A Wideband Resonant Cavity Antenna Assembled Using a Micromachined CPW Fed Patch Source and a Two-Layer Metamaterial Superstrate

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Abstract—This paper reports the development of a wideband resonant cavity antenna (RCA). The RCA device was obtained by using an optimized aperture coupled CPW (coplanar waveguide) fed wideband patch antenna and a metamaterial based superstrate design. The wideband behavior is based on the effects of Fabry-Perot cavity on either side of the resonant frequency of the metamaterial superstrate and the finite size of the superstrate to obtain enhanced gain around this frequency. In addition, the metamaterial superstrate in our work contains two identical layers of a frequency selective surface (FSS) based on a two dimensional patch array rather than dissimilar arrays as used in the previous studies. Two such FSS layers are assembled using a laser micromachined PMMA rim and a SU8 based bonding method. The air spacer based metamaterial design offers better performance by minimizing the dielectric loss between the metallic patch arrays and also offers flexibility in control of the separation between the two FSS layers as well as resulting in a light weight RCA device. The RCA device was designed to operate in the X-band. The dimensions of the compact RCA device are 45x45x24 mm$^3$. The gain of the device was measured to be ~13 dBi with a 3-dB bandwidth of 46% and a corresponding 1-dB ripple bandwidth as wide as 40%. The measured impedance bandwidth was 44%.

Index Terms—Resonant cavity antenna, fabrication, assembly, partially reflective surface (PRS), directive antennas, gain bandwidth, wideband antenna.

I. INTRODUCTION

The resonant cavity antenna (RCA) has been studied for many years due to its ability to provide a narrow beam response with enhanced directivity over the conventional single element antenna devices [1-28]. In a typical RCA device the feed (source) antenna is placed inside a resonator which is usually a Fabry-Perot (FP) based cavity structure. The bottom reflector is commonly made of a blank metal surface or a patterned (defected) surface or an impedance surface which also acts as the ground plane of the feeding antenna device. The top reflector (superstrate) can be a single dielectric substrate or more dielectric layers called an electromagnetic band gap (EBG) structure. The required high reflectivity is obtained using a high permittivity dielectric material with a quarter wavelength thickness [1-4]. The resonant condition in the dielectric superstrate based RCA devices has been examined theoretically based on the transmission line model [1][4], the leaky wave propagation model [2] and the EBG based approach [3][5-6]. In EBG based superstrates, Weily et al. used a three layer EBG structure as the superstrate in a RCA device fed by a slot array [7]. The gain and bandwidth of the RCA device were 22.7 dBi and 13.2% respectively. Al-Tarifi et al. proposed a double cavity RCA device consisting of two dielectric superstrates [8] which has a bandwidth of 17.9% based on the results of simulation work as compared to 9% of a single cavity device, but no practical device was constructed to demonstrate the enhanced bandwidth. The recent work by Hashmi et al. [9] demonstrated a wideband RCA device using an all dielectric superstrate consisting of 3 layers of dielectric substrates. A large 3-dB bandwidth of 22% was achieved with a peak gain of 18.2 dBi. Although the dielectric material based superstrate is easy to design, the resultant antenna device is bulky. Recently a new superstrate design made of unprinted dielectric materials having nonuniform permittivity in the transverse direction, has been used to realise a wideband RCA with a 3-dB directivity bandwidth of 52.9% [10]. However the lack of choice in dielectric slab materials with the required thicknesses also restricts design flexibility of dielectric material based superstrates.

In recent years it has been shown that a partially reflecting surface (PRS) consisting of one or more layers of periodic metallic or aperture elements on a dielectric substrate known as a frequency selective surface (FSS), can be used effectively as the superstrate leading to low-profile RCA devices [11-14]. The metamaterial based PRS was first proposed and studied by Trentini [11]. Both the reflection coefficient and the associated
phase are significant factors in design of a RCA device and have been considered in the ray theory [8-25]. Wideband capability of RCA devices based on one FSS layer as the PRS was studied by Feresidis et al. [11] but the available bandwidth was limited by the intrinsic characteristics of the magnitude and phase of the reflection characteristics of the single layer FSS based PRS designs. Therefore bandwidth enhancement has been a subject of significant interest using double FSS layer based PRS structures for RCA devices. Feresidis and Vardaxoglou [22] proposed a double layer superstrate design consisting of two FSS layers with different dimensions of patch elements on each dielectric board. An enhanced bandwidth of 9% was obtained using a waveguide based feed source. In their recent work, a waveguide coupled RCA using 3 dissimilar patch arrays printed on dielectric substrates was demonstrated with a 3 dB bandwidth of 15% [23]. In another study Konstantinidis et al. designed an RCA using a slot coupled microstrip antenna and three double-sided periodic arrays consisting of a patch array and a cross shape based arrays on each side of a dielectric slab [24]. A 3dB directivity bandwidth of 10.7% was achieved. Ge et al. [25] investigated a double layer superstrate for bandwidth enhancement of a RCA device utilizing two dissimilar dipole arrays printed on each side of a dielectric board. A monopole antenna was used as the feed source and a bandwidth of 13.6% was achieved. In [26], Wang et al. has just reported a wideband RCA device using a two layer metamaterial superstrate consisting of a patch array and a perforated metal layer with periodic square holes, the two FSS layers were printed on each side of a dielectric board. In their work a wideband microstrip fed patch antenna with a suspended patch element [29] was used as the feed source. The measured impedance bandwidth was about 25% and the gain bandwidth was 28%. In the recent work by Liu et al. [28], bandwidth enhancement was obtained by using a metasurface as the PRS and a probe fed patch antenna as the primary source. The measured 3 dB gain bandwidth is approximately 20.3%. The metasurface was a layer of square metal rings with progressive reduction of size from the centre of the surface, produced on a PCB substrate. In addition dual-band RCA devices using metallo-dielectric superstrates have also been reported [30, 31] Lee et al. developed a dual-band PCA using a two layer metallo-dielectric superstrate which was based on two dissimilar rectangular patch arrays one on each side of a dielectric board [30]. Recently Abdelghani et al. reported a dual band RCA using a double-layered periodic partially reflective surface with unit cells based the same square ring design but with different dimensions for each layer of the two arrays [31].

In this paper, we present the results of design and implementation of a wideband RCA device using a double layer metamaterial based superstrate (PRS) consisting of identical periodic metallic patch elements on thin film liquid crystal polymer (LCP) substrates [32]. Impedance and gain bandwidth as large as 44% and 46% have been obtained from a practical device. The results were achieved using an optimized wideband patch antenna as the source device with the two layer metamaterial superstrate. In Section II, we describe design and modelling of the wideband RCA device. In Section III, fabrication and assembly of the RCA device are discussed as well as the results of characterization and measurements. In Section IV, we summarize the development and performance of the wideband RCA device.

II. ANTENNA DESIGN AND MODELLING

In this section, the configuration and design principle of the resonant cavity antenna for directivity enhancement and wideband operation are discussed. The design and modelling work was carried out using the Ansys-HFSS software tool. An aperture coupled CPW fed patch antenna with a suspended patch was designed for wideband operation. The design and characteristics of a two layer metamaterial are studied for application as a superstrate for a wideband RCA device. The metamaterial substrate structure is then incorporated into the RCA configuration for modelling and optimization of the resultant antenna device.

A. Configuration of the RCA antenna design

Fig. 1(a) shows a schematic cross-sectional view of the proposed resonant cavity antenna for high directivity and wideband operation. The primary source is a wideband CPW fed patch antenna using a suspended patch design on an FR4 substrate. The patch element is on a thin film liquid crystal polymer (LCP) substrate. The latter is supported using a laser micromachined PMMA (polymethyl methacrylate) based polymer rim. The thickness of the PMMA rim and hence the air gap between the LCP and the FR4 substrates, is denoted by Hg. The layout of the aperture for coupling and the coplanar waveguide for feeding is shown in Fig. 1(b).

![Fig. 1. Geometry of the broadband resonance cavity antenna, (a) a cross sectional view, (b) a plane view of the CPW feed structure, the coupling aperture and the patch element, and (c) the square patch array in each layer of the PRS.](image)

The PRS is a two-layer metamaterial and is separated from the ground plane of source antenna by the cavity height, Hc. Unlike the PRS designs in the previous work, our PRS consists...
of two identical layers of square patch based arrays printed on the same thin film LCP material as that used in the source antenna. Fig. 1(c) shows a schematic layout of the patch array on the LCP film. Two such LCP film substrates are combined together using a PMMA based rim structure by aligning and bonding the LCP films to each side of the PMMA rim.

B. Design of a CPW-fed aperture-coupled patch antenna as a wideband primary source

For wideband operation of a RCA device, it is necessary to use a wideband antenna as the source element. In our previous work [29][32] we showed that wideband patch antenna devices can be obtained by using an aperture coupled design and a suspended patch [29] or patches in the case of stacked patch antennas [33]. Using a microstrip feed design, a bandwidth of ~20% was obtained for a single patch based design [29]. In this work we developed a CPW based feed design to obtain increased bandwidth using a short end CPW line. In the CPW fed configuration shown in Fig. 1, a wide impedance bandwidth can be obtained based on the coupling of the resonances associated with a double tuned aperture [34] and the suspended patch. The design and simulation work was carried out in a similar approach as described in our previous work [29]. Briefly the aperture was designed in the first step, the total length of the aperture was one guided wavelength at 10 GHz and the width was one tenth of the length. Then a short-end CPW was added to the aperture on the ground plane as the feeding structure. The CPW line acts as an impedance transformer and was designed to obtain a double-tuned aperture with wide impedance bandwidth. By studying the reflection characteristic of the CPW fed aperture, it was found that the desired length for the CPW line was one wavelength for wideband impedance operation of the double tuned aperture. In the last design step, a rectangular patch was added to the CPW fed aperture with an air gap between the thin film LCP substrate of the patch and the aperture. The length of the patch was half wavelength at 10 GHz, the patch resonance was coupled to those of the double tuned aperture resulting in triple resonances thus broadening the impedance bandwidth of the antenna design. The air gap determines the coupling between the patch and the aperture. A range of air gap values was investigated and it was found that the air gap of 3 mm provides the best radiation performance. The material properties and design parameters are given in Table I and II respectively.

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<th>TABLE I</th>
<th>PROPERTIES OF THE DIELECTRIC SUBSTRATES</th>
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<th>DESIGN DIMENSIONS FOR WIDEBAND PATCH ANTENNA FEED SOURCE (MILLIMETERS)</th>
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The simulation results of the reflection coefficient and directivity of the wideband patch antenna are shown in Fig. 2. An impedance bandwidth of about 46% has been achieved. It is believed that this is the widest bandwidth obtained for a single patch based antenna device. The directivity is much higher than that of the conventional printed patch antenna on a PCB board by using the air gap based design and a low loss LCP thin film substrate [29].

C. Design of the metamaterial based superstrate

In this work we have studied design of an effective PRS using a two-layer metallo-dielectric based metamaterial as shown in Fig. 1. The metamaterial based PRS consists of two identical patch arrays each printed on an LCP film substrate and separated by an air gap. In our previous work [38], we investigated Fano resonance in such metamaterials with a narrow bandwidth for high-Q applications. In this paper we demonstrate that the same metamaterial design but with broad resonance characteristics can be used to design an effective PRS for a wideband RCA device. Unlike in [38], in this work approximately quarter wavelength pitches have been found to provide suitable transmission and reflection characteristics for incorporating into a RCA device for broad band operation. The resonant frequency of the metamaterial PRS was chosen to be 10 GHz matching that of the source antenna as discussed previously. The resonant frequency of the two-layer material PRS depends on the pitch of the patch array, the dimensions of the square patch element and the gap between the two LCP film substrates. The design work was carried out using a unit cell based approach thus assuming an infinite array size [13] [16] [18] [22-27]. The implementation of the unit cell for design and simulation work is shown in Fig. 3(a). Full wave EM simulation was performed based on the Floquet’s theorem using the Ansys HFSS software tool. It has been shown that this method is accurate and efficient in study of infinite size two dimensional periodic arrays [39].
Five such metamaterial designs have been considered for PRS applications. The pitch of the patch array was 7 mm in all cases. The values of the air gap between the two arrays are 1, 2, 3, 4 and 5 mm respectively. To maintain the resonant frequency of the material structures, the dimensions of the square patch elements were adjusted in the design process. The corresponding values were found to be 6.95 mm, 6.77 mm, 6.45 mm, 6 mm and 5.3 mm respectively. Fig. 4 shows the transmission and reflection characteristics of the two-layer metamaterial designs. The resonant behavior has a strong dependence on the air gap thickness between the two array layers. As the air gap increases, the effect of Fano resonance decreases since the electromagnetic coupling between the scattered waves becomes weaker [38]. Fig. 4(c) shows the associated reflection phase change as a function of frequency corresponding to the magnitude of the reflection coefficient shown in Fig. 4(b). The reflection phase change contributes to the total phase of the Fabry-Perot cavity of the RCA device (Fig. 1(a)) determining the cavity condition and the operation of the RCA device [11]. The reflection phase behavior of the metamaterial as the PRS is included in the simulation work described in Section II D.

The properties of the metamaterial designs for RCA applications are studied by forming a Fabry-Perot cavity between the metamaterial superstrate and the ground plane of the source antenna. The latter is considered to be an infinite perfect electric conductor (PEC). This approach allows easy study of the behavior of the metamaterial based PRS designs for RCA applications. Both the magnitude of the reflection coefficient and the associated phase change contribute to the transmission characteristics of the Fabry-Perot cavity. The transmission study is based on the electromagnetic image theory [6] [40], the unit cell for this purpose is shown in Fig. 3(b). The unit-cell is excited by a plane-wave source at normal incidence. It was found that the air gap value of 4 mm provides the best performance in terms of low ripple transmission over a broad band, although based on the transmission characteristics shown in Fig. 4(b) the 5 mm air gap design should also provide wideband transmission. Fig. 5 shows the results of transmission for different values of the cavity height (Hc) for an air gap (Hr) value of 4 mm between the two patch arrays. As Hc increases the broad band transmission shifts to the lower frequency side. The cavity height also has an effect on the profile of the transmission band as frequency. The results show unity of transmission coefficient at 10 GHz as expected from Fig. 4(b) with zero reflectivity at this frequency. The weak resonance at each side of the frequency is associated with the defect mode of the PEC [6]. The weak resonance is due to the broad reflection characteristic around 10 GHz of the metamaterial as shown in Fig. 4(b) resulting in wideband transmission for broad band antenna applications.

Fig. 3. Unit cell structures for simulation work on (a) PRS design and (b) cavity model for antenna application based on image theory.

Fig. 4. Simulation results for the PRS design based on the unit cell shown in Fig. 3(a), (a) transmission magnitude, (b) reflection magnitude, and (c) reflection phase.
D. Design of RCA for practical implementation

Synthesis of a wideband RCA device is carried out by implementing the corresponding 3D structure of the cross-sectional view as shown in Fig. 1(a) in Ansys HFSS environment. The source antenna as described in section II B was incorporated in the RCA design without modification. As described before, the analysis of the metamaterial based PRS is initially made based on the infinite-size condition and a plane-wave excitation. However, the actual PRS structure in a RCA device has a finite array of patch elements. Therefore the RCA synthesis work was carried out using finite element based full wave simulation to take into account of the effect of the finite size of the PRS. For compactness both of the PRS and the substrate of the primary source should be small while maintaining a wideband performance. Fig. 6 shows the results of broadside directivity as a function of frequency for array sizes of 5x5, 7x7 and 9x9 in the superstrate respectively. It can be seen that the bandwidth of directivity is strongly affected by the size of the superstrate. This effect has already been observed in other RCA devices [6][14] and has been discussed in detail in [9]. A larger superstrate results in lateral propagation within the cavity and phase non-uniformity across the radiation aperture thus causing degradation in antenna performance. Hence a smaller superstrate is better for a RCA device, the leaked wave from the edges of the superstrate also increases the radiation bandwidth [9]. In our case it was found that the optimum array size for a wideband RCA device is 5x5. Further reduction of superstrate size weakens the effect of the Fabry-Perot resonator and thus reducing the performance of the RCA device. Comparing the results in Figs. 2 and 6, it can be found that as the superstrate becomes very large (e.g. 9x9 array) no enhancement in directivity can be obtained at 10 GHz since there is no cavity effect at this frequency as the metamaterial superstrate is at resonance with 100% transmissivity as shown in Fig. 4(a) and correspondingly zero reflectivity as shown in Fig. 4(b). In effect there is no Fabry-Perot cavity at 10 GHz between the superstrate and the ground plane of the patch antenna when the former is very large since it behaves like an infinite size superstrate.

Fig. 6. Comparison of broadside directivity of the RCA design for different arrays in the finite-size PRS. The cavity height (Hc) is 20 mm.

Fig. 7 shows the results of both radiation and reflection characteristics of the RCA device with the 5x5 array based PRS design for different cavity heights. It can be seen that the cavity height has a significant effect on the radiation response of the cavity. The best RCA performance is obtained at the cavity height of 20 mm with the lowest ripple response in antenna directivity. The corresponding impedance bandwidth is 45% as shown in Fig. 7(b).

Fig. 7. Radiation (a) and reflection (b) characteristics of the RCA device.

Fig. 8 illustrates the radiation patterns in both E- and H-plane at 10 GHz for three different superstrate designs. Beam-splitting is observed and is found to be associated with the 9x9 array based superstrate. Beam splitting is an undesirable behavior for RCA devices and can occur in designs with an
infinite [41-42] or a finite superstrate [43-44]. The total radiation aperture for the optimal superstrate with 5x5 array of patch elements is approximately 1.2λ x 1.2λ, comparable to the aperture size of 1.5λ x 1.5λ for the RCA device with an all dielectric based superstrate [9] but in our case the superstrate structure is substantially thinner (4 mm as compared to 14 mm).

![Image](https://via.placeholder.com/150)

Fig. 8. Radiation characteristics (a) H-plane and (b) E-plane for finite-size FSS designs in PRS and the source (patch) antenna at 10 GHz.

III. FABRICATION AND ASSEMBLY

A. Fabrication and assembly of the primary patch antenna

The wideband patch antenna was produced on an FR4 substrate. The thickness of the substrate was 1.6 mm. A similar fabrication approach was used as in our previous work [33]. However a laser micromachined PMMA rim was used in this work to obtain a suspended patch instead of the SU8 based polymer rim that was produced by a surface micromachining based method. The new approach is efficient and better for producing millimeter thick polymer structures than the previous method. The CPW feed line and the coupling aperture was produced on a copper clad FR4 board using a microfabrication approach. A layer of photoresist (AZ9260) was deposited on the FR4 board by spin coating. After drying and baking the photoresist layer, the exposed copper was etched in a FeCl3 based solution. The photoresist was then then removed to obtain the aperture and CPW structure as well as the surrounding ground plane. The patch was fabricated on a thin film (100 μm) copper clad LCP substrate using a similar process. The PMMA rim for supporting the patch on the LCP substrate was produced using a CO2 laser based micromachining system [45]. The inner dimensions of the rim were 36 x 36 mm2 and the width of the PMMA track was 2 mm. A PMMA plate of 3 mm of thickness was used in this work to match the design requirement for wideband operation of the resultant patch based source antenna. In the assembly process, the PMMA rim was aligned to the aperture on the FR4 substrate and attached to it using the SU8 based bonding method [33]. The patch on the LCP film substrate was then aligned to the coupling aperture and the LCP substrate was bonded to the PMMA rim using the same method as for bonding of the PMMA rim to the FR4 substrate. Finally a SMA connector was mounted to the FR4 board by soldering to complete the construction of a wideband patch antenna as the primary source for a wideband RCA device.

B. Fabrication and assembly of the PRS structure

Based on the results of design and simulation work as described in section II, the PRS design with a 5x5 array of square patch elements in each FSS layer was chosen for construction of a RCA device. As shown in Fig. 7, the best performance for a RCA device is expected from incorporation of this PRS design. The 5x5 array of square patch elements was fabricated on a copper clad LCP film substrate. The patch array was the fabricated on the LCP substrate using the same microfabrication method as for fabrication of the primary source antenna. Two arrays were fabricated each on an LCP film as necessary for construction of the double layer metamaterial based PRS. Two 2 mm thick laser machined PMMA rims were prepared and stacked together to a total rim thickness of 4 mm as required for optimal performance for the RCA device. The two LCP layers were then aligned and attached to each side of the stacked PMMA rim to complete the construction of the PRS structure.

![Image](https://via.placeholder.com/150)

Fig. 9. A photograph of the assembled RCA device showing a CPW-fed aperture coupled patch antenna and the PRS superstrate. The cavity height is 20 mm.

C. Assembly of RCA device

The primary source antenna and the PRS as described in the above sections were assembled to complete the construction of the wideband RCA device. A screw based method, similar to that used in [44], was used to mount the PRS on the FR4 substrate of the source antenna. Alignment was made using 4 pre-drilled matching holes on the FR4 substrate and the PRS
structure. The holes were located on each corner of the square FR4 board and the PRS assembly. Fig. 9 shows an optical image of the assembled wideband RCA device. The cavity height can be controlled by adjusting the position of the screws securing the PRS structure.

IV. MEASUREMENTS

Microwave measurements for antenna characterization were made in an anechoic chamber using a vector network analyzer (HP 8510). The gain measurements were made using a far field approach based on the gain transfer method [46]. Two standard gain horn antennas were used, one was used as the transmitter and the other one as the reference antenna. The latter has an average gain of 20 dBi over the operation band between 8.2 GHz and 12.5 GHz. Reflection and radiation measurements were carried out for both the wideband patch based source antenna and the resultant RCA device after it was assembled with the metamaterial superstrate.

Fig. 10 shows the results of reflection and gain measurements for the source (feed) antenna. Good impedance matching through coupling of multiple resonances was obtained with an impedance bandwidth of 43%. The 3dB-gain bandwidth is 40% covering the X-band with a peak gain of 8 dBi. To our knowledge the results are the largest bandwidth values obtained for a patch antenna device. It provides the necessary feed source for a wideband RCA device. The differences between the results of simulation and measurement in Fig. 10(a) are probably due to the fact that the SMT connector was not included in the simulation work and the accuracy of the dimensions of the fabricated structures. More detailed analysis of the results may be made using the FSV (Feature Selective Validation) method [47]. The large difference between the results of simulation and measurement below 8.2GHz in Fig. 10(b) is the effect of the cutoff frequency of the gain horn antenna used in the measurement work.

Fig. 10. The measured and simulation results of reflection (a) and radiation (b) characteristics of the broad band feed antenna

Fig. 11. (a) Results of reflection from measurement and simulation, and (b) results of gain from measurement and simulation as well as the calculated directivity of the RCA device.

Fig. 11 presents the results of both measurement and simulation for the RCA antenna device as shown in Fig. 9. The cavity height was 20 mm. The measured impedance bandwidth is 44% between 8 GHz and 12.4 GHz from the results shown in Fig. 11(a). The discrepancy between the results of simulation and measurement is due to the same factors as discussed for the results in Fig. 10(a). The measured 3dB gain bandwidth is 46% from the results shown in Fig. 11(b). The device has excellent flat-ripple response with a 1-dB-ripple gain bandwidth as wide as 40% over the frequency band between 7.6 and 11.6 GHz. The calculated directivity is obtained using the results of gain from measurement and radiation efficiency from simulation. To investigate the spatial characteristics of the radiation, angle dependent measurements were carried out at selected frequencies and the results are shown in Fig. 12. In general the measured results are in good agreement with the predicted performance, except the E-plane results at 10 and 12 GHz which may be due to the fact that the SMA connector of the
source antenna was on the E-plane and was not included in the model of the simulation work. The results of E-plane and H-plane measurements show the same value of 40° for the 3dB bandwidth at the frequencies of both 8 GHz and 10 GHz. It is slightly narrower at 12 GHz with a value of 30°. Therefore the results illustrate the desirable radiation behavior of the RCA design for broad band applications maintaining similar radiation patterns over the band of operation.

Fig. 12. E- and H-plane far-field radiation patterns of the RCA device at three different frequencies of 8 GHz, 10 GHz and 12 GHz respectively.

V. CONCLUSION

A resonance cavity antenna with the characteristics of the broad radiation bandwidth has been proposed and demonstrated successfully. A new PRS design based on two identical arrays of square patch elements was used as the superstrate in the RCA device. Wideband performance has been achieved in conjunction with an optimized wideband patch antenna as the primary source. Thin film LCP substrates were used in construction of the RCA device enabling high performance and light weight devices. The associated fabrication and assembly methods were developed to produce the RCA device. The impedance and 3 dB radiation bandwidth of the device were measured to be 44% and 46% respectively representing considerable improvement over the bandwidth of the similar devices reported in the previous work. The peak gain of the device was about 13 dBi. The RCA device is also very compact with dimensions of only 45x45x24 mm³.

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REFERENCES


