

FDTD Analysis of a Probe-Fed Dielectric Resonator Antenna in Rectangular Waveguide

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Abstract—Dielectric resonator antennas (DRA) are characterized for operation in a guided-wave environment with the ultimate goal of their use in modeling of waveguide-based DRA amplifier arrays for spatial power combining. Performance of a single probe-fed DRA element in rectangular waveguide is analyzed by varying design parameters of the DRA and the feeding probe to optimize the structure for the scattering characteristics (port matching and coupling). The effect of hard walls on the DRA behavior is also studied. The numerical analysis of waveguide-based DRA elements is based on the Finite-Difference Time-Domain (FDTD) method and a coaxial probe is modeled by a thin wire approximation implemented in the FDTD algorithm. The numerical results are compared with those generated by using commercial software and exhibit a very good agreement.

Index Terms—Dielectric resonator antenna, rectangular waveguide, hard wall, Finite-Difference Time-Domain method.

I. INTRODUCTION

DIELECTRIC resonator antennas (DRA) became potentially useful as antenna elements a few decades ago [1]. The DRA's have several attractive features, such as small size, light weight, inherently wideband nature, high radiation efficiency, and high power handling capability as compared with microstrip antennas, which suffer from higher conduction loss and surface waves in antenna array applications. The use of additional structural parameters (shape, volume, etc.) and a wide range of permittivities makes the design of DRA's more flexible. In addition, different feeding mechanisms can be used for the excitation of DRA elements, which allows for control of DRA input impedance, bandwidth, and radiation pattern. This includes the excitation by slots, probes, microstrip lines, coplanar lines, and dielectric image guides [2]-[4]. Also, the use of dielectric materials with high permittivity in DRA's enables enhancement of the radiation resistance of electrically short probes and loops [5]. Subsequently, systematic theoretical and experimental investigations of DRA's have been reported in [6]-[12] and extensive results of DRA's of cylindrical [1], [3], [8]-[10], rectangular [6], and spherical [7] shapes have been published.

In this paper, coaxial probe-fed DRA elements are studied for operation in a rectangular waveguide with the ultimate goal of their use in waveguide-based DRA amplifier arrays for spatial power combining. Traditionally, the spatial power combiner is formed by an array of amplifying unit cells, with

each cell receiving, amplifying, and then radiating a signal into free space [13]-[15]. The key challenges of spatial power combining design are the modeling of receive/transmit antenna elements and the uniform excitation of the antenna arrays. Thus, modeling of one element in rectangular waveguide is important to fully understand the behavior of the DRA in the waveguide environment. Regarding the uniform excitation of amplifier arrays, hard electromagnetic walls have been recently realized by dielectric loading along narrow sides of the waveguide to obtain a uniform field distribution in the waveguide cross-section [16], [17]. The interaction between the DRAs and the hard walls needs to be studied since it significantly affects the resonance frequency and matching characteristics of the DRA.

Here, a single probe-fed DRA element is first investigated for operation in a rectangular waveguide. The scattering parameters are studied by varying geometrical and material parameters of the DRA and the coaxial probe feed. Then, the effect of a dielectric-loaded waveguide on the DRA performance is analyzed. The FDTD method [18], [19] is chosen for the numerical analysis since it provides a full-wave solution of the electrically large and complicated structures, which include different dielectric materials. In the proposed FDTD algorithm, DRA elements and the rectangular waveguide are discretized by using a traditional Yee-cell gridding and the coaxial probe is modeled by a thin wire approximation. The scattering parameters are computed using the FDTD method and compared with the results obtained using the commercial software QuickWave3D [20] and HFSS [21].

The paper is organized as follows. In Section II, a brief description of the FDTD method used in the numerical analysis of waveguide-based probe-fed DRA's is presented. In Section III, an initial design of a single free-space DRA element is presented, followed by the analysis of DRA behavior in an open-ended rectangular waveguide using WIPL-D [22]. Next, the developed FDTD algorithm is used for the parametric analysis of a probe-fed DRA element in a rectangular waveguide to optimize the structure for the scattering characteristics (port matching and coupling). Section IV presents the analysis of a dielectric-loaded waveguide and the effect of hard walls on the DRA performance. Conclusions are summarized in Section V.

II. THEORY

The structure to be analyzed here consists of a coaxial probe-fed DRA element inside a rectangular waveguide as shown in Fig. 1. The geometry is analyzed by using the FDTD

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$$\begin{aligned}
 &= \sum_{j=1}^{N_y} \frac{\Delta y_j}{2} [E_x(x_i, y_j, z_0, t) \phi_x(y_j) \\
 &\quad + E_x(x_i, y_{j-1}, z_0, t) \phi_x(y_{j-1})], \\
 &\quad \int_0^a E_y(x, y_j, z_0, t) \phi_y(x) dx \\
 &= \sum_{i=1}^{N_x} \int_{x_{i-1}}^{x_i} E_y(x, y_j, z_0, t) \phi_y(x) dx \\
 &= \sum_{i=1}^{N_x} \frac{\Delta x_i}{2} [E_y(x_i, y_j, z_0, t) \phi_y(x_i) \\
 &\quad + E_y(x_{i-1}, y_j, z_0, t) \phi_y(x_{i-1})].
 \end{aligned} \tag{7}$$

Integrals $\int_{x_{i-1}}^{x_i} \phi_x(x) dx$ and $\int_{y_{j-1}}^{y_j} \phi_y(y) dy$ in (6) are calculated in closed form.

The coaxial line is modeled by rectangular prisms instead of two concentric cylinders, since the amount of power travelling into the coaxial line is mainly dependent on the characteristic impedance of the coaxial line [27] and weakly dependent on its specific shape. The inner conductor of the coaxial line can be represented either by a thin wire or by a number of cells. In our work the inner conductor is approximated as a thin wire with radius smaller than half of the FDTD mesh size [28]. With $E_z(i, j, k) = 0$ along the wire axis, the spatial dependence of magnetic fields in the vicinity of the wire can be calculated by

$$\begin{aligned}
 H_y^{n+\frac{1}{2}}(i, j, k) &= H_y^{n-\frac{1}{2}}(i, j, k) \\
 &\quad + \frac{\Delta t}{\mu \Delta z} [E_x^n(i, j, k) - E_x^n(i, j, k+1)] \\
 &\quad + \frac{2\Delta t}{\mu \Delta x \ln(\frac{\Delta x}{r_0})} E_z^n(i+1, j, k),
 \end{aligned} \tag{8}$$

$$\begin{aligned}
 H_x^{n+\frac{1}{2}}(i, j, k) &= H_x^{n-\frac{1}{2}}(i, j, k) \\
 &\quad + \frac{\Delta t}{\mu \Delta z} [E_y^n(i, j, k+1) - E_y^n(i, j, k)] \\
 &\quad - \frac{2\Delta t}{\mu \Delta y \ln(\frac{\Delta y}{r_0})} E_z^n(i, j+1, k),
 \end{aligned} \tag{9}$$

where the wire radius r_0 is assumed to be less than half of the cell size.

III. SINGLE DRA ELEMENT IN RECTANGULAR WAVEGUIDE

Our investigation begins with information available in the literature and then we learn step by step about the DRA in different environments. Therefore, we start with a DRA in free space and end up with a DRA in a waveguide loaded with hard walls. Since the FDTD method is one of the methods used in the analysis, the rectangular DRA is a geometry that can be easily analyzed. A single, probe-fed rectangular DRA placed on an infinite ground plane and radiating in free space, as shown in Fig. 3(a), is considered first, and is analyzed by commercial Method of Moments (MoM) software WIPL-D

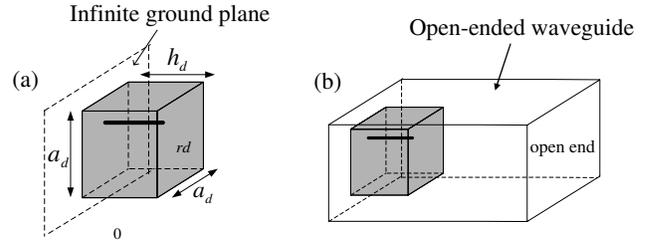


Fig. 3. (a) Geometry of infinite conductor-backed, probe-fed DRA; (b) Geometry of probe-fed DRA inside semi-infinite waveguide.

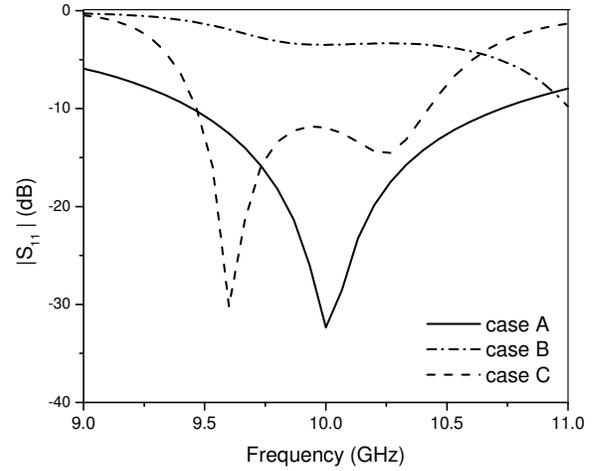


Fig. 4. Reflection coefficient for different configurations of the DRA. Case A: DRA of Fig. 3(a); Case B: DRA with parameters of Fig. 3(a) placed in waveguide as in Fig. 3(b); Case C: DRA in waveguide with $h_d = 9.5$ mm and $\delta_d = 1.5$ mm as in Fig. 3(b).

[22]. The initial dimensions of the DRA structure $a_d = 5.0$ mm, $h_d = 12.0$ mm, $\epsilon_{rd} = 12.0$ are chosen so that the resonant frequency of the $TE_{11\delta}$ mode is centered around 10 GHz [29]. The probe length l_d is 4 mm, the probe axis is offset by $\delta_d = 1.0$ mm from the waveguide centerline in the vertical direction, and the probe radius r_w is 0.3 mm. Then, the probe-fed DRA with dimensions from case A (Fig. 3(a)) was placed into an open-ended standard X-band waveguide with cross-sectional dimensions $a = 22.86$ mm and $b = 10.16$ mm (case B with geometry shown in Fig. 3(b)).

Figs. 4 shows dispersion behavior of the reflection coefficient for the geometries shown in Figs. 3(a) and 3(b) (cases A and B in Fig. 4). Due to placement of the DRA inside of the rectangular waveguide, the resonant frequency of the DRA in case B is shifted to a frequency higher than 11 GHz, which is out of frequency band of interest. Subsequently, the height of the DRA and the probe position were tuned to $h_d = 9.5$ mm and $\delta_d = 1.5$ mm, respectively, and results are presented as case C. Considerable changes of the resonant frequency and bandwidth are observed in Fig. 4. These dimensions serve as starting values for a numerical study that follows.

An analysis of the waveguide-based coaxial probe-fed DRA (Fig. 1) with the parameters from case C is performed by the full-wave FDTD method described in Section II. For the rectangular coax of radius 1.2 mm and filled with the dielectric

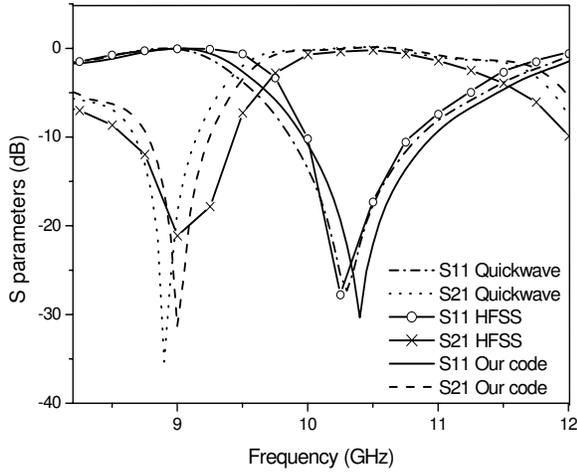
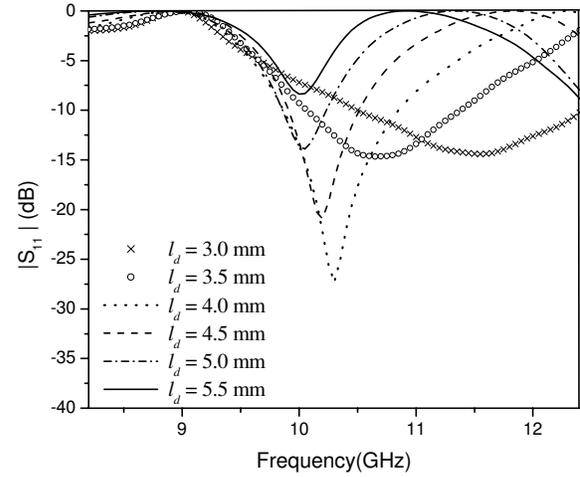


Fig. 5. S-parameters for the waveguide-based probe-fed DRA ($a_d = 5.0$ mm, $h_d = 9.5$ mm, $\delta_d = 1.5$ mm, $l_d = 4.0$ mm).

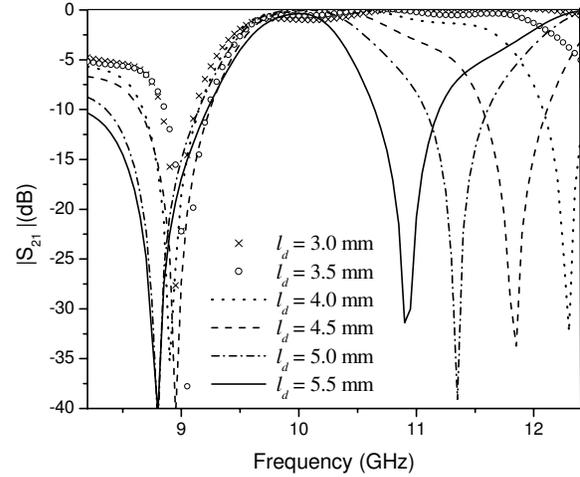
of permittivity $\epsilon_r = 2.56$, the characteristic impedance Z_0 is 51.98Ω , and only the TEM mode is supported as the cutoff frequency of the TE_{11} coaxial line mode is approximately 26 GHz [30]. The probe length l_d is 4 mm and the probe position is offset by $\delta_d = 1.5$ mm from the waveguide centerline in the vertical direction. Fig. 5 shows the dispersion behavior of the S-parameters. The bandwidth for this case, based on -10 dB level, is 10% (compared to the 3% bandwidth of a microstrip patch antenna used in a similar configuration [31]). The results in Fig. 5 are verified with commercial FDTD software QuickWave3D [20] and HFSS [21] and exhibit very good agreement. Once our FDTD code is verified, we depend on it in the following analysis.

The effect on port matching and bandwidth of different parameters of the DRA are then investigated. For the structure operating in the X-band, it is found that position and length of the probe both have a significant effect on the matching as well as the overall frequency response. Figs. 6(a) and 6(b) show the return loss and insertion loss of the structure with different values of l_d . It is found that a short probe couples weakly to the DRA. As the probe length increases, the coupling is increased and a shift to lower resonant frequency is observed. When the probe lengths equal 3.5 mm and 4.0 mm, wide bandwidth and less reflections are achieved, respectively. As the probe is increased to 4.5 mm and beyond, the coupling to the DRA starts decreasing.

The effect of the probe position δ_d with respect to the waveguide centerline is illustrated in Figs. 7(a) and 7(b), which show the return loss and insertion loss of the structure for different values of δ_d with $l_d = 4.0$ mm. It is found that the maximum -10 dB bandwidth occurs when δ_d reaches 2.0 mm and also good insertion loss is achieved. It is clear that both the probe length and position can be used to tune and control the response for both port matching as well as wide bandwidth.



(a)



(b)

Fig. 6. Effect of varying the probe length l_d in the DRA on (a) return loss and (b) insertion loss, ($a_d = 5.0$ mm, $h_d = 9.5$ mm, $\delta_d = 1.5$ mm).

IV. SINGLE DRA ELEMENT IN DIELECTRIC LOADED RECTANGULAR WAVEGUIDE

The ultimate goal of this work is to design an efficient spatial power combining system which needs to achieve a uniform power division among the antenna elements in the DRA array by using hard walls. For one element design, hard electromagnetic walls in the hollow rectangular waveguide can be created by loading its narrow walls with dielectric material. By appropriately choosing the dielectric thickness for a given dielectric material, a uniform field distribution can be achieved over the cross-section of the waveguide. In a standard X-band waveguide, the PEC boundaries define the TE_{10} mode of propagation. The dielectric material loading along the sidewalls in the rectangular waveguide changes the boundary condition so that the LSE_{10} mode will propagate. The LSE_{10} mode provides a uniform field distribution in the inner waveguide region (in between dielectric slabs) when the dielectric thickness d is calculated according to the following

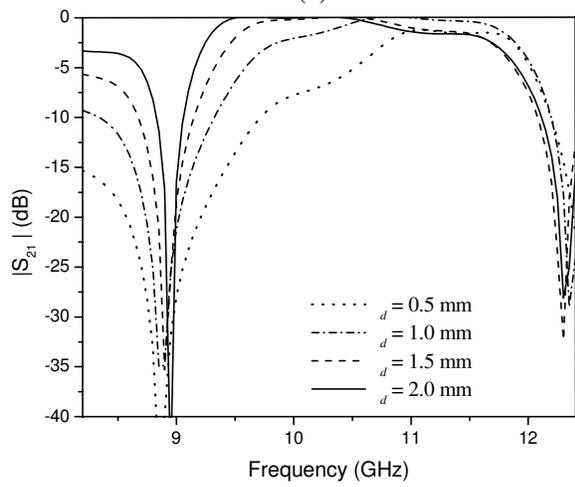
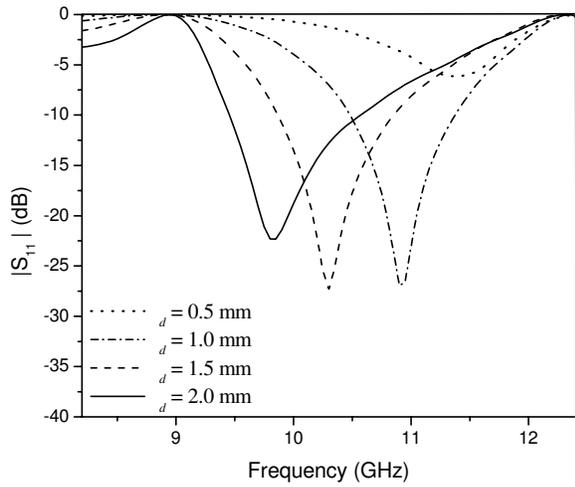


Fig. 7. Effect of varying the probe position δ_d with respect to the DRA centerline on (a) return loss and (b) insertion loss, ($a_d = 5.0\text{mm}$, $h_d = 9.5\text{mm}$, $l_d = 4.0\text{mm}$).

formula [32]:

$$d = \frac{\lambda}{4\sqrt{\epsilon_r - 1}} \quad (10)$$

where λ is the wavelength in free space and ϵ_r is the relative permittivity of the dielectric material. Hence, at the center frequency of operation, the thickness of the dielectric wall is approximately $\lambda_d/4$, where λ_d is the wavelength in the dielectric. In Fig. 8, the electric eld amplitudes for the LSE₁₀ mode of the dielectric loaded waveguide and the TE₁₀ mode of the hollow waveguide are plotted along the x -axis at 10 GHz. Both of these amplitudes are normalized to unity power.

Since the eld distribution for the TE₁₀ mode of operation in a standard X-band rectangular waveguide is sinusoidal in the waveguide cross-section as shown in Fig. 8, the electric eld in the middle of the waveguide is stronger than that offset from the centerline. Consequently, the coaxial probe-fed DRA couples more energy when it is placed in the middle

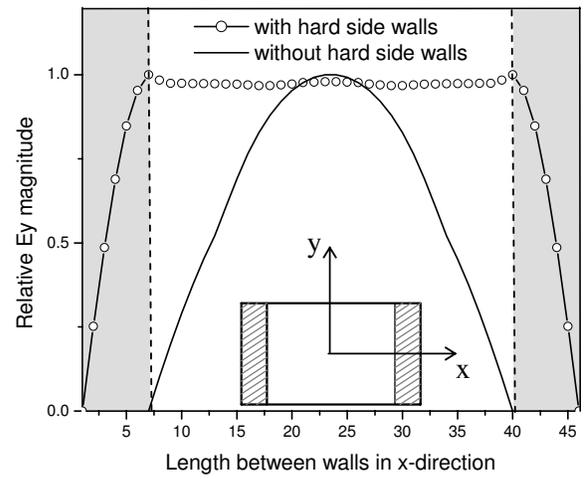


Fig. 8. The electric eld magnitude of the TE₁₀ mode in a hollow rectangular waveguide and the LSE₁₀ mode in rectangular waveguide with hard walls at 10 GHz.

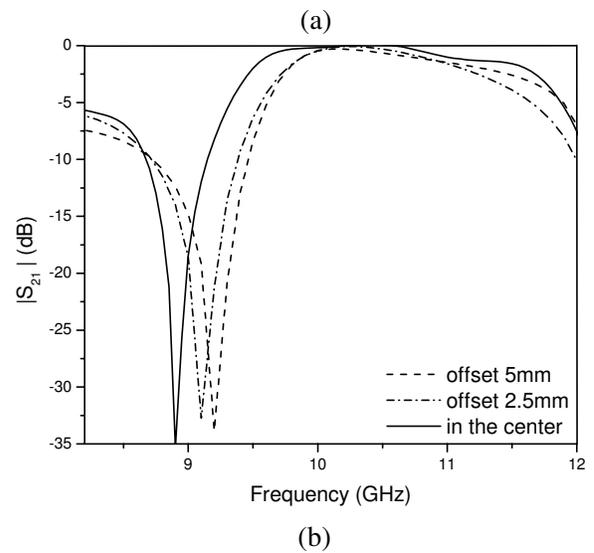
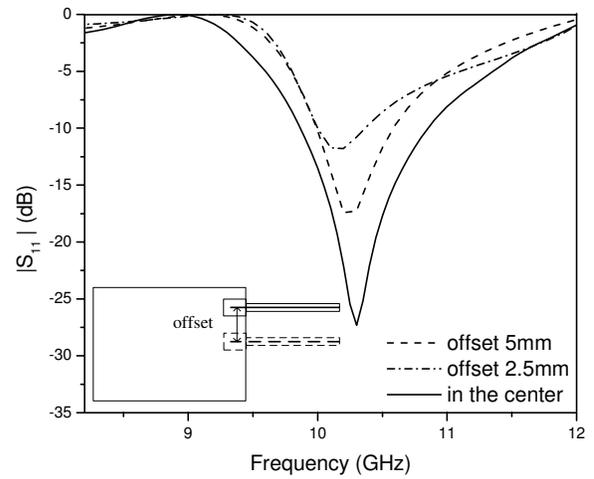


Fig. 9. (a) return loss and (b) insertion loss of the DRA element offset from the centerline of the waveguide, ($a_d = 5.0\text{mm}$, $h_d = 9.5\text{mm}$, $\delta_d = 1.5\text{mm}$, $l_d = 4.0\text{mm}$).

of the waveguide. As seen in Figs. 9(a) and 9(b), the scattering parameters are obtained for the cases when the DRA is placed in three different positions: in the first case the DRA is in the middle of waveguide, the second and the third cases are for the DRA placed 2.5 mm and 5 mm offset from the waveguide centerline in the horizontal direction, respectively. Figs. 10(a) and 10(b) show the field distributions (at 10 GHz and $\lambda/2$ away from the surface of the DRA) for the coaxial probe-fed DRA in the center of the waveguide and 5 mm offset from the centerline, respectively. In Fig. 10(b), 8 dB power difference between the middle and 5 mm offset can be observed from the magnitude of the field. These results verify that the element closest to the side wall of the waveguide will couple less power from the source than the one in the middle.

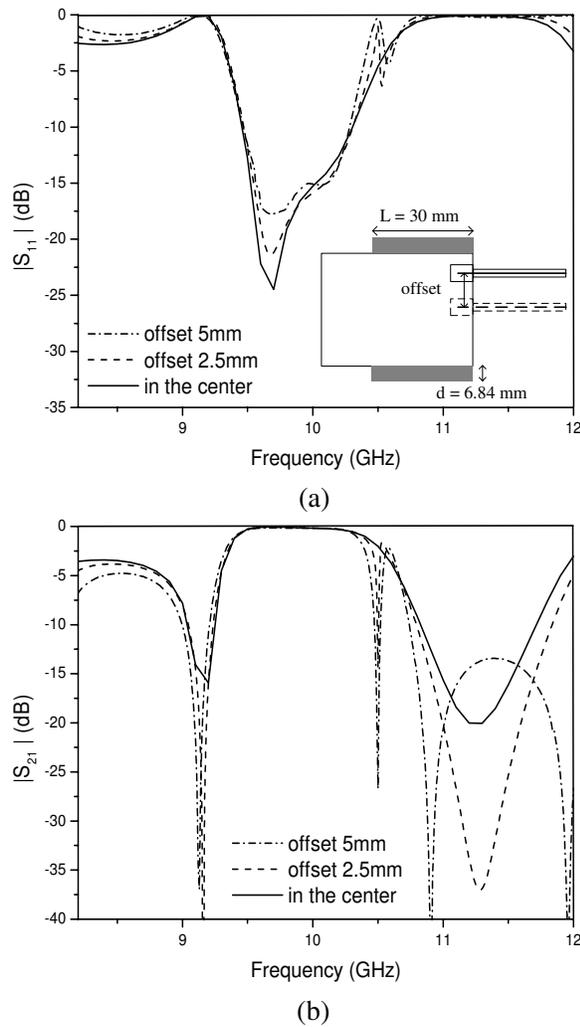


Fig. 10. (a) return loss and (b) insertion loss of the DRA element offset from the centerline of the waveguide loaded with hard walls, ($a_d = 5.0$ mm, $h_d = 7.5$ mm, $\delta_d = 2.0$ mm, $l_d = 3.5$ mm).

As seen in the inset in Fig. 11(a), a coaxial probe-fed DRA is placed in the rectangular waveguide with dielectric hard walls. The approximate depth of the hard wall, $d = 6.48$ mm, is calculated by Eq. (10) and the length of the hard wall L

equals to 30 mm. The choice of dielectric material affects the bandwidth of the uniform field. It has been found that dielectrics with permittivities from 1.2 to 2.2 can be used to achieve a good uniform field distribution across the waveguide aperture [32] and, therefore, $\epsilon_r = 2.2$ is used in our analysis. The coaxial probe-fed DRA element is placed in three different positions: in the middle of waveguide, and 2.5 mm and 5 mm offset from the waveguide centerline. Figs. 10(a) and 10(b) demonstrate that the resonance frequency and scattering parameters of these three cases do not change significantly as compared to the cases of DRA in the waveguide without hard walls (Figs. 9(a) and 9(b)). The field distributions (at 10 GHz and $\lambda/2$ away from the surface of the DRA) for the coaxial probe-fed DRA in the center of the waveguide loaded with hard walls and 5 mm offset from the centerline are shown in Figs. 12(a) and 12(b). One can see (Fig. 12(b)) that 3 dB power difference between the middle and 5 mm offset is achieved, so the DRA element couples approximately the same energy around the center frequency for these three different positions, which verifies that the uniform field distribution is achieved across the waveguide aperture as shown in Fig. 8.

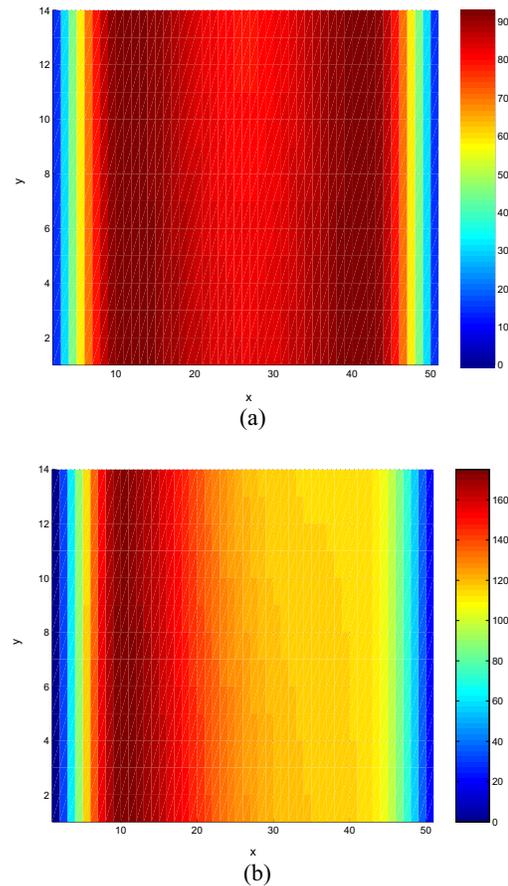


Fig. 11. Field distribution of the DRA element; (a) in the center of the hard-walled waveguide and (b) offset 5 mm from the centerline of the waveguide loaded with hard walls, ($a_d = 5.0$ mm, $h_d = 9.5$ mm, $\delta_d = 2.0$ mm, $l_d = 3.5$ mm).

V. CONCLUSION

A coaxial probe-fed DRA in a rectangular waveguide excited by the dominant mode was analyzed by using a custom FDTD technique. This analysis provides the necessary information for the optimization of design parameters, such as DRA dimensions and the position and length of the feeding probe. Consequently, 10% bandwidth was achieved over the frequency band of interest. A waveguide loaded with hard walls was studied to obtain a uniform field distribution at the waveguide aperture. It is shown that the DRA element couples approximately the same energy around the center frequency when it is placed in the middle of the waveguide and offset from the centerline. This study is a useful step in the extension to the case of the DRA array for increasing the output power and the power combining efficiency of waveguide-based spatial power combiner.

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