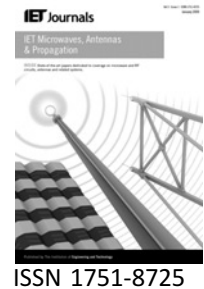


Published in IET Microwaves, Antennas & Propagation
 Received on 18th October 2007
 Revised on 9th April 2008
 doi: 10.1049/iet-map:20080072



Design of multi-frequency microstrip antennas using multiple rings

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Abstract: An electromagnetically coupled feed arrangement is proposed for simultaneously exciting multiple concentric ring antennas for multi-frequency operation. This has a multi-layer dielectric configuration in which a transmission line is embedded below the layer containing radiating rings. Energy coupled to these rings from the line beneath is optimised by suitably adjusting the location and dimensions of stubs on the line. It has been shown that the resonant frequencies of these rings do not change as several of these single-frequency antennas are combined to form a multi-resonant antenna. Furthermore, all radiators are forced to operate at their primary mode and some harmonics of the lower resonant frequency rings appearing within the frequency range are suppressed when combined. The experimental prototype antenna has three resonant frequencies at which it has good radiation characteristics.

1 Introduction

With the wide proliferation of wireless systems and the trend to incorporate multiple functions into a single terminal, the design of multi-functional mobile terminals has come to the forefront of research. Microstrip antennas are widely accepted to use in these systems because of their compact size, light weight and low cost [1]. Various shapes of patches and rings are studied for these antennas [1–4]. The primary mode of operation in these rings is usually TM_{11} [1]. These antennas are usually excited either with capacitive strip [5] or with patches or rings in other layers of a stack [6]. Most of the popular feed schemes in (solid) patch antennas are not preferred for ring antennas [7, 8]. In general, ring antennas provide narrower bandwidth [9, 10] and higher radiation resistance than a similarly sized regular patch antenna [1]. In this paper, we propose an approach for the design of a multi-frequency antenna using ring geometry.

The multi-ring multi-frequency antenna proposed here can use several concentric rings and each of these rings may be individually coupled to a common transmission line on a dielectric layer beneath. A somewhat similar feed structure has been used recently to realise ultra-wideband impedance

characteristics for rings [2, 11, 12]. There have also been attempts at using two or more rings with similar objectives [13, 14]. However, the aim of the present paper is to investigate the design of multi-frequency antennas in which the individual rings maintain their own resonant frequencies even after combined to a single feed antenna. The dual of this radiator configuration has been reported as triple ring-slot antennas [15].

The design of the basic configuration of the antenna and some parametric studies are described in Section 2. To demonstrate the usefulness of this scheme for multi-frequency operation, we have designed an antenna with three resonant frequencies. As shown in Section 3, resonances of individual rings do not depend on those of other rings and hence each of these resonances can be specified independently. Investigations are reported on the possible extensions and limitations of this approach. In principle, this approach can be generalised for multi-ring antennas with any number of non-overlapping concentric rings of any shape, including fractals. Such a systematic approach to design a multi-frequency microstrip antenna using patches of any shape could not be found in the literature. Some of these simulation results are experimentally verified in Section 4. Comments on the

usefulness and limitations of the proposed approach are summarised in Section 5.

2 Proposed antenna configuration and its design

In order to facilitate a systematic approach for multi-frequency operation, the proposed antenna structure has three layers: two dielectric layers and an air gap between them, suitably adjusted to maximise the antenna performance. In our study, we use standard microwave substrate RO 3003 ($\epsilon_r = 3$, $\tan \delta = 0.0013$, thickness = 1.56 mm). The dielectric layer at the bottom has a microstrip transmission line patterned on one side to form the feed structure. The top dielectric layer has a radiating ring on the outer side. A spacer between the dielectric slabs provides the necessary air gap. The schematic of the antenna configuration is shown in Fig. 1.

In this design, the feed microstrip line has a rectangular strip placed at its end to couple energy to the radiating ring. The dimensions of these strips have the effect of changing the input resistance of the antenna at its resonant frequency and hence can be optimised easily. It has been observed that optimum width of this strip is usually more than the width of the ring itself. This strip is placed symmetrically beneath the near side of the ring.

As one could imagine there are several parameters that could be varied to arrive at an optimum antenna design. These include the width of the ring (w_r), the air gap (g_0) between dielectric sheets and the dimensions (l_s , w_s) of the strip attached to the transmission line. However, the mean perimeter of the ring is very critical in deciding its resonant frequency. Based on the ring antennas we have designed, the resonant frequency is found to be inversely proportional to the mean perimeter expressed in wavelengths [1]. The design expression for ring antennas available in the literature can be used to calculate the resonant frequency

$$f_r = \frac{c}{4(l_r - w_r)\sqrt{\epsilon_{\text{eff}}}} \quad (1)$$

where ϵ_{eff} is the effective permittivity of this multilayer microstrip structure for a line of width w_r (same as that of

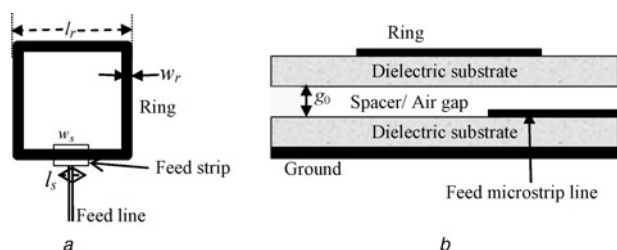


Figure 1 Schematic of the ring antenna

a Top view
b Cross section

the ring) and l_r is the outer length of the square ring. We used the expressions available in [16, 17] to calculate the quasi-static value of permittivity for our configuration. An accurate model of closed-form expressions for frequency-dependent effective permittivity available in [18] has been used to design these antennas. When the above design formula is applied for the design of square rings with a substantial range in lengths ($10 \leq l_r \leq 30$ mm) and widths ($0.5 \leq w_r \leq 3$ mm), it has been observed that this approach results in antenna designs with simulated resonant frequencies within 2% of calculations. This error could not be reduced any further because of the presence of discontinuities such as corners of the ring and the finite dimensions of the feed region.

Dimensions of such single ring antennas can be easily optimised for resonant frequencies of interest. Three such cases are listed in Table 1 [19]. The feeding microstrip line (50Ω) has a width of 3.9 mm. The radiating ring has a fixed width (w_r) of 1 mm. In all these cases, an air gap of 0.5 mm between the dielectric layers has been used. The resonant frequency for these rings calculated using the above expression is included for comparison with simulations. The input impedance of these antennas obtained using Agilent ADS Momentum tool are presented in Fig. 2.

A parametric study was conducted to analyse the effect of air gap between dielectric layers in the performance of the antenna. As shown in Fig. 3, there is a monotonous increase in the resonant frequency of the antenna as the air gap is increased. This is consistent with intuition, as the effective permittivity actually decreases with the air gap. However, as shown in Table 2, the dimensions of the feed strip are required to be altered to retain the impedance match of the antenna.

Table 1 Resonant frequencies and geometrical parameters for different single-ring antennas

Antenna parameters	Design 1	Design 2	Design 3
outer dimension of the ring l_r , mm	23.7	16.8	10.4
width of feed strip w_s , mm	1.4	1.6	1.3
length of feed strip l_s , mm	6.5	7.6	8.4
calculated resonant frequency, GHz	2.393	3.438	5.778
resonant frequency by simulation, GHz	2.433	3.509	5.846
simulated boresight gain, dBi	5.40	5.45	7.00

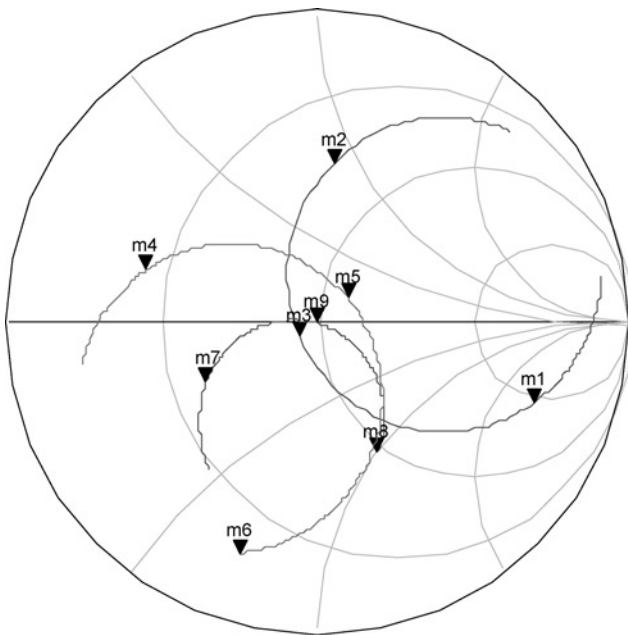


Figure 2 Combined Smith chart for the input characteristics of various ring antennas designed for single frequency operation

The curves correspond to Designs 1 (red), 2 (green) and 3 (blue) in Table 1

Markers (m1: 2.4 GHz, m2: 2.45 GHz, m3: 2.433 GHz; m4: 3.45 GHz, m5: 3.509 GHz, m6: 3.6 GHz; m7: 5.7 GHz, m8: 6 GHz, m9: 5.846 GHz) are shown to indicate various design bands

We have also performed parametric studies on the dimensions of the feed strip on the lower dielectric layer. These are shown in Fig. 4. In these cases, the resonant frequency does not shift appreciably, but the impedance match is affected by changing the dimensions from the optimum values. However, there are no specific trends in their optimum values as these are also affected by the width of the transmission line in that layer, the frequency of operation and the presence of other feed strips located nearby. Hence the feed strip will have to be re-designed

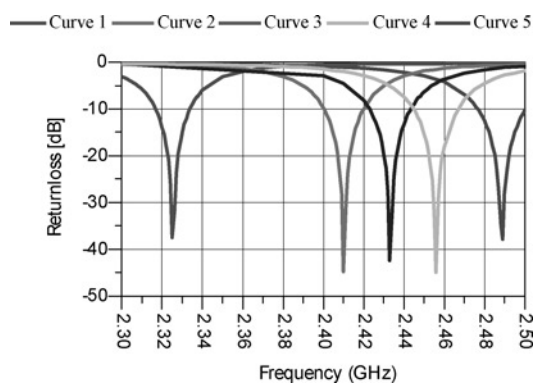


Figure 3 Effect of air gap on the return loss of the proposed ring antenna

The dimensions of feed strip are adjusted as in Table 2 for impedance matching

using electromagnetic simulations for any change in the antenna configuration.

These parametric studies indicate that the air layer between dielectric substrates has a marginal role in the resonance characteristics of the antenna. Although these studies indicate that this may help the impedance match, it would be easier to control the impedance match by changing the dimensions of the feed strip. Hence, it may be possible to re-design these antennas even without the air layer. In the present study, we use a fixed air gap of 0.5 mm. The feed strip dimensions, however, do not have a significant role in deciding the resonant frequency of the antenna.

3 Design of a multi-resonant antenna

After studying the effects of various design parameters, we propose the extension of the scheme for multi-resonant antennas as shown in Fig. 5. To compare with previous studies on single-resonant antennas, we have retained the same dimensions for the rings and the same stack of dielectric layers. Table 3 lists the geometrical parameters for this combined antenna. Although the dimensions of the rings are not changed, those of the feed strips are changed to improve the impedance matching under the new scenario. This optimisation may be easily performed using standard electromagnetic simulation softwares.

The design of multi-frequency antenna may be performed in the following simple steps.

- (i) Determining the effective permittivity for the dielectric stack used.
- (ii) Obtaining the mean dimensions for concentric ring geometries based on (1).
- (iii) Modeling the antenna using full-wave solvers and tune the length (l_s) and width (w_s) of the feed strips individually.

It may be noted that the effective permittivity depends on the width (w_r). Hence, a width (for the ring geometry) has to be assumed in the beginning. However, iteration of steps (i) and (ii) would be required if this results in overlap of geometries, or if the gap between them would become infeasible. Furthermore, the dimensions of the feed strip do not seriously change the resonant frequency of the antenna. However, these do have a role in the impedance match at the resonant frequency. Hence, these feed strips may be adjusted independent of one another for the best impedance match at each of the operational frequencies.

As shown in Fig. 6, the resonant frequencies of these rings do not change when these are combined. Furthermore, resonances due to the excitation of higher-order modes for the single-frequency antennas (c.f. the resonance at about

Table 2 Resonant frequencies and feed dimension for single-frequency antennas with different air gaps (shown in Fig. 3) between dielectric layers

	Air gap g_0 , mm	Width of the feed strip w_s , mm	Length of the feed strip l_s , mm	Resonant frequency, GHz
curve 1	0.1	0	0	2.325
curve 2	0.4	1.4	6.5	2.410
curve 3	0.5	1.4	6.4	2.433
curve 4	0.8	1.4	7.8	2.458
curve 5	1	1.4	10.2	2.489

4.7 GHz for the outer ring) have disappeared in the multi-frequency design. Therefore we can conclude that this antenna configuration ensures that only useful mode is excited. This is contrary to the approach in [2, 11–14] where the focus was on including additional rings to improve the bandwidth of the innermost ring. Hence, although the antenna showed additional resonant frequencies, the gain at these frequencies were not good enough. In the proposed structure, this issue is avoided by facilitating coupling to all rings by means of appropriately designed feed strips.

The performance characteristics of these antennas obtained using Momentum tool in ADS do not show appreciable cross polarisation. The simulated values for the boresight gain at the resonant frequencies of the antenna are also listed in Table 3. Resonant frequencies simulated for this antenna shows only a marginal difference from those of individual rings presented in Table 1. These results validate the most important proposition of this work, that resonant frequency of the individual rings is not affected by the presence of additional rings.

It has been found that the optimum widths of these strips (w_s) are usually slightly more than the width of the ring (w_r)

itself, and hence may limit minimum separation between adjacent rings. It may, however, be pointed out that we were able to design rings with a separation of 0.05 mm between them (which is typically the fabrication limit) with separate resonant bands which are consistent with their own resonant frequencies when designed as single-band antennas. The geometric dimensions and resonant frequencies of the single and multi-resonant antennas are given in Table 4. Note that the resonant frequencies of individual ring geometries are not significantly altered when combined. The shift in resonant frequency is within 2% (which is also the error in the design formula) for these cases.

In this respect, the antenna proposed here has a clear advantage over the ring-slot geometries proposed in [15, 20]. Conducting strip between slots is used there for impedance matching, whereas in the present design this is achieved by individual feed strips below the rings, adding design flexibility. Furthermore, the ring configuration has a better gain compared with its slot counterpart [15].

On the other extreme, it may be of interest to know how separate the first and last resonant frequencies could be. This is important in the overall performance of the antenna as some higher-order modes of the outermost ring may

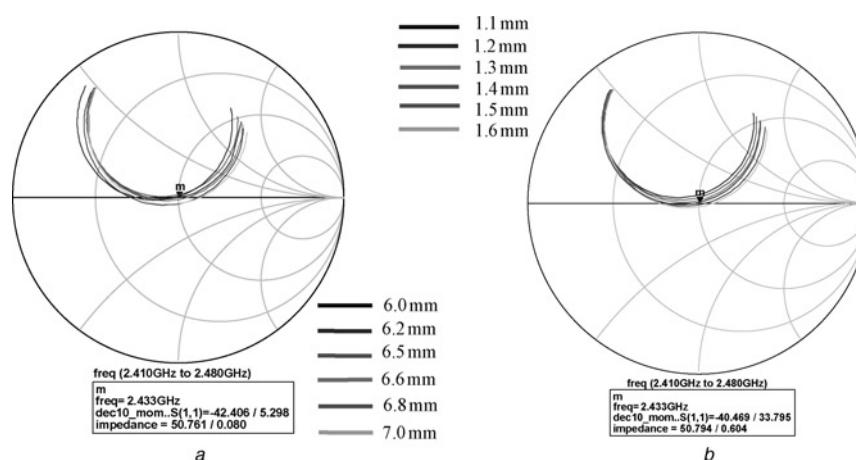


Figure 4 Input impedance variation with dimensions of the feed strip

a Length of the feed strip (l_s)
b Width of the feed strip (w_s)

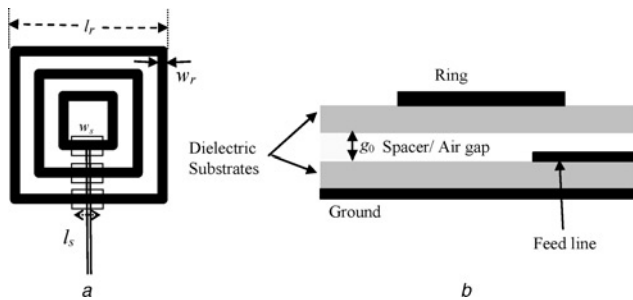


Figure 5 Proposed configuration for the antenna with three resonant frequencies

a Top view
b Cross section

Table 3 Geometrical parameters and results of simulations for the antenna with three rings combined

Antenna parameters	Ring 1	Ring 2	Ring 3
side dimension of the ring l_r , mm	23.7	16.8	10.4
width of feed strip w_s , mm	1.6	1.6	2.6
length of feed strip l_s , mm	7.0	6.8	4.4
resonant frequency, GHz	2.433	3.509	5.779
simulated gain, dBi	5.69	5.26	6.63

interfere with the radiations from the innermost ring. Based on our studies on antennas with three rings, these frequencies may be separated by as much as 1:3. This factor can be increased by having more number of rings.

An example is shown for the case of five rings in Fig. 7. Mean perimeters (p) of the rings are indicated in the figure. The ratio between the first and the last useful resonant frequency is 1:5.4. All resonances of individual rings are captured in the combined antenna. Although the second harmonic frequencies of the three outermost rings present in the range are avoided in the final configuration,

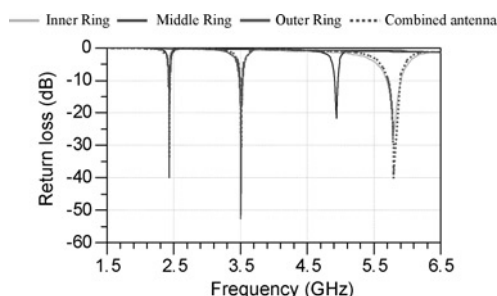


Figure 6 Simulated return loss characteristics of the tri-band antenna with those of single-band antennas with rings of same dimensions

Although the resonant dimensions of these rings are kept the same, the dimensions of feed strips are re-optimised

Table 4 Resonant frequencies and geometrical parameters for the combined antenna with three closely placed rings (separation between adjacent geometries = 0.05 mm) along with those of individual elements

Antenna parameters	Ring 1	Ring 2	Ring 3
outer length of the ring l_r , mm	18.9	16.8	14.7
width of the ring w_r , mm	1	1	1
calculated resonant frequency, mm	3.035	3.438	3.965
simulated resonant frequency (individual rings), GHz	3.095	3.509	4.035
simulated resonant frequency (combined structure), GHz	3.05	3.438	3.985

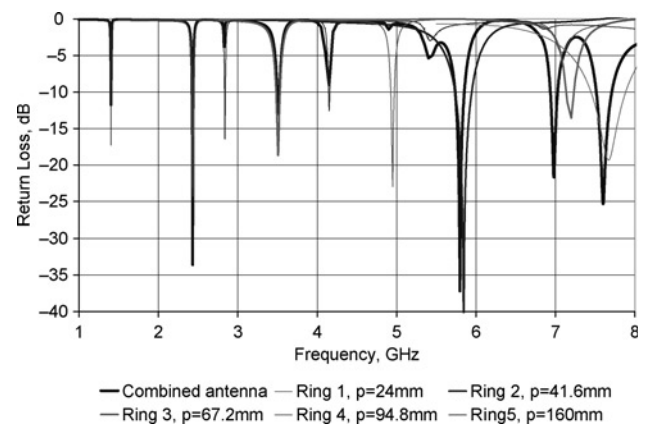


Figure 7 Return loss characteristics of the combined five-ring antenna along with that for the individual rings

the simulation results show that the third harmonic is still present. However, the radiation pattern at this frequency has a peak towards the boresight direction and hence these offer additional operational frequencies. As the dimensions

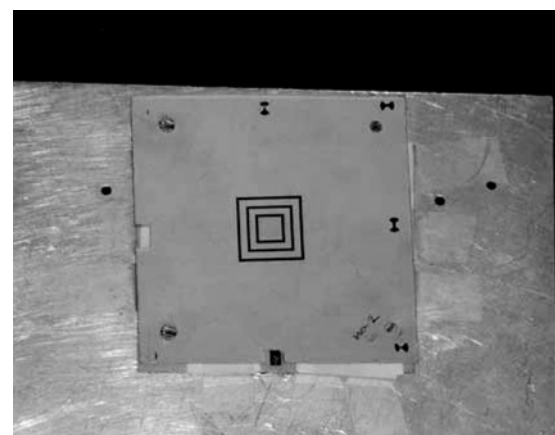


Figure 8 Fabricated antenna with three resonant frequencies

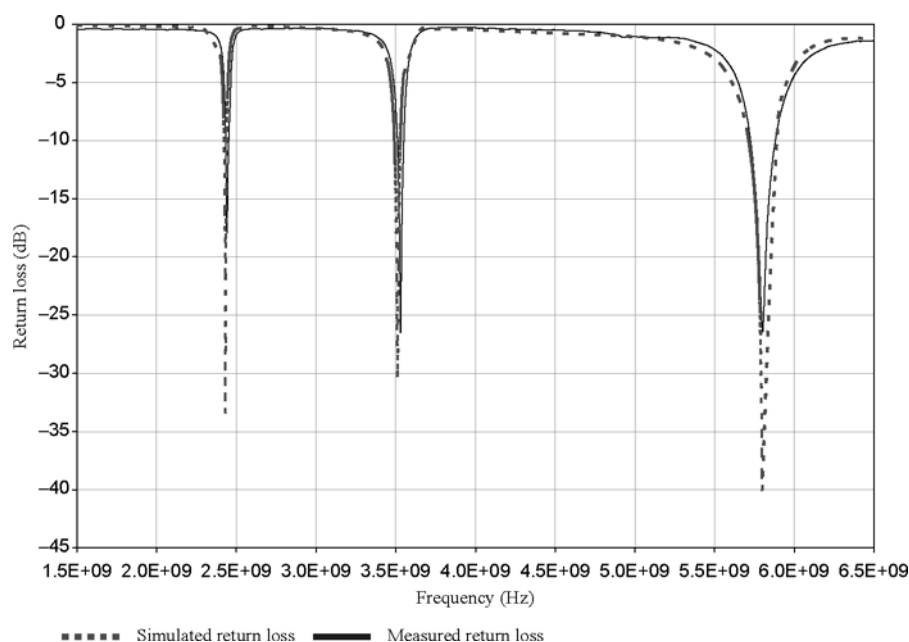


Figure 9 Simulated and measured return loss characteristic of the combined antenna with three rings

Table 5 Gain characteristics of the combined antenna with three rings at its resonant frequencies

resonant frequency, GHz	2.433	3.509	5.799
simulated boresight gain, dBi	5.69	5.26	6.63
measured boresight gain, dBi	5.31	5.17	6.89

of feed strips may be adjusted individually in this approach, it is possible to avoid some of the unwanted resonances of the radiating structure. It is believed that this feature also prevents resonances of two rings to combine together, as happens in [2, 11–14].

These results also show that the approach proposed here can indeed be generalised for designing a multi-frequency

antenna using multiple resonant rings. Furthermore, it may also be possible to increase the design flexibility by incorporating suitably meandered geometries such as fractals for the ring. On the other hand, due to radiations from higher-order modes in the microstrip line, care should be taken while designing antennas for operational frequencies typically above 10 GHz.

4 Experimental validation and discussion

The antenna for three resonant frequencies designed in Section 3 has been fabricated using standard printed circuit fabrication techniques and characterised using a vector network analyser. One of the dielectric sheets has all the rings on one side of it. The other sheet has the

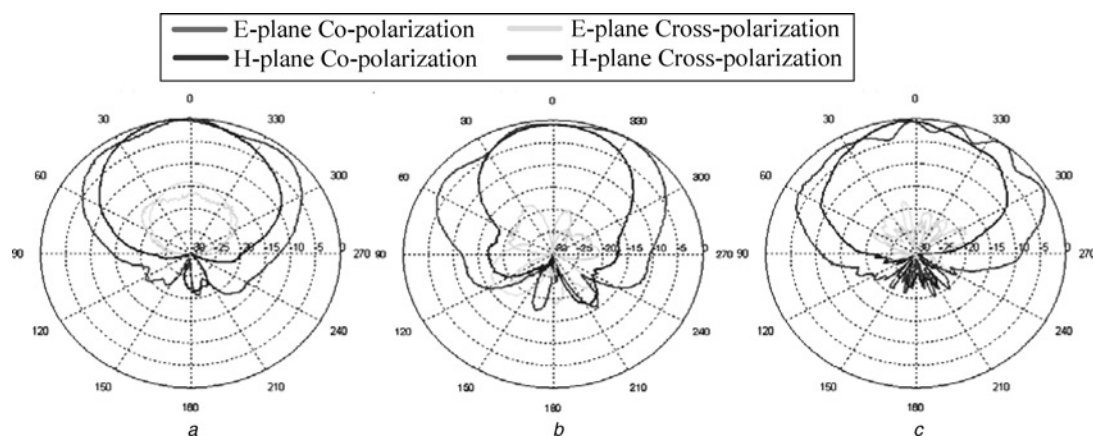


Figure 10 Measured radiation patterns of the combined antenna at its three resonant frequencies

a 2.45 GHz
b 3.5 GHz

transmission line and the feed strips on one side and ground plane on the other. An SMA connector is attached to the end of this line to feed the antenna. An aluminium sheet of $150 \times 150 \text{ mm}^2$ supports the antenna structure. A photograph of the fabricated antenna is shown in Fig. 8. The measured return loss is compared with simulation in Fig. 9. The marginal shift may be due to the infinite ground used in simulations and/or slight inaccuracies in assembling two layers of dielectric substrates.

The simulated and measured gain characteristics at three resonant frequencies are given in Table 5. This shows that the measured gain is compared well with the simulation results. The radiation patterns measured in an anechoic chamber are given in Fig. 10. The co and cross polarisation patterns in the E- and H-planes of the antenna are presented at the three resonant frequencies. The H-plane of this antenna is aligned with the length of the feed strip. These radiation patterns confirm that all these resonant frequencies correspond to TM_{11} modes of individual rings [21]. The antenna shows a cross polarisation level better than -15 dB at all these frequencies.

5 Conclusions

In this work, we proposed a coupled feed mechanism for ring-type microstrip antennas to enable systematic design of multi-resonant antennas. The ring is fed by a transmission line in another dielectric layer by means of electromagnetic coupling. The antenna is on a stacked structure consisting of two dielectric layers separated by an air layer in the middle. The dimensions of the feed strip have been designed so that the coupling between the ring and feeding line is maximum. Furthermore, we have studied the possibility of combining several of such square-shaped microstrip ring antennas for multi-resonant operation. This feed scheme may be easily adapted for applications that require multiple operational frequencies each with a narrow bandwidth. However, bandwidth may be enhanced by modifying the antenna geometry.

For making the antenna resonate at the desired frequencies at which individual rings designed, only a slight change in the feeding structure was required. Some of the higher-order modes of individual ring geometries are absent in the combined antenna. It has been shown that the rings can be as close as fabrication processes allow. The direct capacitive coupling between the transmission line and the rings does not allow the resonant bands to merge to form a wider bandwidth single-frequency antenna. It is also shown that it would be possible to combine any number of rings by this approach. The combination of five rings resulted in an antenna with several resonant frequencies which corresponded to the resonances of individual antennas. Even though the third harmonics are present, these result in radiation directed towards boresight, and hence may not cause degradation in performance.

The experimental results for an antenna with three rings agree well with simulations. The antenna gain is above 5 dBi at all resonant frequencies. The cross polarisation level is below 15 dB . Therefore we feel that this new kind of feeding arrangement for ring antennas has prospects in the systematic design of multi-resonant antennas. An additional benefit is that the proposed feed scheme is expected to be independent of the geometry of the ring and hence other non-intersecting concentric ring geometries including fractals may be used in the antenna design for improved performance.

6 Acknowledgments

This work was partially supported by the Department of Science and Technology, Government of India (New Delhi) under the project no. SR/FTP/ETA-36/2003. The authors also thank Agilent Technologies Inc. for donating ADS used in this work.

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