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DESIGN AND MODELING OF PLANAR LENS ANTENNA ELEMENT IN X-BAND APPLICATIONS

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ABSTRACT

This paper presents the modeling and design of compact planar lens antenna element in X-band applications. The antenna element is realized by using aperture-coupled patches with simple and less fabrication complexity phase-control mechanism. The lumped-element parameters of the equivalent circuit model were determined analytically considering the physical structure of the unit cell at 8 GHz. The proposed lens antenna element achieves phase shift range of 205° with almost uniform transmission coefficient of better than -1 dB. The equivalent circuit theoretical simulations were validated with CST MWS simulations and a very good agreement was demonstrated.

Key words: Lens Antenna • Aperture-Coupled • Equivalent Circuit • X-band •

INTRODUCTION

A flat lens antenna (also known as transmitarray or discrete lens) has a low profile, less cost and lightweight properties which are the main requirements of today's communication systems. In addition to these, flat lens antenna has narrow beamwidth and high gain which made it a good fit for airborne applications. The antenna consists of an array of microstrip receiving and transmitting patches which are coupled or connected together by phase shifters. A feed antenna usually horn, patch, open ended waveguide or arrays of antenna elements are used to illuminate one side of the array lens to create a space-fed antenna system (Thornton and Huang, 2012). The basic conceptual operation of flat lens antenna can be divided into three processes. First, an incident spherical wave-front radiated from the feeding source is received by the reception interface of the array. Secondly, the received signal is collimated or converted into a planar wave-front by the phase-error correction mechanism. And finally, the processed signal with the desired wave-front properties is transmitted by the transmit patches of the lens antenna as illustrated in Figure 1 (a) (Padilla et al., 2010).

Several phase shifting mechanism approaches have been developed in the last decades. A lens antenna unit cells using metallic phase delay lines were proposed in (Padilla et al., 2010), (McGrath, 1986). Other techniques for phase error compensation are coupled patch antennas using element rotation (Phillion and Okoniewski, 2011), (Kaouach et al., 2011), aperture coupling (Pozar, 1996), (Awaleh et al., 2014) and using a periodic FSS inspired elements (Abbaspour-Tamijani et al., 2004). However, reaching a compromise between antenna physical requirements, such as compact size and less manufacturing complexity and electromagnetic properties has become a challenging task.

The aim of this paper is to design a high performance and compact size flat lens antenna element using simple and less fabrication complexity phase correction mechanism. Two rectangular slots embedded on the common ground plane were used to realize the desired phase error compensations. In order to get more physical insight of the element, an equivalent electrical circuit model was proposed and simulated. This equivalent circuit model which is not reported much in lens antenna literature, gives the designer more degrees of freedom in analyzing and optimizing the antenna elements. The rest of the paper is organized as follows: First, the unit cell design configurations and modeling are presented, followed by the results and discussion. Finally, the conclusion of the work is given in the last section.

UNIT CELL DESIGN AND MODELING

Description of the Proposed Unit cell

A compact flat lens antenna element based on aperture-coupled concept has been proposed in this work as shown in Figure 1. The main function of flat lens antenna unit cell is to collimate or re-phase the incident spherical wave from feed antenna into planar radiated wave. Therefore, each antenna element must be designed according to the amount of desired phase adjustment, considering the element's position on the surface of the array.

The unit cell structure consists of two back-to-back square patches with non-resonating aperture-coupled common ground plane. Two identical rectangular apertures are embedded at the center of the common ground plane. The element dimensions are organized in a square pattern, where the unit cell size equals 18.8×18.8 mm^2 ($\lambda_o/2 \times \lambda_o/2$ at 8 GHz). Two square patches of size 9.3×9.3 mm^2 are printed on two standard FR4 substrates having relative permittivity (ε_r) of 4.3, dielectric loss tangent (tan δ) of 0.02 and physical thickness of 1.6 mm. The two slots lengths are systematically varied simultaneously to compensate phase delays that the incident signal encounters while travelling from the source to the flat lens antenna array surface.

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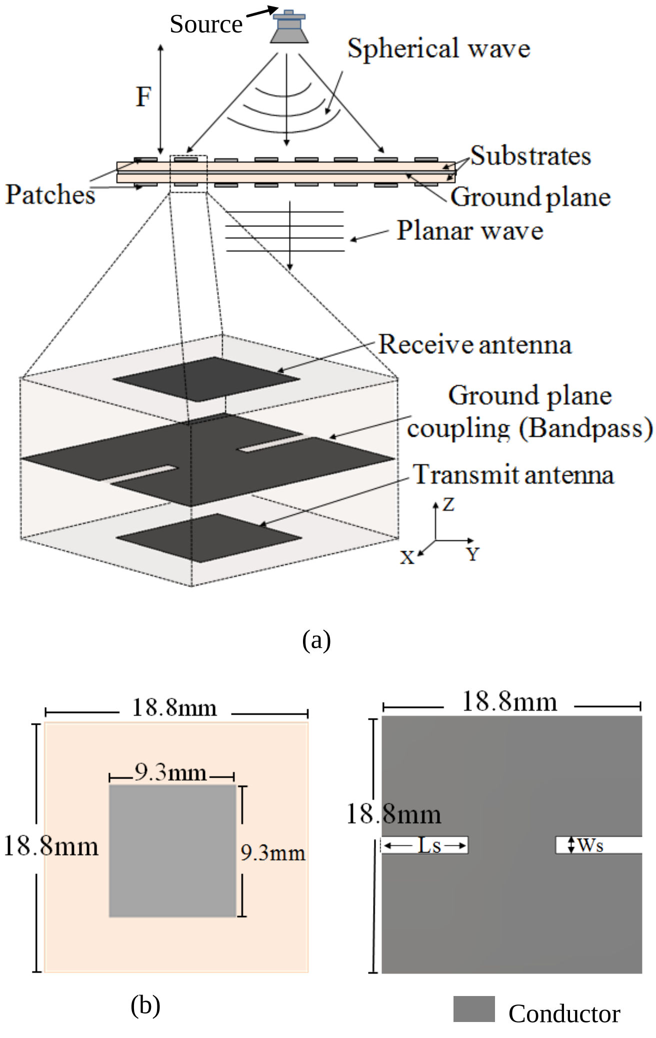

Figure 1: Geometry of the proposed unit cell (a) Flat lens antenna and unit cell illustrations (b) square patch (c) Slotted common ground plane.

The slots have dimensions of L_s and W_s with an equal separation distance from the center of the structure as depicted in Figure 1(c), in which the slot length (L_s) controls the amount of coupling or decides the phase compensation capability of the structure, while the slot width (W_s) has a much lesser affect. In this study, the phase range performance of the flat lens antenna elements were examined using the two identical slots embedded in the common ground plane. Slots lengths (L_s) variations from 4 mm to 8 mm and a uniform width (W_s) of 2 mm are carried out to study how much phase shift range can be achieved with this simple design structure.

The major requirement of designing a unit cell for planar lens antenna array is to achieve the desired phase delay compensation range of up to 360°. Therefore, each element for the array lens must be designed to provide the desired phase error correction. These can be determined using the following equation (Datthanasombat, et al., 2001).

$$\varphi_i = (2\pi/\lambda_0)(S_i - F) \pm 2\pi N + \varphi_0 \qquad (1)$$

Where φ_i is the desired phase delay of an individual element from the array; λ_0 is the free space wavelength while φ_0 is the phase of the central unit cell on the lens array. S_i is the distance between phase center of the feed antenna and i^{th} unit cell on the array surface. F is the focal distance (see Figure 1(a)), whereas N is an integer number which satisfies $0<\varphi_i \leq 2\pi$.

Equivalent Electrical Circuit Model

In order to obtain more physical insight of the antenna element, an equivalent electrical circuit model of the square patches and the slotted common ground plane was designed and simulated. The proposed circuit comprises of two parallel RLC resonators connected by a coupling transformer model as shown in Figure 2. The circuit model has two ports represented by two ideal transformers for free-space impedance transformation.

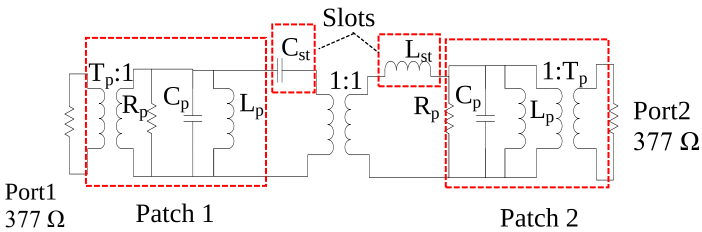

Figure 2: Equivalent circuit model of the back-to-back patch element.

Ordinary rectangular patch antenna can be modelled and analysed as parallel RLC components which are based on microstrip patch antenna cavity model (Garg et al., 2001). The equivalent capacitance (C_p), inductance (L_p) and resistance (R_p) of the patch can be determined analytically while considering the element's physical characteristics (Kaouach et al., 2012).

The value of R_p, L_p and C_p can be defined as:

$$C_p = \frac{\varepsilon_{ef}\,\varepsilon_o\,LW}{2h}\cos^{-2}\left(\frac{\pi y_o}{L}\right) \qquad (2)$$

$$L_p = \frac{1}{C_p.\omega_r^2} \qquad (3)$$

$$R_p = \frac{Q_r}{C_p.\omega_r} \qquad (4)$$

Where L and W in equation (2) represent the length and width of the patch respectively; ε_{ef} is the effective dielectric constant, ε_o is the free-space permittivity, h is the substrate thickness while y_o is the feed point position. Q_r and ω_r are the radiation quality factor and the angular frequency at the resonance of the patch respectively (Garg et al., 2001), (Kaouach et al., 2012).

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The rectangular slots on the ground plane are modelled as series inductance (L_{st}) and gap capacitance (C_{st}) and can be calculated as (Bahl, 2003).

$$L_{st}=\frac{Z_C}{16\pi f_r F}\tan(\pi f_r L_S) \tag{5}$$

$$C_{st} = 2L_s\frac{\varepsilon_o}{\pi}\left[\ln\left(2\frac{1+\sqrt{k'}}{1-\sqrt{k'}}\right)+\ln\coth\left(\frac{\pi W_s}{4h}\right)\right] \tag{6}$$

Where Z_c is the characteristic impedance of the patch, k' represents number of waves that couple through the aperture and $F = \cos^{-2}(\frac{\pi y_o}{L})$.
Three ideal transformers were used to represent the input and output ports ($\eta = 377\Omega$) of the patches and coupling aperture of the element. The radiation resistances (T_p and T_c) of the transformers are considered and calculated as (Awaleh et al., 2014). The equivalent circuit model is simulated using Multisim$^{v13.0}$ software and the calculated values of the circuit parameters are summarized in Table 1.

Table 1: Calculated equivalent circuit parameters at 8 GHz

Parameter	Value
C_P	8.7 pF
L_p	45.5 pH
R_p	79.4 Ω
T_c	1
T_p	0.25
C_{st}	0.48 pF
L_{st}	0.94 nH

RESULTS AND DISCUSSION

In this flat lens antenna unit cell design, the required phase error correction and planar radiated wave is achieved by the variations of the slots dimensions. The double rectangular slots have dimensions of L_s and W_s in which the slots lengths (L_s) contribute significantly the amount of aperture coupling and phase delay response of the element. As illustrated in Figure 3 (b) the phase shift performance of this antenna element is a function of frequency. The phase range performance of the element is investigated by varying the slot lengths (L_s) from 4 mm to 8 mm. A 205° range of phase shift is obtained at 8 GHz with an almost uniform transmission coefficient of better than -1 dB as shown in Figure 3.

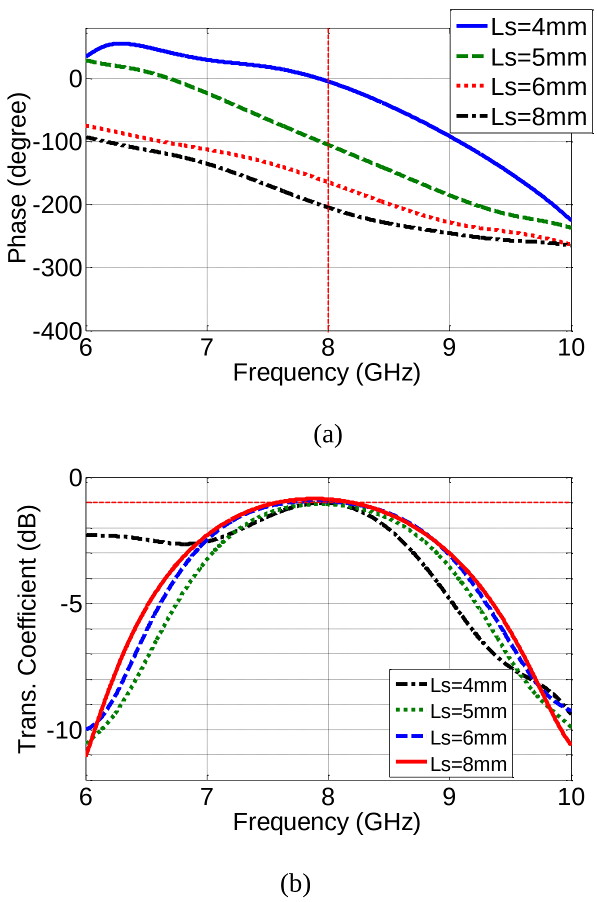

Figure 3: Effect of different slots lengths and (constant W_s = 2 mm) on (a) Transmission phase (b) Transmission coefficient.

The unit cell equivalent electrical circuit model is simulated using Multisim^{v13} and its transmission phase and reflection coefficient performances are recorded. The coupling inductance L_{st} and coupling gap capacitance C_{st} are varied to examine the S-parameter responses of the element. It is observed that the length of the slot controls the value of the series coupling inductance L_{st} in the circuit model, where larger slots lengths contribute to lower L_{st} values and vice versa. On the other hand, the gap between the two rectangular slots develops a capacitance which most affects the resonance frequency of the element. This means that increasing the slot length causes the fundamental resonance frequency to shift to lower frequencies. For the coupling aperture equivalent circuit components, no resistance element is introduced as the signal couples through the non-radiating aperture and its loss contributions are very less.
Figure 4 illustrates the reflection coefficient and transmission phase for three different values of gap capacitance C_{st}. This is to observe the effect of C_{st} on the S-parameters of the element. As mentioned, over this range of capacitances, the resonant frequency of the unit cell changes as shown in Equation (7). Hence, the required phase shift range of the lens array can be obtained by tuning the slot capacitance. Further increase of C_{st} value causes the structure to have two resonance frequencies as illustrated in

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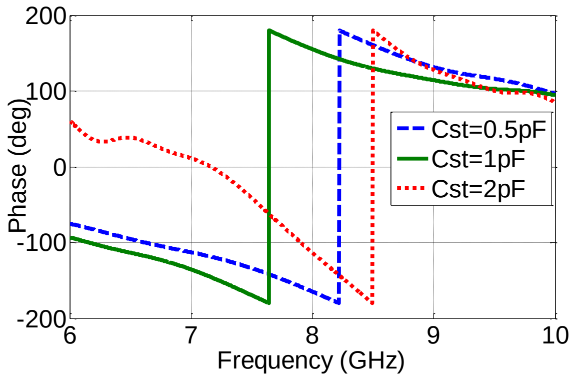
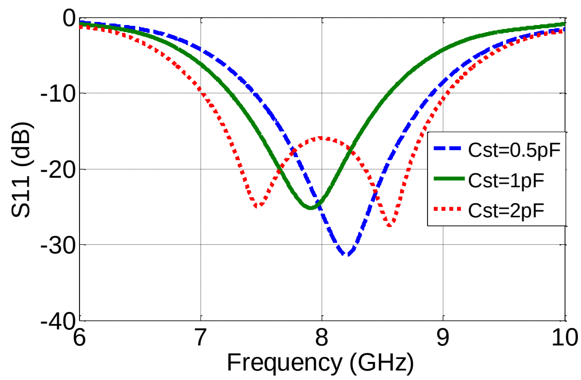
Figure 4(b). Thus, the slots lengths (L_s) of the element can be calculated by using this equivalent circuit model and this eliminates the need of performing a lot of parametric studies to realize the desired phase compensation of the antenna element. In this study, in order to reduce the mutual coupling a uniform and periodic unit cell patch size was employed.

$$f \propto \frac{1}{\sqrt{LC}} \qquad (7)$$



(a)



(b)

Figure 4: Effect of different capacitance C_{st} values on (a) Transmission phase (b) Reflection coefficient. (L_{st} also varies as C_{st} changes depending on the slot length value (L_s))

The transmission and reflection coefficients characteristics obtained from the equivalent circuit model simulations are compared with CST Microwave Studio software simulations. This is to validate the acquired circuit simulation results or to verify the performance of the proposed equivalent circuit model. To assume the analysis of large lens array, an infinite periodic boundary condition (PEC and PMC) are utilized as demonstrated in Figure 5 (Awaleh and Dahlan, 2014). The unit cell E-M simulated results demonstrate a good agreement with the model simulations as shown in Figure 6. The slight difference between the theoretical and simulated s-parameter results could be the difference between the simulations set up of the two software.

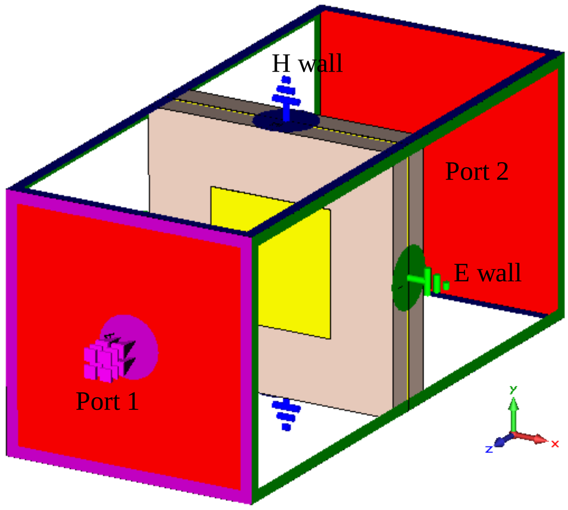


Figure 5: Unit cell boundary condition in waveguide simulator set up.

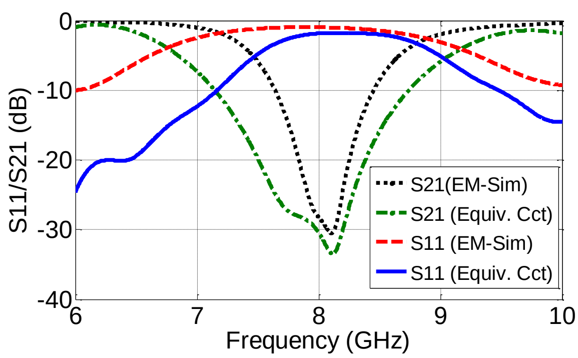


Figure 6: Equivalent circuit and E-M simulations for S-parameters performance comparison

CONCLUSION

A flat lens antenna unit cell design and its equivalent electrical circuit model are proposed and simulated. The designed element has compact structure with simple and less fabrication complexity mechanism for transmission phase control. The equivalent circuit model provides more physical insight to analyze and understand the performance characteristics of the element. The theoretical results are validated using CST Microwave simulations. Further investigations and experimental results will be presented during the conference.

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