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DEVELOPMENT OF POLYMER-BASED DIELECTRIC RESONATOR ANTENNAS FOR MILLIMETER-WAVE APPLICATIONS

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Abstract—The goal of this paper is to use polymer-based materials (instead of hard ceramics) in fabrication of dielectric resonator antennas at millimeter-wave frequencies. The soft nature of polymers facilitates machining of antennas, while the low permittivity of polymers naturally enhances the bandwidth. More importantly, advantageous properties (e.g., flexibility and photosensitivity) of some polymers introduce special capabilities which can not be achieved by ceramics. A photosensitive polymer is utilized in this paper to fabricate polymer-based resonator antennas. As a result, deep X-ray lithography is enabled to produce high quality antenna structures. The proposed dielectric resonator antennas which inherently have very low relative permittivity (usually in a range from 3 to 5) are excited effectively using a slot-coupled feeding method and analyzed in both the frequency and time domains. Impedance and radiation properties are compared with higher permittivity ceramic antennas. Impedance bandwidths up

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to 32 percent are measured and stable radiation patterns with low cross polarization levels over the entire bandwidth are achieved for the prototype antenna. This method enables lithography-based batch fabrication of structures with fine features and complex geometries.

1. INTRODUCTION

The demand for higher bit rates to support new services and more users is shifting wireless systems to millimetre-wave frequency bands with more available bandwidth and less interference. However, at these frequencies, antenna dimensions are dramatically reduced complicating the fabrication process. Conductor loss is also significant, reducing the efficiency and gain of fabricated metallic antennas. To better utilize millimetre-wave frequencies for wireless applications, antennas with simple fabrication, higher efficiency, and larger impedance bandwidth are required.

Dielectric Resonator Antennas (DRAs) offer many appealing features such as larger impedance bandwidth and higher radiation efficiency due to the lack of conductor and surface wave losses [1]. Nevertheless, compared to their metallic counterparts, fabrication of DRAs is challenging since they have traditionally been made of high permittivity ceramics, which are naturally hard and extremely difficult to machine. The fabrication of these three dimensional structures is even more difficult at millimetre-wave frequencies where the size of the antenna is reduced to the millimetre or sub-millimetre range, and tolerances to common manufacturing imperfections are even smaller requiring a wideband antenna to compensate the possible inaccuracies.

Several methods have been considered in the literature to increase the bandwidth of DRAs. Exotic shapes [2–4], parasitic metal strips [5–7], and stacking parasitic DRAs [8–10], are among the most common ways, all of which are less suitable for millimetre-wave fabrication due to their complicated structures and use of metallic parts.

Advanced micromachining technologies and lithographic processes have been developed in recent years to overcome the fabrication problems and therefore utilize the attractive features of DRAs for millimetre-wave applications. For instance, micromachining technologies are used to fabricate DRAs for focal plane array, system on-chip, and WLAN applications [11–13]. Ceramic stereolithography has been used to construct DRA arrays and periodic antenna structures [14, 15]. However, the inherent hardness of ceramics makes micromachining very difficult and expensive [16]. Structuring softer pre-ceramic compounds through, for instance, lithographic fabrication processes is compelling, but normally complicated by the requirement for sintering as the final step. This step can result in shrinking and cracking which can severely degrade the final structure, making it difficult to achieve the small, precise structures and features required for high performance millimetre-wave applications [17].

A new approach is to use polymer-based materials, which dramatically simplifies fabrication due to the natural softness and results in wide impedance bandwidth due to the very low permittivity of polymers. However, two problems can appear in this regard. First, wavelength dependence of the dimensions leads to larger antenna. Nevertheless, this is less problematic at millimeter-wave frequencies where the wavelength is small. Second, critical coupling cannot generally be achieved by usual simple feeding methods. For instance, obtaining critical coupling for DRAs having a dielectric constant of 20 or less is not possible by the direct microstrip feeding method [18]. Moreover, matching the impedance is difficult with low permittivity DRAs using CPW excitation [19].

In this paper, polymer-based DRAs are investigated as easy-to-fabricate, wideband antennas. Impedance characteristics and radiation properties of polymer-based antennas with inherently very low permittivities (as low as 4) are examined using a simple rectangular structure. The dominant mode of the DRA is excited using a slot-coupled excitation method. Magnetic near fields at resonant frequencies are studied. Two commercial software, based on the Finite Element Method (FEM) and Finite Integral Technique (FIT), are used to verify the effectiveness of this approach. Polymer-based antennas with high structural quality are fabricated in thick layers using deep X-ray lithography processing. Measurements on impedance bandwidth and radiation patterns of the fabricated antennas are presented. Comparisons between low permittivity polymer-based and high permittivity ceramic DRAs are provided.

2. INVESTIGATIONS ON POLYMER-BASED LOW PERMITTIVITY DRAs

In this section, the characteristics of isolated and slot-coupled polymer-based DRAs are investigated and compared with higher permittivity ceramic DRAs (e.g., $\varepsilon_r = 10$).

2.1. Isolated Antenna

It is well known that polymer materials have very low relative permittivity which can increase the resonant frequency and impedance

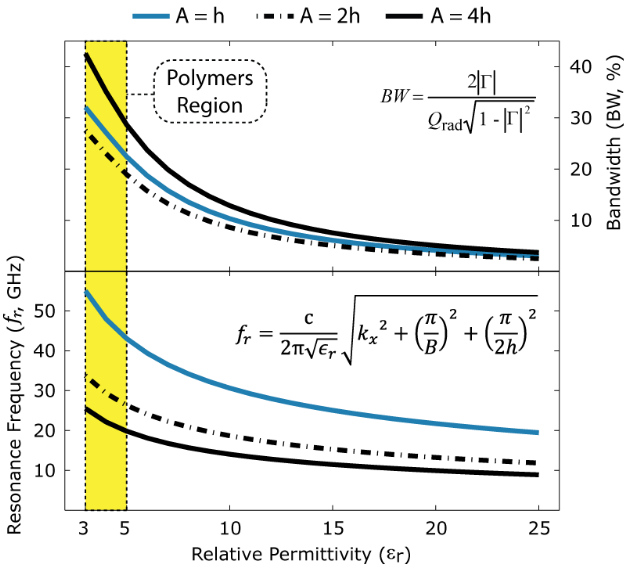


Figure 1. Impedance bandwidth and resonant frequency vs. dielectric constant of the rectangular DRA. Equations are derived from [18] and [20] for dominant mode of TE^x_{111}. $|\Gamma|$ is the reflection coefficient value (-10 dB is considered here).

bandwidth of the antenna while decreasing the radiation quality factor. The degree of this dependence is shown in Fig. 1 for a rectangular structure with cross section of $A \times B$, height of $2h$, and permittivity of ε_r. It is supposed that A in the x direction is equal to B in the y direction, and h is kept constant at 2 mm. Three geometric cases are considered, square ($A = 2h$), high aspect ratio ($A = h$), and low profile ($A = 4h$) structures. Radiation quality factor (Q_{rad}) for the proposed structures, derived from [18], is as follows:

$$Q_{rad} = \frac{\varepsilon_r A k_x^2 \left[\left(\frac{\pi}{B}\right)^2 + \left(\frac{\pi}{2h}\right)^2\right]\left(1 + \frac{\sin(k_x A)}{(k_x A)}\right)}{5\pi B(2h)\varepsilon_0 f_r^5 \left(\frac{16}{c}\right)^4 (\varepsilon_r - 1)^2 \left(\sin^2(\frac{k_x A}{2})\right)} \tag{1}$$

where ε_r is the relative permittivity of the resonator, f_r is the resonant frequency, c is the wave velocity in free space, and k_x is the wave number inside the resonator along the x direction.

A range of dielectric constant is indicated as the polymer region in Fig. 1. Most polymers with microwave applications have permittivities that lie in this region or very close to it. For instance, liquid crystal polymer (LCP) [21], polydimethylsiloxane (PDMS) [22], and polyoxymethylene (POM) [23] have the permittivity of 3.1, 2.7, and 3.7 respectively. With small portions of additives (e.g., ceramic powder), on the other hand, many microwave polymers can be moved into the region while the fabrication advantages of polymers are maintained. For example, adding 10 volume percent Mg-Ca-Ti (MCT) or Bi-Ba-Nd-Titanate (BBNT) moves the permittivity of PDMS to 4.5 and 4.1 respectively and the elastic behavior of PDMS is still maintained for special microwave applications [22].

A polymer-based low profile structure with dielectric constant of 4 can result in a bandwidth of 35.2% at 22.1 GHz frequency, as derived from Fig. 1, while these values are 12.8% and 14.1 GHz respectively for a ceramic antenna with dielectric constant of 10. This shows that the bandwidth is almost tripled and resonant frequency is increased by 56%. Similar variations in bandwidth and resonant frequency are achieved for the other two structures, although the high aspect ratio and low profile DRAs have larger bandwidth (smaller Q_{rad}) than square shaped resonators due to higher surface to volume ratio [24]. Therefore, very low permittivity polymer-based materials, besides their fabrication advantages, could considerably improve antenna performance especially at millimetre-wave frequencies in which expanding antenna dimensions are well tolerated.

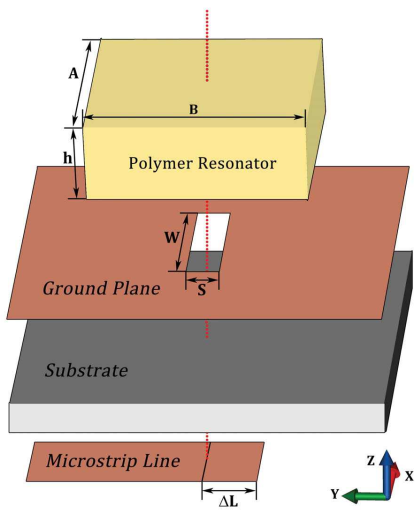
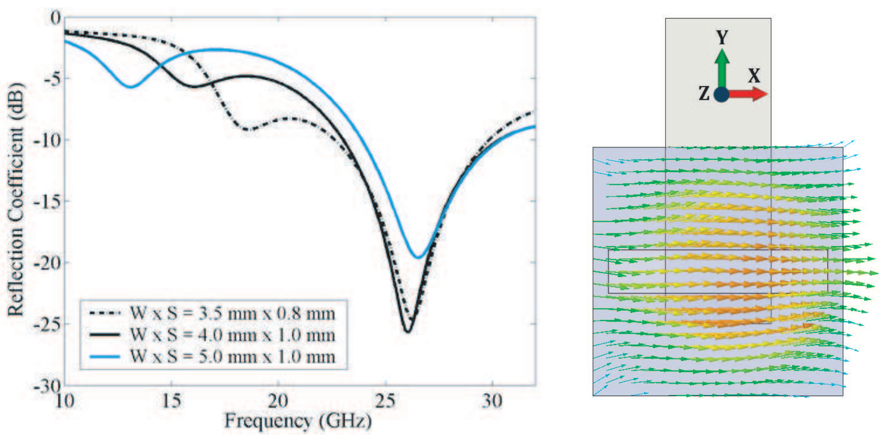


Figure 2. Explosive view of slot-coupled antenna.

2.2. Slot-coupled Excitation

To fulfill the feeding requirements of polymer-based DRAs, a slot-coupled excitation method is used [25] and the structure is analyzed using numerical methods in the frequency domain (Ansoft $^{\mathrm{TM}}$HFSS).

A diagram of the slot-coupled structure is shown in Fig. 2. Both the aperture and resonator positions are adjusted to be in the middle of the ground plane to attain a symmetrical geometry. It is supposed that the dielectric resonator with permittivity of $\varepsilon_r = 4$ has dimensions of $A = B = 5.7$ mm and $h = 2$ mm. The resonator is fed by the aperture through a $50\,\Omega$ microstrip line designed on the bottom of a substrate with dielectric constant of 2.2. The aperture size (W, S) and microstrip length variation (ΔL) are changed in order to improve impedance matching. Fig. 3(a) shows the reflection coefficient of the antenna for different aperture sizes. Two resonant frequencies are quite obvious in this figure. The lower resonant frequency increases with smaller slots from ~ 13 GHz to ~ 18 GHz, and therefore is related to the slot radiation. The upper resonant frequency remains fixed at ~ 26 GHz and is due to the DRA radiation. The magnetic field distribution inside the resonator at 26 GHz is shown in Fig. 3(b). The distribution is equivalent to a horizontal magnetic dipole and confirms that it is due to the dominant TE^x_{111} mode of the low permittivity DRA. It can be concluded that the polymer-based DRA with low permittivity of $\varepsilon_r = 4$ could achieve high coupling of -26 dB and 28% -10 dB impedance bandwidth.



(a) (b)

Figure 3. Slot-coupled DRA with permittivity of 4. (a) Reflection coefficients with different slot sizes; (b) Top view of the magnetic field distribution inside the resonator at 26 GHz.

2.3. Comparison

In this section, the characteristics of polymer-based DRAs with low permittivity ($\varepsilon_r = 4$) are compared with higher permittivity ceramic DRAs ($\varepsilon_r = 10$). Similar dimensions of 5.7 mm by 5.7 mm by 2.0 mm are considered for both cases. The comparisons and discussions are based on Ansoft $^{\mathrm{TM}}$HFSS FEM simulations and, as shown in the following table and figure, are confirmed by CST$^{\mathrm{TM}}$ Microwave Studio FIT results.

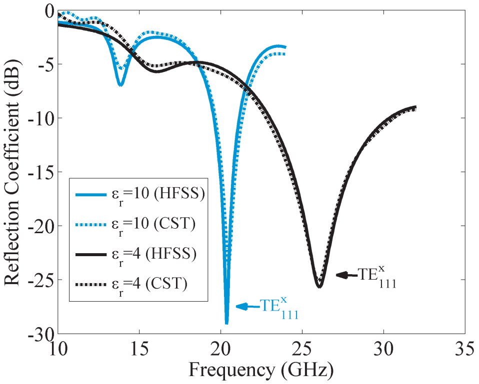


Figure 4. Comparison of reflection coefficients of slot-coupled DRAs with high and low permittivities.

Figure 4 shows the reflection coefficients of ceramic and polymer-based antennas. The -10 dB impedance bandwidth from 23.0 GHz to 30.4 GHz is achieved for the polymer-based antenna, while the impedance bandwidth is from 19.5 GHz to 21.2 GHz for the ceramic antenna. The achieved coupling for the polymer-based antenna is quite comparable to the coupling of the ceramic DRA. The obtained impedance bandwidths are the result of TE^x_{111} mode radiation for both cases. Table 1 shows the slot dimensions, slot and DRA resonances, antenna impedance bandwidths, and directivity at the DRA resonance for the slot-coupled very low permittivity polymer-based antenna and ceramic DRAs with higher permittivity. The antennas having moderate permittivities are also analysed and the results are depicted for comparison. In order to achieve the best impedance matching for lower permittivity antennas, the slot length is increased from 3.0 mm to 4.0 mm. However, the slot resonant frequencies remain far from the DRA resonant frequencies for all cases. The TE^x_{111} resonant frequency is about 30% increased from 20.4 GHz for the ceramic DRA, to 26.1 GHz for the polymer-based DRA. On the other hand,

Table 1. Physical parameters and simulation results of slot-coupled DRAs. The proposed antennas have the same dimensions of 5.7 mm by 5.7 mm by 2 mm.

Dielectric Constant	Slot Dimensions (mm)	Slot Resonance (GHz)		TE^x_{111} Resonant Frequency (GHz)		-10 dB Impedance Bandwidth (GHz)		-10 dB Impedance Bandwidth (%)		Directivity at TE^x_{111} Resonance (dBi)	
		HFSS	CST-MS	HFSS	CST-MS	HFSS	CST-MS	HFSS	CST-MS	HFSS	CST-MS
4 (Polymer)	4.0 x 1.0	16.1	16.0	26.1	26.0	23.0~30.4	22.8~30.6	27.7	29.2	5.6	5.7
6	4.0 x 1.0	13.9	13.8	23.2	23.1	21.0~25.9	20.9~25.9	20.9	21.4	5.6	5.7
8	3.5 x 0.8	13.9	13.7	21.3	21.2	19.9~22.7	19.8~22.7	13.2	13.7	5.7	5.8
10 (Ceramic)	3.0 x 0.7	13.8	13.6	20.4	20.4	19.5~21.2	19.4~21.3	8.4	9.3	5.9	6.0

the -10 dB impedance bandwidth is tripled from 8.4 percent to 27.7 percent. The directivity of the antenna does not dramatically change and remains around 5.6 dBi $\sim$ 6.0 dBi for all cases. It should be noted that lowering the permittivity of the DRA from 4 to 2 leads to very poor coupling between the antenna and feed, restricting direct application as antenna structures.

3. FABRICATION PROCESS AND EXPERIMENTAL RESULTS

An X-ray resist polymer, EPON^{TM} SU-8, is used with deep X-ray lithography fabrication to realize antenna structures in thick polymer-based materials. With the addition of 16 volume percent alumina micropowder, the X-ray sensitivity of the polymer composite is still maintained and the dielectric constant and loss tangent of the material are measured to be 4.2 and 0.008 respectively.

The fabrication process begins with mixing the material to achieve a homogeneous composite. A specific amount of the mixture is put into a metallic frame with 100 microns polyimide foil on the bottom side, to create a 2 mm thick polymer composite layer. After pre-baking at 95°C, the polymer composite is exposed to X-rays at the Angstroemquelle Karlsruhe storage ring at the Karlsruhe Institute of Technology. An X-ray mask with rectangular-shaped patterns is used in the process and exposure time and bottom dose are adjusted to be 18 minutes and 200 J/cm^3 respectively. The sample is then developed at room temperature using propylene glycol monoether acetate (PGMEA). Fig. 5 shows structures inside the metallic frame during the development process. The scanning electron microscope (SEM) picture of the structure after development and post-baking processes is shown in Fig. 6, demonstrating the smooth and vertical sidewalls in the thick polymer composite. More descriptions on deep X-ray lithography fabrication of polymer composites and their structural quality can be found in [26].

The fabricated polymer-based structure is excited using the microstrip slot coupling method and measured to experimentally verify the results of previous section. The 2.4 mm wide 50 Ω microstrip feedline is machined on the bottom of a 0.787-mm thick Taconic TLY-5 substrate with dielectric constant of 2.2 and loss tangent of 0.0009. The polymer-based rectangular DRA with dimensions of 5.7 mm ×

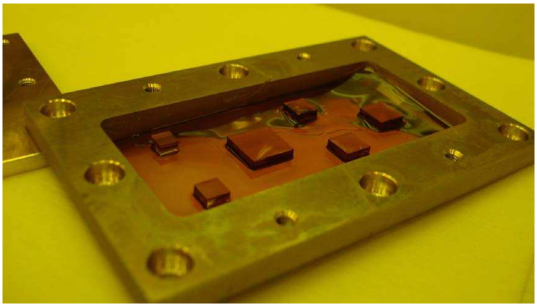


Figure 5. 2 mm-thick polymer-based structures during development.

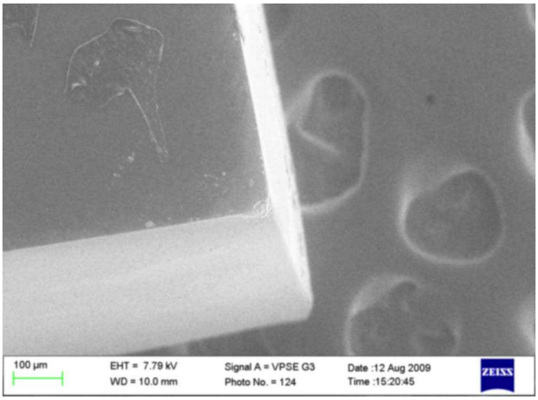


Figure 6. SEM micrograph of the 2 mm-thick polymer-based structure.

5.7 mm × 2.0 mm and permittivity of 4.2 is coupled by a 4 mm × 1 mm slot on a 35 mm × 35 mm rectangular ground plane. The antenna and the slot are symmetrical under the microstrip line with $\Delta L = 1$ mm. The DRA is glued to the ground plane by silicone adhesive sealant. The reflection coefficient is measured using an Agilent 8722ES vector network analyzer. The universal substrate test fixture WK-3001-G from Inter-continental Microwave and a 2.4 mm HP 85133 flexible test cable is used to directly measure the antenna without additional connectors. In order to de-embed the loading effect of the test fixture and the cable on the input impedance of the proposed antenna, a standard calibration was performed using the Agilent 85056A Calibration Kit over a 17 GHz to 30 GHz frequency range. The measurement setup and both sides of the antenna are shown in Fig. 7.

The measured reflection coefficient of the prototype is presented in Fig. 8 along with simulated results of Ansoft $^{\mathrm{TM}}$HFSS which are in reasonable agreement. Impedance bandwidth of 32% from 21.25 GHz to 29.25 GHz is achieved in the measurement. The measured resonant frequency of the fabricated DRA is 26.1 GHz, which is within 0.8% from the simulation (HFSS: 25.9 GHz), and is consistent with dielectric waveguide model theory (DWM: 24.2 GHz).

For comparison, a DRA with dielectric constant of 10.2 is also fabricated and measured. All the feeding parameters are the same as the previous antenna, except the slot dimension which is 3.2 mm × 0.7 mm in this case. The measured and simulated reflection coefficients are shown in Fig. 8. The −10 dB impedance bandwidth of 9% is from 19.0 GHz to 20.7 GHz and agrees well with the simulation.

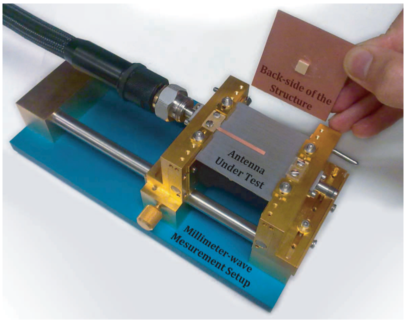


Figure 7. Photograph of the reflection coefficient measurement setup.

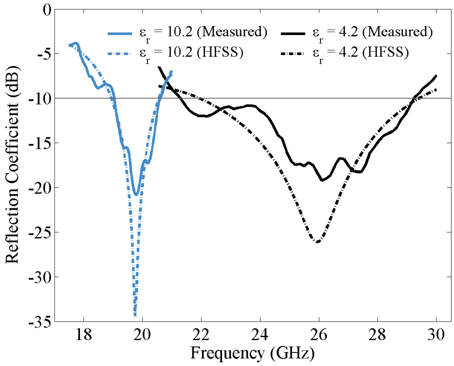


Figure 8. Measured and simulated reflection coefficients of fabricated slot-coupled antennas.

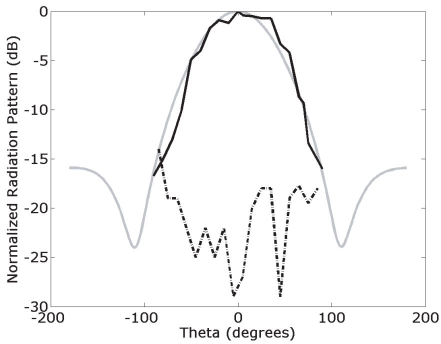


Figure 9. Measured and simulated radiation patterns of the polymer-based slot-fed antenna structure. Measured co-pol and cross-pol are shown in solid black and dot-dash black respectively, and simulated co-pol is shown in solid gray. (a) H (xz)-plane at 26.1 GHz; (b) E (yz)-plane at 26.1 GHz.

The differences between the simulation results and the measurement are not unusual and could be attributed to configuration imperfections, e.g., caused by the air gaps between the DRA and the substrate which is filled with the silicone adhesive. This effect is well studied and it can be minimized by using dielectric powder between the DRA and the slot [27].

To ensure the functionality of the proposed polymer-based antenna, its radiation patterns are simulated and measured at the resonant frequency of the antenna. Figs. 9(a) and (b) show the radiation patterns at H-plane and E-plane. Low cross polarization levels are achieved for both cases. Symmetric and stable radiation patterns are observed in the H (xz)-plane while the slight asymmetry of the E (yz)-plane is primarily due to the small size of the ground plane, and shadowing from the microstrip feedline, connectors, and cables. The measured antenna gain at 26.1 GHz frequency is about 4.9 dBi.

4. CONCLUSION

It was shown that polymer-based resonator structures with permittivity as low as 4 can be utilized as wideband antennas with various fabrication advantages. Resonant frequency and impedance bandwidth of DRAs in the polymer region ($\varepsilon_r = 3 \sim 5$) were discussed and compared with higher permittivity areas. Slot-coupled excitation was used to feed the low permittivity resonators and realize polymer-based resonator antennas. To take advantage of deep X-ray lithography in fabrication of ultra thick polymer-based structures, a modified X-ray resist (84 vol% SU-8 and 16 vol% alumina micropowder) having a permittivity of 4.2 was used to create polymer-based antenna structures. For comparison, a ceramic antenna with similar dimensions and permittivity of 10.2 was fabricated and measured. It was observed that the polymer-based antenna results in an impedance bandwidth which is 3.5 times more than the impedance bandwidth of the ceramic antenna. The possibility of utilizing softer materials like polymers as very low permittivity dielectrics in the fabrication of millimetre-wave DRAs facilitates simple fabrication processes for conventional structures, and also enables fabrication of small structures with fine features and complex geometries through lithographic batch fabrication.

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