulate 1x2 CCMAs array. The EBG technique has played a vital role in enhancing CCMA's performance. The coefficients of return loss are improved as the distance between the centers of two adjoining patches increased, while the coefficients of mutual coupling are reduced, additionally, better directivity has been acquired at d=1.2λ. Hence, this study confirms that using EBG structure reduces the values of the elements mutual coupling with increasing the coefficients of return loss.

Author's declaration:

- Conflicts of Interest: None.
- I hereby confirm that all the Figures and Tables in the manuscript are mine. Besides, the Figures and images, which are not mine, have been given the permission for re-publication attached with the manuscript.
- Ethical Clearance: The project was approved by the local ethical committee in University of Al-Qadisiyah.

References:

1. Wa'il A, Shaaban RM,Ahmed ZA .Designing a Microstrip Patch Antenna in Part of Ultra-Wideband Applications. Baghdad Sci J. 2020; 17(4): 1216. https://doi.org/10.21123/bsj.2020.17.4.1216
2. Naik M N. Design of compact annular ring microstrip antenna for multiband communication system. JNCET.2017; 7(8): 24-28.
3. Josefsson L,Persson P.Conformal Array Antenna Theory and Design. Canada: Wiley-IEEE Press; 2006, 512 p.
4. Hati K, Sabbar N, El Hajjaji A, Asselman H.A novel multiband patch antenna array for satellite applications. Procedia Eng. 2017; 181: 496-502.
5. Ijaz B, Sanyal A, Mendoza-RadalA, Roy S, Ullah I, Reich M, et al. Gain limits of phase compensated conformal antenna arrays on non-conducting spherical surfaces using the projection method. In: IEEE Int. Conf. Wirel. Extreme Environ. conf. dig. (WiSEE); 2013: 1-6.
6. Zhu S, Langley R. Dual-band wearable textile antenna on an EBG substrate. IEEE Trans. Antennas Propag. 2009; 57(4): 926-935.
7. Galli H S, Ahmed Z A, Abood A H. Mutual Coupling Reduction in Microstrip antenna array Using ebg. J Basrah Res Sci. 2018;44(1): 122-132.
8. Areebi N A, Ahmed Z A, Aubais M M. New Design of Cylindrical Rectangular Microstrip Antenna (CRMA) By Using The Slots Technique. J Kufa phys..2020; 12(1): 1-8.
9. Guo Z, Tian H, Wang X, Luo Q, Ji Y.Bandwidth enhancement of monopole UWB antenna with new slots and EBG structures. IEEE antenn wirel pr. 2013; 12: 1550-1553.
10. Azita L Y, Hafizi H, NorsuzilaY, Nur H M H. Performance Analysis of Propagation in VHF Military Tactical Communication System. Baghdad Sci J. 2021; 18(4): 1378-1386. https://doi.org/10.21123/bsj.2021.18.4(Suppl.).1378
11. Kohar S, SinghS,De A .Design of Low Profile Cylindrical Conformed Microstrip Patch Antenna for Wideband Operation. IETE J Res. 2021 Jul; 29: 1-10.
12. Godara LC. Handbook of Antennas in Wireless Communications. USA: 1st Ed. CRC press; 2002, 936 p.
13. Al-Hillo M M, Nabeel A A. Bandwidth Enhancement of Hexagonal Patch Microstrip Antenna with Several Approaches. J. Basrah Res Sci. 2017; 35: 1-11.
14. Bérenger JP . Perfectly matched layer (PML) for computational electromagnetics. Synth Lect Comput Electromagn. 2007; 2(1):1-117. https://www.ate.uni-due.de/data/coft1/JOCP_1994_Berenger.pdf
15. Taflove A, HagnessSC,Piket-May M.Computational electromagnetics: the finite-difference time-domain

method. The Electrical Engineering Handbook. 2005; 3: 629-670. https://doi.org/10.1016/B978- 012170960-0/50046-3

تقليل الاقتران المتبادل لمصفوفة هوائيات شريطية اسطوانية ذات المشع الدائري باستخدام تقنية فجوة الطاقة الكهرومغناطيسية

نبيل عباس عريبي

قسم الفيزياء، كلية التربية، جامعة القادسية، القادسية، العراق.

الخلاصة:

قدم العمل الحالي دراسة نظرية لدراسة وتصميم الهوائيات الشريطية التي تعرف على انها الهوائيات التي من الممكن تثبيتها على الاجسام المنحنية وبأشكال مختلفة. تستخدم هذه الهوائيات في القطارات عالية السرعة , الطائرات , انظمة الملاحة وفي انظمة الاتصالات فضلا عن الاجهزة التي من الممكن ان ترتدى كملبس. بالمقارنة مع الهوائيات المستوية, يمتاز هذا النوع من الهوائيات بتغطية واسعة للإشعاع وبمساحة مقطع راداري قليلة مما يجعلها اكثر ملائمة في ما يسمىRadome , لكن العيب الرئيسي لها هي عرض الحزمة الضيق. استخدمت طريقة الفروق المحددة في مجال الزمن لكونها مفيدة للغاية في تصميم ومحاكاة التراكيب الهندسية المعقدة حيث توفر حلا مباشرا لمعادلات ماكسويل المعتمدة على الزمن . صممت مصفوفة 1 X 2 بالشكل العمودي من الهوائيات الشريطية الاسطوانية ذات المشع الدائري وتمت عملية محاكاة مصفوفة الهوائيات هذه باستخدام طريقة الفروق المحددة في مجال الزمن والمعروفة بالرموز FDTD. تمكنا من الحصول على هوائيات تمتاز بربح اتجاهية عالي بتصميمنا هذا الشكل من المصفوفات. العمل الحالي تضمن دراسة ما يعرف بالاقتران المتبادل بين عناصر المصفوفة بالإضافة الى دراسة تأثير المسافة الفاصلة بين تلك العناصر على خواص الهوائي. تم تغذية المشع الدائري باستخدام طريقة التغذية المحورية وذلك لعدة اسباب منها, كون هذه التقنية تقلل من الاشعاع الزائف الناتج عن تيار المغذي, اضافة الى سهولة تصميمها ومحاكاتها بشكل نظري وتصنيعها عمليا. لاحظنا ان قيم معاملات الاقتران ستتناقص عند زيادة المسافة بين عناصر المصفوفة. شملت الدراسة ايضا حساب العديد من معاملات الهوائي الشريطي الاسطواني ذو المشع الدائري والذي يعمل بتردد رنيني مقداره 3.5 كيكا هرتز وبنمط انتشار من نوع TM_{01} , من هذه المعاملات, عامل الفقد وممانعة الدخل وعرض الحزمة بالإضافة الى دراسة معاملات المصفوفة كمعامل الاقتران المتبادل ومقدار ربح الاتجاهية ولقيم مختلفة للمسافة الفاصلة بين مركزي المشعين الدائريين, حيث تقاس هنا المسافة بدلالة الطول الموجي (λ) والذي يتوافق مع تردد الرنين الذي يعمل به الهوائي. علاوة على ذلك, تم استخدام تركيب فجوة الطاقة الكهرومغناطيسية EBG كتقنية تعمل من اجل تقليل قيم الاقتران المتبادل الناتج عن الموجات السطحية بهدف تحسين عمل واداء الهوائي في مصفوفة قيد الدراسة من الممكن ان تكون اصغر حجما. تم تصميم ثلاثة مثلثات متطابقة ومتساوية الاضلاع لتكون شكل فجوة الطاقة الكهرومغناطيسية المقترح والذي يقع في المسافة الداخلية بين عناصر المصفوفة. ان قيمة معامل الاقتران المتبادل S_{12} قلت الى سالب 69 ديسيبل عندما كانت المسافة بين مركزي المشعين 102.84 ملم. النسبة المئوية لعرض الحزمة ازداد الى 34.3% وكذلك فأن الاتجاهية قد تحسنت. تمت المحاكاة باستخدام لغة البرمجة الماتلاب.

الكلمات المفتاحية: هوائيات المصفوفة، الهوائيات الشريطية المنحنية، تركيب الفجوة الكهرومغناطيسية، طريقة الفروق المحددة في مجال الزمن، الاقتران المتبادل