Modeling and Analysis of a Dual-Band Dual-Polarization Radiator Using FEKO

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Abstract — A dual-band hybrid antenna element comprising of microstrip and waveguide radiating elements is theoretically investigated through computer simulations. The low band radiator is a Shorted Annular Ring (SAR) microstrip antenna and the high band antenna is an open ended circular waveguide. First, the characteristics of a SAR patch antenna are presented and reviewed. Then the dual-band antenna configuration is described, which is realized by forming a waveguide radiator in the shorted region of the SAR microstrip antenna. Modeling and analysis of the SAR patch antenna and the hybrid element are investigated using the method-of-moment-based software package FEKO. The analysis includes return loss computations showing the element bandwidth at different frequency bands and the radiation patterns in the E- and H- planes. Feeding the element in phase quadrature produces circular polarizations (CP). The radiation patterns of the CP dual-band element are also analyzed using FEKO and the axial ratio performance is subsequently assessed.

I. INTRODUCTION

Dual-band antennas operating from a single aperture are desired in several modern communications, satellite communications, remote sensing, and multi-function radar systems. Providing multiple antennas to handle multiple frequencies and polarizations becomes especially difficult if the available space is limited (as with airborne platforms and submarine periscopes). Few techniques are currently available to achieve such dual band operation with microstrip antennas [1]. A rectangular patch can be operated at dual bands using the first resonance of the two orthogonal dimensions of the rectangular patch, which are the TM_{100} and TM_{010} modes. The frequency ratio is roughly equal to the ratio between the two orthogonal sides of the patch. Multiple radiation elements are also used for operation at dual bands. A third popular approach is the introduction of reactive loading to a single patch.

The orthogonal mode patch can have simultaneous matching of the input impedance at the two frequencies with a single feed structure. But then it gives two orthogonal polarizations from the two frequencies. A probe-fed patch can be used to accomplish this approach where the location of the probe is displaced from the two principal axes of the patch. Slot coupling can also be used to implement single feed dual matching.

The dual band operation can also be achieved using multiple radiating elements. In this case, each of the radiating elements supports strong currents and radiation at its resonance frequency. This category includes multilayer stacked patches. This approach can also be used to broaden the bandwidth of a single band antenna when the two frequencies are forced to be closely spaced. Multi-band antennas can also be obtained by printing more resonators on the same substrate.

Another popular technique for obtaining a dual band operation is the use of reactively loaded patch. A stub can be connected to one radiating edge of the patch so as to create a further resonant length for another operating frequency. The radiating edge can also be loaded with an inset or a spur-line. However, if a higher value of the frequency ratio is intended then shorting vias or lumped capacitors can be used between the patch and the ground plane. Etching slots on the patch can also introduce reactive loading.

A dual band element is presented in this paper and uses a hybrid of microstrip and waveguide radiators each resonating at a different frequency [2]. The hybrid antenna is realized by forming an open ended waveguide in the shorted region of a Shorted Annular Ring (SAR) microstrip antenna [3]. The SAR microstrip antenna acts as the low band radiator and the open ended waveguide acts as the high band radiator.

The upper to lower frequency ratio can be controlled by the proper choice of various dimensions and dielectric material. Operation in both linear and circular polarization is possible in either band. Moreover, both broadside and conical beams can be generated in either band from this antenna element. The following sections present a modeling and analysis of this dual band antenna element using the moment-based software package FEKO [4].

II. MODELING OF SHORTED ANNULAR RING (SAR) PATCH ANTENNAS

Annular ring and rectangular or square ring are popular geometries for microstrip antennas. They have one more design variable than the conventional circular patch, which is the inner dimension. Both inner and outer dimensions can be used to control the resonant frequency of the patch. They also generally offer greater impedance bandwidth. If the patch is shorted at the inner radius of the annular ring, the element is called Shorted Annular Ring (SAR) patch and it can offer some special advantages. Similar shorting at the inner dimension of the rectangular or square ring produces the same properties. The configurations of the circular and square versions of the SAR element are shown in Figure 1.

The SAR microstrip antenna was first investigated by Goto's group [5-6] for dual frequency use and subsequently as a circular polarization self-diplexing antenna [7] for mobile communications. Lin and Shafai [8] have used cavity method to analyze the characteristics of TM_{11} as well as TM_{21} modes of SAR patch antenna. Iwasaki and Suzuki investigated an electromagnetically coupled shorted patch antenna [9] and Boccia, et al. reported GPS application of elliptical annular microstrip antenna [10].

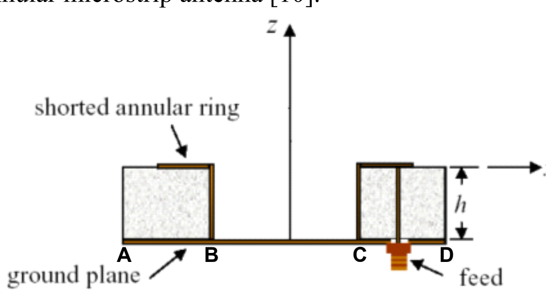


Fig. 1. Shorted annular ring (SAR) microstrip antenna.

To reduce the mutual coupling between the SAR in array environments, the surface waves propagating along the array structure has to be reduced. Jackson, et al. [3] showed that reduced surface wave excitation can be achieved by proper choice of the inner and outer radii of a SAR microstrip antenna. Therefore, if SAR microstrip antenna is designed accordingly, it is then called Shorted Annular Ring Reduced Surface Wave (SAR-RSW) microstrip antenna. The relationship between the outer radius a and inner radius b at resonance is

$$J_n'(ka)Y_n(kb) - J_n(kb)Y_n'(ka) = 0 \quad (1)$$

where J_n and Y_n are the Bessel functions of the first and second kind. If the values of a, b, and the substrate dielectric constant ε_r are given, the frequency can be varied and a number of roots can be determined for n = 0, 1, 2,……. This gives the different resonant modes of operation of the SAR microstrip antenna.

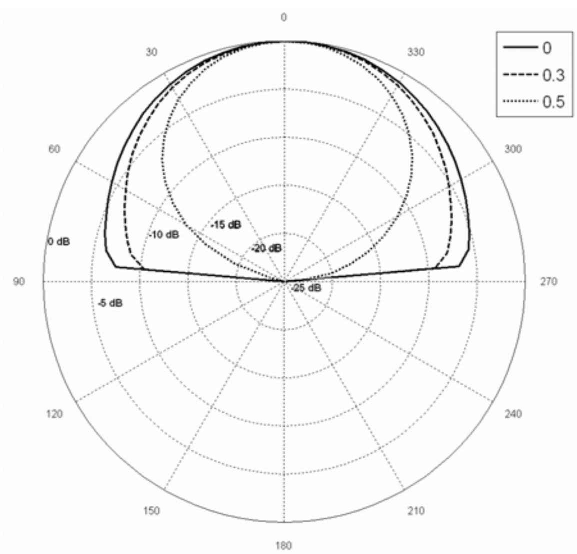
Table 1. Resonant frequency using FEKO and equation (1).

Inner/Outer radius	Res. freq. (GHz) from FEKO	Res. freq. (GHz) from equation 1
0	2.82	2.77
0.1	2.87	2.82
0.2	3.02	2.98
0.3	3.29	3.25
0.4	3.68	3.66
0.5	4.29	4.28

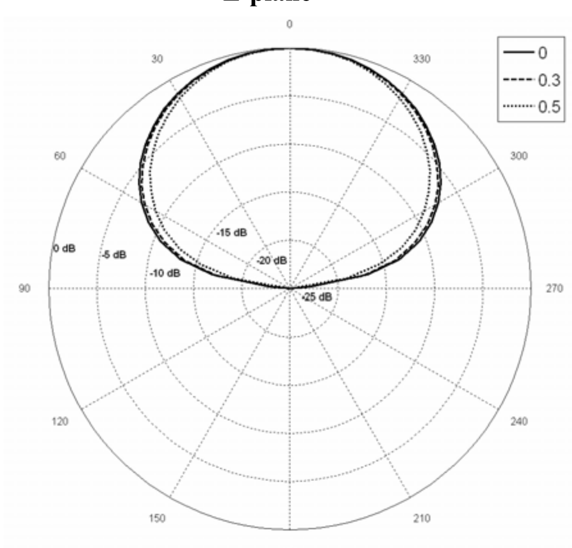
A simulation of the SAR element was performed using FEKO for $\varepsilon_r = 2.5$, $h = 1.5$ mm, and $a = 19.2$ mm. Table 1 compares the resonant frequency results using FEKO and equation (1). The broadside radiation patterns in the E- and H-planes were also computed using FEKO and the results are shown in Figure 2 for different inner/outer radius ratios.

Another interesting feature of the SAR antenna is that the lowest order mode produces a conical radiation pattern unlike the conventional microstrip antennas. This result was first reported by Goto [6] for use as a planar conical beam antenna, but this feature has not received attention. With suitable choice of outer and inner radii, a single feed antenna design, which produces conical pattern at lower frequency and broadside pattern at higher frequency, can be realized. Figures 3 and 4 present the return loss and radiation patterns, respectively, calculated using the full-wave MoM simulation FEKO for an optimized SAR antenna producing conical (at 3.85 GHz) and broadside (at 5.0 GHz) patterns from a single point feed. The peak directivity of the monopole-like pattern is 3.0 dB at about 15º from the horizon and that of the broadside mode is 8.0 dB. The bandwidth (in terms of -10 dB return loss) is about 2% and 3%, respectively, for conical and broadside modes.

Conical patterns are typically generated using higher order mode excited circular microstrip antennas [11-12]. A TM_{21} excited circular microstrip resonating at 3.85 GHz requires a radius of 20 mm. On the other hand, the radius of SAR patch antenna resonating at the same frequency is 13.7 mm, which is 25% less in size. A comparative study of compact circular microstrip antennas producing conical patterns was presented in [12].



E-plane



H-plane

Fig. 2. E- and H- plane patterns of SAR element for different inner/outer radius ratios.

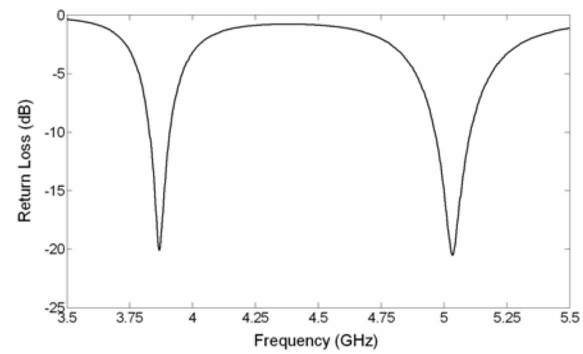
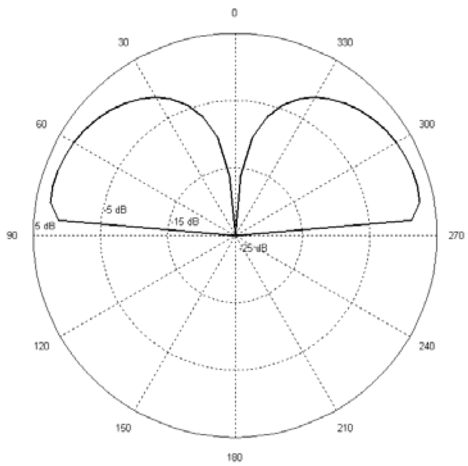


Fig. 3. Computed return loss of optimized SAR antenna; Parameters: a=13.4 mm, b=4.7 mm, h=1.5 mm, ε_r=2.35.

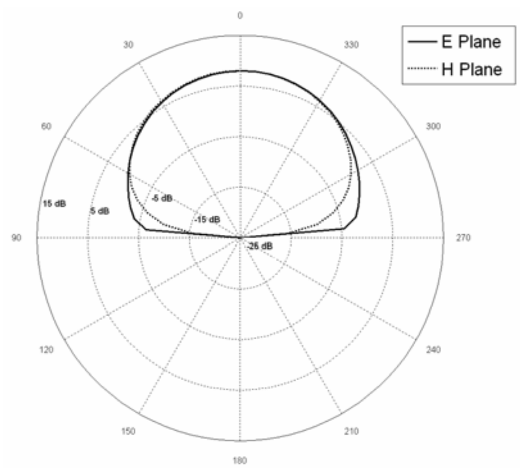
III. MODELING OF LINEARLY POLARIZED HYBRID DUAL BAND RADIATOR

The hybrid dual band element uses the annular or square ring as the low-frequency radiator in consistence with the SAR-RSW patch design. Figure 5 shows circular and square configurations for the hybrid dual-band element. The ground plane in its shorted annular region at the center creates an aperture that can be used as an open-ended waveguide radiator and can be designed to operate at the higher frequency band. The dimensions and dielectric materials of the SAR patch antenna and the waveguide radiator are appropriately chosen for the required dual band operation. The cut-off frequency of the dominant mode for the waveguide defines its higher band frequency. In general, the cut-off frequency of the dominant mode is far above the lower band frequency. Thus, the waveguide acts as a high pass filter in the lower band and yields good isolation between the ports. Although the dimension of waveguide is fixed, the higher band frequency can be reduced by dielectric loading the waveguide. The cut-off frequency can be changed to a desired value by loading of the waveguide with dielectric material of appropriate permittivity.

As in the SAR element, the hybrid antenna can be operated for a conical radiation pattern in either band. The lowest resonant mode of the SAR microstrip antenna is TM_{01}, which produces a conical radiation pattern. If the SAR microstrip antenna dimension is designed such that the resonant frequency in TM_{01} mode becomes the desired frequency, the antenna will produce a conical beam in the lower band. In order to generate a conical radiation pattern in the higher band, an appropriate feed design in the waveguide is required to generate higher order modes, which will produce conical radiation patterns.



3.85 GHz



5.0 GHz

Fig. 4. Computed radiation pattern at 3.85 GHz and 5.0 GHz; Parameters: a=13.4 mm, b=4.7 mm, *h*=1.5 mm, ε_r=2.35.

The circular hybrid element, comprising of an annular ring and a circular open-ended waveguide, was simulated using FEKO for insertion losses, radiation patterns, and port-to-port isolation at the two frequency bands. The simulation model is shown in Figure 6. The return loss at the lower frequency band is shown in Figure 7 indicating a -10 dB return loss of 3%. Figures 8 shows radiation patterns at the lower and higher frequencies of 3.0 GHz and 7.3 GHz for a circular element of parameters: a = 27.8 mm, b = 13.9 mm, ε_r = 2.2, and h = 2.54 mm. At 3 GHz, the calculated peak directivity is 8.8 dB and the 3 dB beam widths are 55º and 63º in the E- and H- planes, respectively. The dual-band antenna produces a peak directivity of 9.5 dB and beam widths of 33º (E-plane) and 48º (H-plane) at 7.3 GHz. The higher frequency represents a margin of 16% over the cut-off frequency of 6.3 GHz for the air-filled circular waveguide.

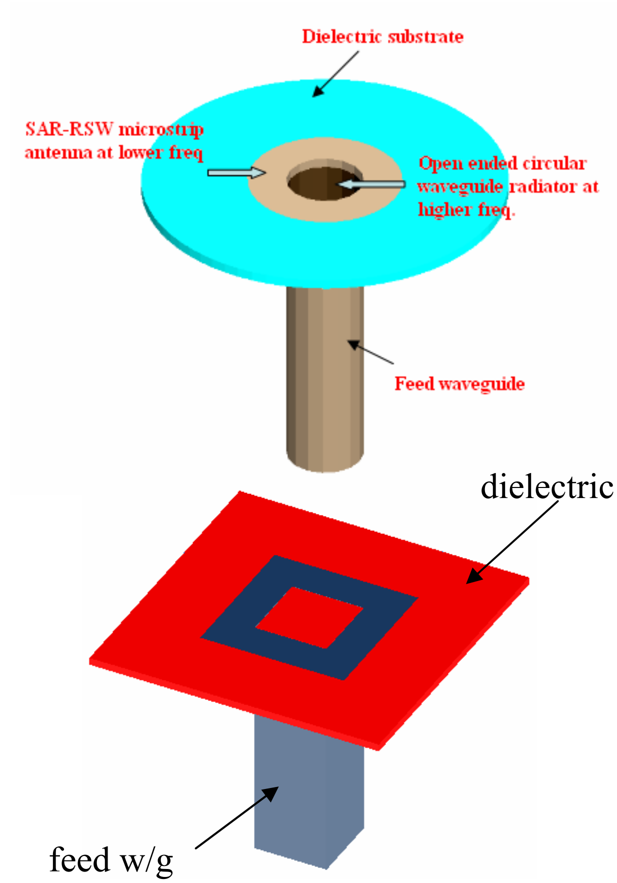


Fig. 5. Circular and square configurations for the hybrid dual-band element.

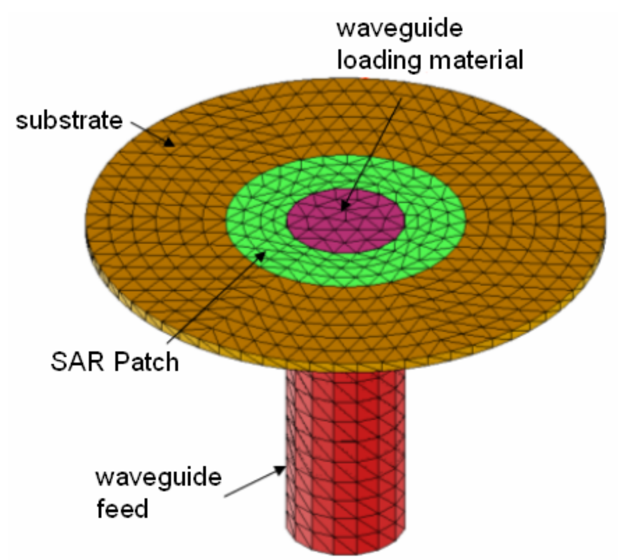


Fig. 6. Modeled dual-band antenna using FEKO.

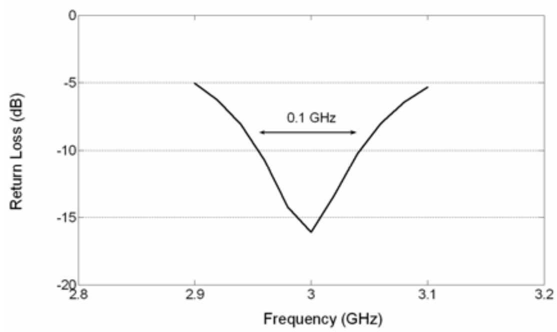


Fig. 7. Computed return loss of dual-band antenna at lower frequency; Parameters: a=27.8 mm, b=13.9 mm, h=2.54 mm, ε_r=2.2.

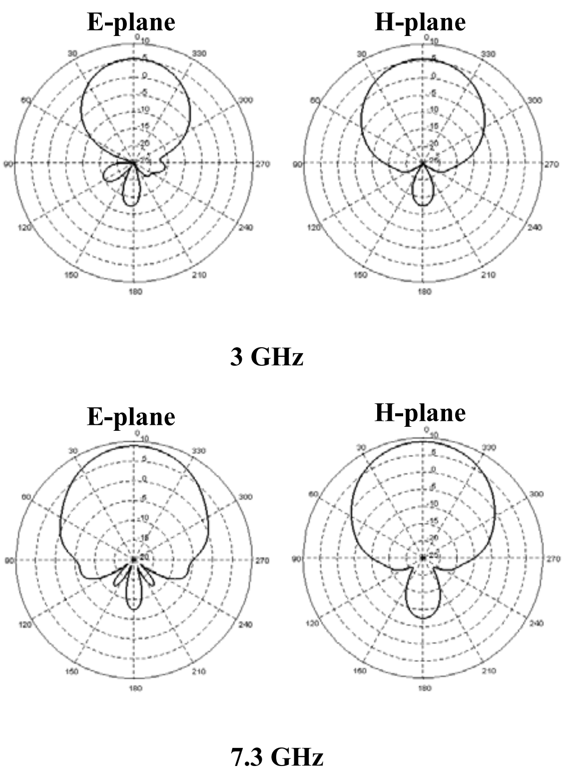


Fig. 8. E- and H- plane radiation patterns of the hybrid dual-band element.

One of the features of this dual-band configuration is the good inherent port-to-port isolation at lower frequency. For low frequency signals, the circular waveguide acts as a high-pass filter and good isolation between the ports is achieved in the low frequency band. In other words, the length of the waveguide feed section determines the isolation between the ports. The computed isolation data at the two bands are shown in Figure 9. Isolations in excess of 85 dB at the lower frequency band and 31 dB at the higher frequency band were calculated.

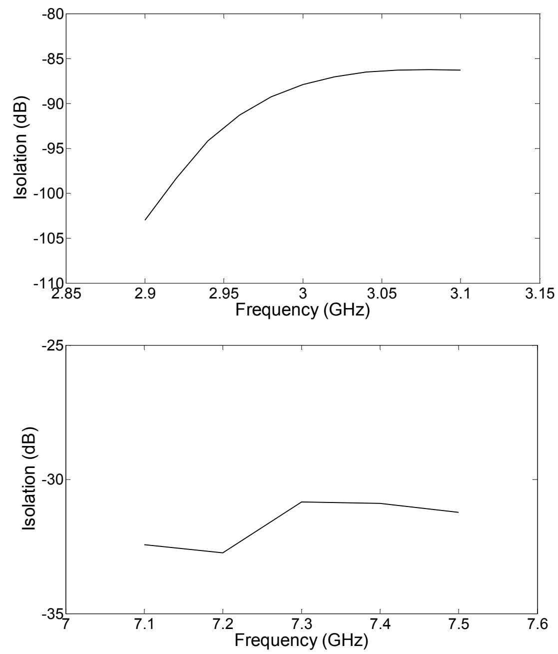
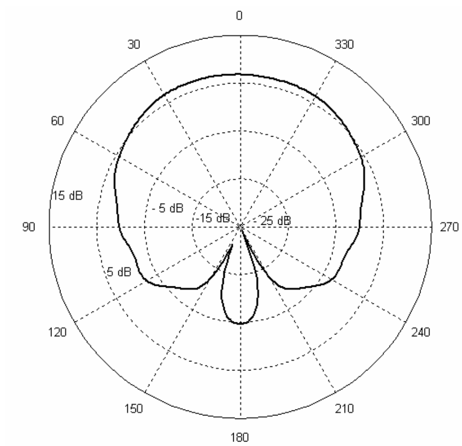


Fig. 9. Port-to-port isolation at the two frequency bands of the hybrid element.

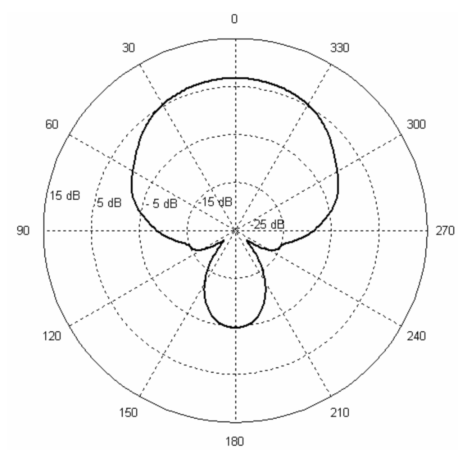
Another parameter to control one of the operating frequencies is the permittivity of the dielectric material inside the waveguide. The higher frequency can be reduced by dielectric loading of the waveguide. The present work considers only the dominant mode excitation in the circular waveguide, which produces broadside patterns. Higher order modes, for example TM_{01} mode, can be made possible with an appropriate waveguide feed design and will generate conical patterns. An example is shown in Figure 10 for the radiation patterns of a dielectric loaded waveguide radiating element with a dielectric constant of 3.0. The upper frequency is reduced to 4.2 GHz. The lower frequency characteristics remain almost unaffected except for the isolation between the ports, which depends on the separation between the operating and waveguide cut-off frequencies. The increase in beam width and the reduction in directivity are due to the decrease in the size of the radiating element.

IV. MODELING OF CIRCULARLY POLARIZED HYBRID DUAL BAND RADIATOR

Feeding the radiators within the hybrid element at two orthogonal points with equal amplitudes and in phase quadrature produces circular polarization. The feeding can be such that dual circular polarizations are produced. Feeding at four points with sequential 90-degree phase shifts will produce lower axial ratios. This was simulated using FEKO for the hybrid element at the two frequency bands of operation. The models for dual and quad feeding of the shorted annular ring are shown in Figure 11. All design parameters required in simulation such as, inner and outer radii, feed position, dielectric constant, substrate height, ground plane size, and operating frequency were the same as used in linear polarization of the hybrid antenna.



E-plane



H-plane

Fig. 10. Computed E- and H- plane patterns at 4.2 GHz for dielectric-loaded waveguide.

Simulation results at the lower frequency band for the circular hybrid antenna are shown in Figures 12 and 13 for the dual-fed element and in Figures 14 and 15 for the quad-fed element. The results of the simulation indicated that low axial ratios can be obtained on axis over a bandwidth greater than the impedance bandwidth. Quad feeding produced broader impedance bandwidth and perfect axial ratio on axis. It also produced larger beamwidth over which the axial ratio is below certain level, e.g. 3 dB. Resulting radiation patterns were almost identical in the E- and H-planes, supporting the low axial ratio results.

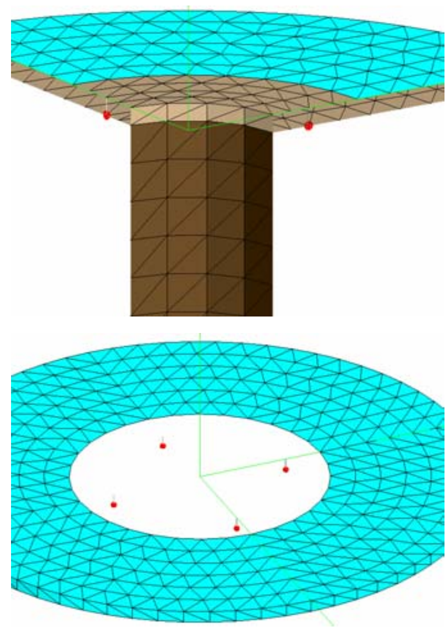


Fig. 11. FEKO model for dual and quad feeding of hybrid element for circular polarization.

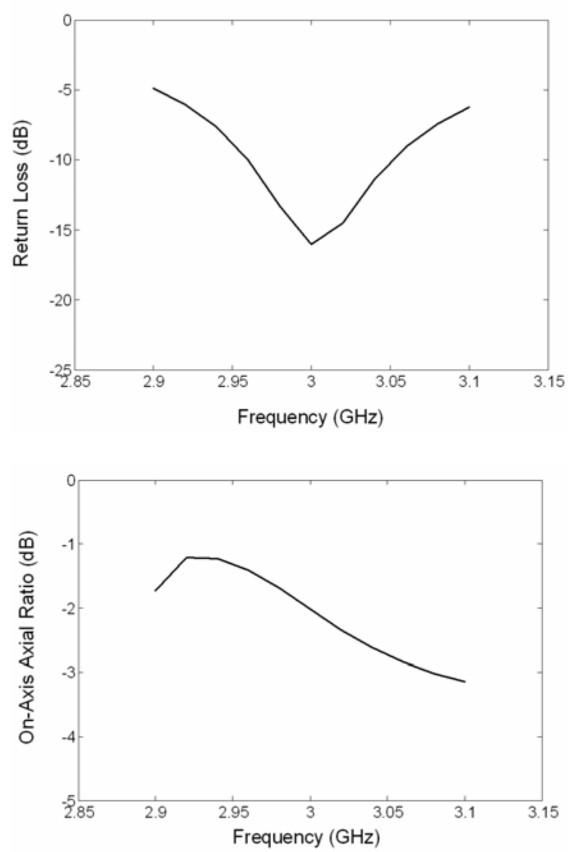
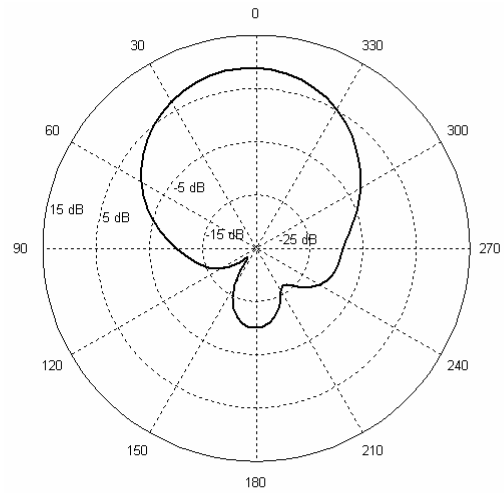
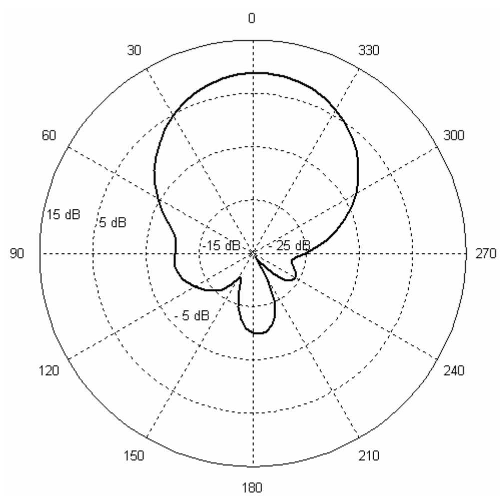


Fig. 12. Return loss and on-axis axial ratio at lower band for circular hybrid element with dual-fed circularly polarized SAR.

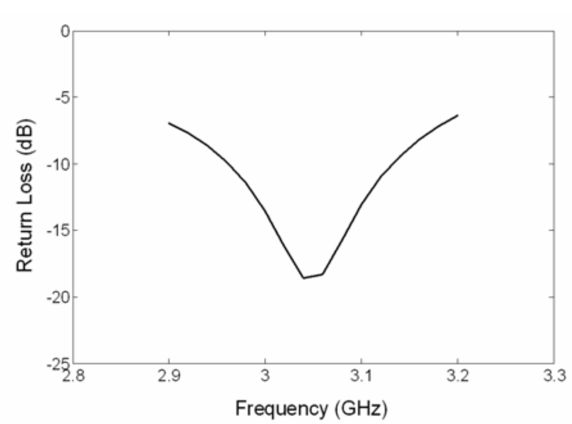


(a)



(b)

Fig. 13. Radiation patterns at 3 GHz for circular hybrid element with dual-fed circularly polarized SAR: (a) φ = 0° plane and (b) φ = 90° plane.



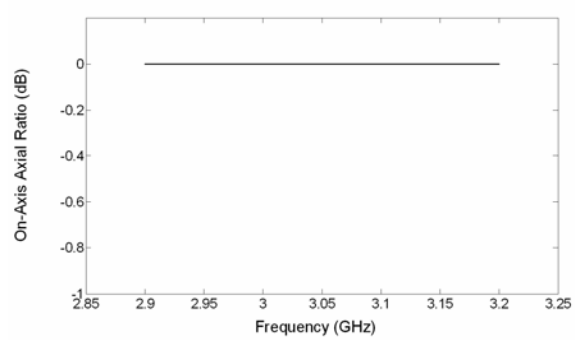
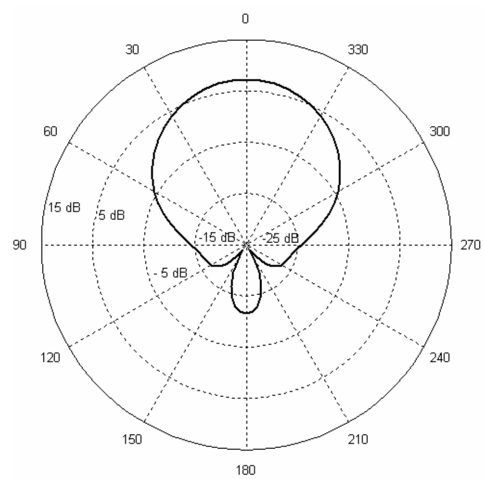
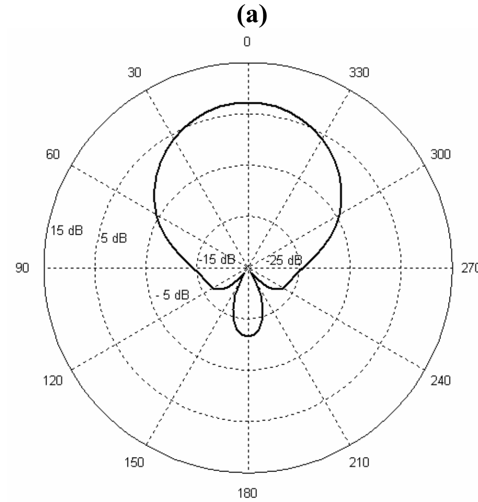


Fig. 14. Return loss and on-axis axial ratio at lower band for circular hybrid element with quad-fed circularly polarized SAR.



(a)



(b)

Fig. 15. Radiation patterns at 3 GHz for circular hybrid element with quad-fed circularly polarized SAR: (a) φ = 0° plane and (b) φ = 90° plane.

V. CONCLUSIONS

A dual-band dual polarization radiating element was modeled using the electromagnetic software package FEKO. Return loss, radiation patterns, and port-to-port isolations were calculated. The program was also used to design and optimize the element parameters in order to achieve the dual-band operation at the desired frequencies. Circular polarization operation was simulated by feeding the element at two orthogonal points in phase quadrature or at four points in sequential phase progression.

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