electrodes, and (iii) an output collimator. To achieve optimal performance, the whole modulator, including the input collimator, sandwiched crystal module, and output collimator were carefully aligned so that an incoming light signal would be equally distributed between the pair of electro-optic crystals. In the operation, the same amounts of electric fields, but in opposite directions, were applied on two crystals. These positive and negative electric fields changed the index of refraction in opposite directions, which increased the relative phase differences between the crystals and reduced the required driving voltage. The main advantages of the presented modulator technique are: (i) polarization independence, (ii) insensitivity to ambient temperature fluctuations, and (iii) capability of handing high input power as compared with integrated optic modulators. These unique features make it possible for the modulator be widely used in optics communication networks, in which low polarization dependent loss (PDL), highly stabilized temperature performance, and high power handing capability are critically required.

REFERENCES

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Figure 5  Plot of normalized output light intensity versus external voltage. Solid line corresponds to the result at 0°C and dashed line corresponds to the result at 65°C
modes in microstrip and patch antenna structures [3]. Later, we extended this technique to investigate the 3D resonant modes of DRAs [4]. In the present work we continue our efforts to analyze the resonant modes of rectangular DRAs by using the FDTD method, and to investigate the effects of the DRA’s dimensions and its surface metalization, and the feed location on the formation of the resonant modes.

2. SIMULATION PROCEDURE

We have modeled a variety of DR antennas, all of which have a dielectric constant of 88. However, they have different dimensions and different types of surface metalization, such as metal strips on the faces of the dielectric block or on the sides. The resonators are assumed to be located on an infinite ground plane, which serves as one of the boundaries of the computational domain, while perfectly matched layers (PML) are placed at all other boundaries. The resonator is excited by a microstrip transmission line, which is terminated at the side surface of the resonator. We have investigated different locations of the microstrip by shifting it along the length of the dielectric block, as shown in Figure 1. An electric field source of Gaussian type with a bandwidth of 12 GHz modulated by a sinusoidal wave of 6 GHz was employed to excite the microstrip line.

The time-domain simulations are used to model the distributions of electric- and magnetic-field components inside the DRAs, and the fast Fourier transform (FFT) is subsequently applied to derive the corresponding amplitude and phase distributions at different frequencies. The input return loss spectra have also been simulated in order to determine the resonant frequencies. The analyses of the resonant amplitude and phase distributions have enabled us to plot the 3D charts of the resonant modes, and to describe them as combinations of magnetic or electric dipoles located within the DRA. This type of equivalent dipole representation is useful for predicting the radiation efficiency and directivity of the DR antennas at different resonant frequencies.

3. RESONANT MODE ANALYSIS

Figure 2 presents an example of the analysis of the resonant mode excited at 7.2 GHz in the DR, whose dimensions are 5.6 × 12 × 1.8 mm. The contour plot and the 3D distribution of the amplitude of the normal electric field component, as well as its phase distribution in the plane located 0.5 mm above the ground plane, are depicted in Figures 2(a)–(d), respectively. We also have simulated the distributions of all other field components of the DR at different cross sections. The obtained data enabled us to construct the 3D field chart of the mode, which is depicted in Figure 2(d). The observed mode is of TM_{241} type and its fields are similar to the ones produced by two vertical

![Figure 2](image)

**Figure 2** (a) Contour plot; (b) 3D plot; (c) phase plot of the normal electric field component of the TM_{241} mode (7.2 GHz) in the DRA with dimensions of 5.6 × 12 × 1.8 mm in the plane located 0.5 mm above the ground plane; (d) mode chart of the TM_{241} mode.

The time-domain simulations are used to model the distributions of electric- and magnetic-field components inside the DRAs, and the fast Fourier transform (FFT) is subsequently applied to derive the corresponding amplitude and phase distributions at different frequencies. The input return loss spectra have also been simulated in order to determine the resonant frequencies. The analyses of the resonant amplitude and phase distributions have enabled us to plot the 3D charts of the resonant modes, and to describe them as combinations of magnetic or electric dipoles located within the DRA. This type of equivalent dipole representation is useful for predicting the radiation efficiency and directivity of the DR antennas at different resonant frequencies.

![Table 1](image)

**Table 1** Dipole Representation of the Modes in the DRA with the Dimensions of 3 × 12 × 1.8 mm

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>6.2 GHz</th>
<th>7.0 GHz</th>
<th>7.6 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field schemes</td>
<td>E</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>Dipole location</td>
<td>y</td>
<td>z</td>
<td>z</td>
</tr>
<tr>
<td>Mode types</td>
<td>TE_{111}</td>
<td>TE_{111}</td>
<td>TE_{111}</td>
</tr>
<tr>
<td>Radiation ability</td>
<td>Nonradiating</td>
<td>Radiating</td>
<td>Nonradiating</td>
</tr>
</tbody>
</table>

![Table 2](image)

**Table 2** Elimination of Resonant Modes in the DRA with Dimensions of 3 × 12 × 1.8 mm by Changing the Feed Location

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>6.2</th>
<th>7.0</th>
<th>7.15</th>
<th>7.6</th>
<th>7.9</th>
<th>8.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode type</td>
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<td>TE_{111}</td>
<td>TE_{111}</td>
<td>TE_{111}</td>
<td>TE_{111}</td>
<td>TE_{111}</td>
</tr>
<tr>
<td>Dipoles Locations</td>
<td>←</td>
<td>←</td>
<td>←</td>
<td>←</td>
<td>←</td>
<td>←</td>
</tr>
<tr>
<td>Feed type</td>
<td>Asymmetric Feed</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Radiation ability</td>
<td>Nonradiating</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

![Figure 3](image)

**Figure 3** Experimentally measured |S|_{21}| spectra of the DRAs with different feed locations: asymmetric feed (solid curve) and symmetric feed (dashed curve). Geometry of excitation is shown in the inset.
electric dipoles. The conditions for exciting the TM-type modes in the rectangular DRAs will be discussed later in this section.

Table 1 shows the resonant frequencies, the 3D field charts, and their dipole representations for the three modes excited in a DRA with dimensions of \(3 \times 12 \times 1.8\) mm. As seen from the table, only the \(\text{TE}_{111}\) mode is expected to be efficiently radiating, since the other two modes are both equivalent to two oppositely-directed dipoles.

One of the advantages of using the FDTD method for the modal analysis is that it is able to reproduce the real environment of the resonant structure, particularly the type of excitation and location of the feed. Table 2 presents the characteristics of the resonant modes produced by a DRA with dimensions of \(3 \times 12 \times 1.8\) mm, and the corresponding combinations of the magnetic dipoles for the cases of two different locations of the microstrip feedline, which are depicted in Figure 1. We excite a higher number of modes with asymmetric locations of the feedline, while symmetric feeds serve to suppress some of the resonant modes, and this effect is similar to the one observed in microstrip patch structures [5]. The feed point produces an electric wall type of environment and this, in turn, prevents the modes that do not satisfy this condition from getting excited. The understanding of this phenomenon is useful for selective elimination of certain resonant modes in the DRA.

Experimentally measured insertion loss spectra of the DRA for symmetric and asymmetric feed locations, shown in Figure 3, validate the resonant mode elimination concept for symmetric feeds. The geometry of the DRA excitation in these measurements is shown in the inset of the figure. The DRA was placed on top of microstrip line and then shifted with respect to the microstrip for this configuration.

It was found in our study that the variation of antenna dimensions strongly influenced resonant mode formation in the rectangular DRAs. We have observed that increasing the DRA height causes a decrease in the resonant frequency of the mode without altering the nature of the mode. For example, changing the height from 1.8 mm to 3.6 mm causes a decrease of the resonant frequencies by \(\sim 1\) GHz, and this effect can be very useful for tuning the frequency of the desirable modes in a DRA. In addition, it was found that an increase of the DRA height also causes a weakening of some of the modes.

Increasing the DRA width not only decreases the resonant frequencies, but also causes additional new modes to appear. Figure 4 demonstrates the mode transformation in the DRAs with length of 18 mm and height of 1.8 mm, but with slightly different widths, namely, 6.2 mm, 5.6 mm, and 5.3 mm, respectively. It is seen from this figure that decrease of the DRA width transforms the \(\text{TE}_{211}\) mode, which corresponds to two horizontal, oppositely-
oriented magnetic dipoles, into the TM\textsubscript{261} mode, which corresponds to three vertical electric dipoles.

The simplest mode of the same type as the TM\textsubscript{261}, the TM\textsubscript{221} mode, was found to exist in antennas with dimensions of 5.6 × 5.6 × 1.8 mm (Fig. 5(a)), while the TM\textsubscript{341} mode was excited in the DRA with dimensions of 5.6 × 12 × 1.8 mm. All of the modes depicted in Figure 5 have been observed to appear at approximately the same frequency and the only difference between them was the number of electric dipoles placed along the antenna length. An analysis of the phase distributions of this type of modes has shown that the fields of the electric dipoles have the same phases (see Fig. 2(c)). This implies that the observed TM modes could be used to create arrays of electric dipoles.

Our data show that the formation of the TM modes in the rectangular DRAs, described above, is possible only if the antenna dimensions provide sufficient “space” to host each of the dipoles. For the case of only one dipole, the shape of the horizontal cross-section of the DRA should be close to a square, while the additional row of dipoles could be excited in longer rectangular antennas.

We also have studied the effect of surface metalization on the resonant modes in the DRA. It was found that thin metal strips on front faces of the DRA cause an increase of the resonant mode frequency, while the side face metalizations eliminate a number of modes, stimulating, instead, the formation of only one type of modes, namely, the cavity-type modes. Figure 6 demonstrates the effect of metallic strips placed on the sides of a DRA with dimensions of 3 × 12 × 1.8 mm, in which we observed only the TE\textsubscript{111} mode in the absence of the metalization. As seen from the above figure, in the DR antenna without metallic strips, the TE\textsubscript{111} mode that corresponds to a horizontal magnetic dipole, is observed at the frequency of 7 GHz, while the TM\textsubscript{111} mode, which corresponds to the vertical electric dipole, is observed at the same frequency in the DR antenna with metal side strips. The radiation patterns for these two modes shown in Figure 6(c) and (f) have different directivity. The possibility of exciting TM modes in rectangular DR antennas appears to be very attractive, because these modes, in contrast to the TE\textsubscript{111} mode radiating toward the zenith, have a beam maximum along the azimuth plane instead. The latter is often desirable in communication applications.

3. CONCLUSION

We have demonstrated that the FDTD method is very efficient for studying resonant modes in rectangular DR antennas. Standing wave patterns of electric and magnetic field components were simulated and the 3D patterns for different mode types were generated. It was shown that the resonant fields in rectangular DRAs could be represented by combinations of magnetic or electric dipoles located within the DRs. The dimensions of the DRs were found to be critical for the excitation of the different modes types. The effects of DRA dimensions, feed location, and surface metalization on the mode formation were investigated. The possibility of exciting TM modes in rectangular DRAs, particularly the modes equivalent to arrays of vertical electric dipoles, was demonstrated.

ACKNOWLEDGEMENT

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REFERENCES

L-BAND 360° BROAD-BANDWIDTH MONOLITHIC ANALOG PHASE SHIFTER

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ABSTRACT: An L-band 360° broad-bandwidth analog phase shifter is designed using varactor. New design equations for expanding bandwidth and improving linear phase-shift are derived and applied to performances optimization in one circuit. The analog phase shifter is fabricated using MIC and SMT technologies. At 1.2 GHz to 2.0 GHz, the 360° phase shifter can achieve 360° phase shift [4]. Broad-band application of an analog phase shifter is to make phase shifter maintaining 360° phase shift, high linearity (linear voltage-phase relationship), and constant insertion loss at the broadest frequency range.

INTRODUCTION

Analog phase shifters find uses in a number of applications that require continuous linear phase control of RF/microwave carrier signals. Examples of such applications include phased-array radar, heavy ion accelerators, microwave communications, and so on. The L-band 360° phase shifter described here can be applied in microwave phase-shift scanning of an electronic-optic sampling system [1].

Previously reported analog phase shifters operate mostly in the 3-GHz to 18-GHz frequency range [2–4]. There have been few reports on 360° analog phase shifters operating at the L band (1 – 2 GHz). An analog phase shifter for adaptive antennas at 1 GHz has been reported, but it has only 90° phase shift [5].

The ideal electrical control phase shifter should have the following properties: (i) 360° phase shift, (ii) broad bandwidth, (iii) linear phase shift, and (iv) constant insertion loss. Many efforts have been made to solve above problems, but no effort has been made to solve all properties in one circuit. Conventional analog phase shifter generally uses reflection-type structure [4], which minimizes the number of diodes, as only one diode per 180° phase shift network is required. The reflection-type phase shifter produces the phase shift by reflecting the incident wave with a varactor whose capacitance varies according to the bias voltage. In this paper, an optimal design of the reflection-type phase shifter structure is presented and bandwidth design equations are deduced. The three performances: 360° phase shift, broad bandwidth, and linear phase shift were studied in one circuit. We found that the selection of a varactor diode directly affects performances of the phase shifter, and circuit optimization design also decreases the phase shifter’s insertion loss.

BROAD-BANDWIDTH DESIGN

Figure 1 shows that the reflection termination composed of two varactors connected in parallel with \(A_o/4\) transmission line length can achieve 360° phase shift [4]. Broad-band application of an analog phase shifter is to make phase shifter maintaining 360° phase shift, high linearity (linear voltage-phase relationship), and constant insertion loss at the broadest frequency range. In this work, the bandwidth design equations against phase-shift error, varactor gamma value, and relative bandwidth will be derived.

The phase shifter’s termination reactance curve \(A_o − B_o V_n^r\) must closely match the tangent curve \(-\tan(kV_n + \varphi_n)\) when working at centre frequency \(\omega_o\). The linear phase shift can be obtained. This relationship is written as [6]:

\[
A_o - B_o V_n^r = -\tan(kV_n + \varphi_n)
\]  

and

\[
A_o = \omega_o L/Z_o, B_o = 1/(\omega_o C_{\text{min}}Z_o), V_o = (V - V_o)/(V_{\text{max}} - V_o),
\]  

where \(A_o\) and \(B_o\) are the design parameters at \(\omega_o\). \(V_n\), \(\gamma\), and \(\varphi_o\) are the normalized biased voltage of varactor, varactor gamma value, and initial phase angle, respectively, and \(k\) is the proportional constant, \(C_{\text{min}}\) is the minimum capacitance, and \(V_{\text{max}}\) is the contact potential. Since \(A_o\) and \(B_o\) are functions of frequency, Eq. (1) will not be satisfied when the frequency deviating from \(\omega_o\). If the phase shifter still requires a 360° phase shift, the varactor’s reactance curve \(A_o - B_o V_n^r\) with deviated \(\omega_o\) must match another tangent curve. Thus, after selecting the most suitable \(A_o\), \(B_o\), and \(\gamma\), every reactance curve \(A_o - B_o V_n^r\) has a corresponding tangent curve to match, and we can obtain broadband application while ensuring linear phase shift. The reactance curve with deviated \(\omega_o\) is \(A_o - B_o V_n^r\), then give using Eq. (2):

\[
A = \omega L/Z_o, B = 1/(\omega C_{\text{min}}Z_o) = B/\omega\omega_o,
\]  

where \(\omega\) is the optional frequency deviating \(\omega_o\). We can define \(\omega/\omega_o = \alpha\), thus \(A = A_o\alpha\), \(B = B_o/\alpha\), and Eq. (1) becomes

\[
A - B V_n^r = A_o\alpha - (B_o/\alpha) V_n^r = -\tan(kV_n + \varphi_n),
\]  

where \(A_o\) and \(B_o\) are the design parameters at \(\omega_o\).