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Mutual Coupling Compensation for a 1 × 2 Short Helical Antenna Array Using Split-Ring Resonators

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Abstract *In this article, the design, simulation, and realization of an L-band axial-mode 1 × 2 short helical antenna array are presented. The antenna array has a compact size and is lightweight. To improve array performance, special attention is paid to important parameters, such as gain, impedance matching, axial ratio, and mutual coupling. Impedance matching is achieved by optimization of the helix wire radius and the feed length. Axial ratio is improved by adding the optimized incorrect turn at the end of the helix. Finally, to reduce the mutual coupling between the elements, split-ring resonators are designed and installed between the two antennas.*

Keywords axial mode, helical antenna array, mutual coupling, split-ring resonator

1. Introduction

The cylindrical helical antenna, first developed by Kraus, radiates a circularly polarized (CP) wave in the direction of the antenna axis when the circumference of one turn (C) is approximately $\frac{3}{4}\lambda < C < \frac{4}{3}\lambda$, with λ being the free-space wavelength, and the maximum of the radiated power is directed toward its axis (Kraus, 1988). Early studies have mostly been focused on the helix with a large number of turns and pitch angles, while few have considered short helical antennas (Wong & King, 1979; Yamauchi & Samada, 1985; Kraft & Monich, 1990). Nakano et al. (1991) indicated that a two-turn helix with a pitch angle as small as 4° can radiate a CP wave over a 12% bandwidth. Short axial-mode helical antennas with less than three turns are suitable for array applications, especially when an antenna with a relatively small physical size is needed, which is wideband and also broad beamed. In other words, if a broad radiation beam is desired, it is essential to decrease the number of turns of an axial-mode helical antenna (Kraus, 1948), which, on the other hand, deteriorates the axial ratio (AR). It is well known that the AR of the helical antenna can be reduced by tapering the ending and the beginning turns of the helix (Wong & King, 1979; Kraft & Monich, 1990; Nakano et al., 1986). Experimental

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results show that the AR characteristics of a short axial-mode helical antenna (with less than three turns) can be recovered by applying a small taper in the helix and/or adding an incorrect turn at the end of it. However, in the first method, peak gain slightly reduces, and in the second, antenna axial length slightly increases.

One of the major problems that may be encountered in any practical antenna array is the mutual coupling that virtually affects all of the parameters that determine the array performance. It should be noticed that mutual coupling is related to the distance between the elements of the array. In order to prevent the formation of grating lobes in the radiation pattern of an array, element separation must be sufficient. Nakano et al. (1984) showed how the mutual coupling between a pair of identical helices can be reduced by rotating one of them with respect to the other. Moreover, in order to reduce the mutual couplings between the array elements, Shiokawa and Karasawa (1982) enclosed the helical section in a cavity. In 1999, an array of split-ring resonators (SRRs) was fabricated, which presented a negative magnetic permeability in the resonance region (Pendry et al., 1999). If the magnetic excitation field is perpendicular to the plane of the SRR rings, a reduction in mutual coupling between the array elements will be realized over a particular frequency range. In Bait-Suwailam et al. (2009), SRRs were used to decrease the mutual coupling between closely spaced monopole antennas.

In this study, an L-band axial-mode 1×2 short helical antenna array is presented. By optimizing the helix wire radius and the feed length, impedance matching is accomplished. The AR is improved by adding the optimized incorrect turn at the end of the helix. Also, to reduce the electromagnetic coupling, SRRs are designed and inserted between two antennas. Both the simulation and measurement results are provided.

2. Geometry of the Antenna Array with Rectangular Ground Plane

A 1×2 short helical antenna array with a rectangular ground plane is simulated using the CST simulation platform (Computer Simulation Technology; CST Studio Suite 2010, GmbH) as shown in Figure 1. The right-handed helices are oriented along the y-axis, vertical to a perfect ground lying in the x-z-plane. In the simulations, the number of segments for each turn of a helix is chosen to be 15. Furthermore, all of the designs and simulations are performed at the center frequency of $f0 = 1.575$ GHz. The helix is

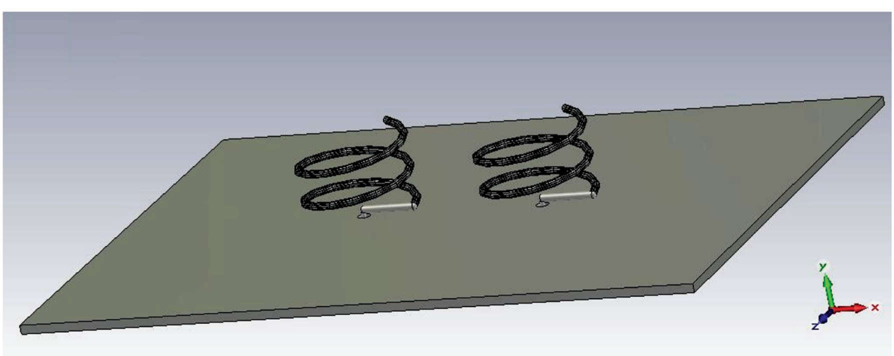


Figure 1. Layout of the 1×2 short helical antenna array with rectangular ground plane. (color figure available online)

Table 1
Design parameters of helices

Symbol	Parameter	Dimension
C	Circumference of helices	19 cm
α	Pitch angle	5.4°
H	Axial length	4 cm

chosen to be uniform (not tapered), with $\frac{C}{\lambda} = 1$, where λ is the free space wavelength at 1.575 GHz. The antenna parameters are the circumference of helix (C), pitch angle (α), radius of helix wire (r), and axial length (H). Design parameters of the helices are calculated and shown in Table 1. Initial values of the antenna array parameters can be obtained by a series of computations according to Kraus (1988).

The array elements are fed by a coaxial cable in the center of the helix. The straight wire connected to the feed point is located at height h above the ground plane and extended to the beginning of the helix. The angle between the straight wire from the feed point to the starting point of the helix and the positive x-axis is 0°. The straight wire helps matching between the antenna and the feed. A standard coaxial cable (LMR 400; Times Microwave Systems, Wallingford, Connecticut, USA) was modeled to feed the helix, with the inner conductor connected to the helical winding and the outer conductor bonded to the ground plane. The inter-element spacing (between the centers of helices) is chosen to be 0.5λ. The dimensions and shape of the ground plane of the axial-mode helical antenna array significantly affect the antenna's gain and AR due to the image effect. In the proposed design, a rectangular plate (copper strip) is chosen, and the optimal dimensions of rectangle are determined to be $2\lambda \times 1.5\lambda$.

3. Impedance Matching and Improving the AR

Impedance matching is attained by optimization of the helix wire radius and the feed height (h), which is the distance between the antenna and the ground plane. Another important parameter is the AR, which is improved by adding the optimized incorrect turn at the end of the helix. From the simulations, it is observed that a shorter feed length leads to better impedance matching to the feed line. It is found that with a feed length of 4 mm, optimal performance can be achieved. Also, the optimum radius of the helix wire and the number of turns are found to be 2 mm and 2.19 turns, respectively (see Table 2). Figure 2 demonstrates the measured and simulated input reflection coefficients for the array with optimized parameters. It is noticed that the value of $|S_{11}|$ is less than −20 dB

Table 2
Optimized parameters

Symbol	Parameter	Dimension
H	Coaxial connector, feed height (LMR 400)	4 mm
R	Radius of helix wire	2 mm
N	Number of turn	2.19

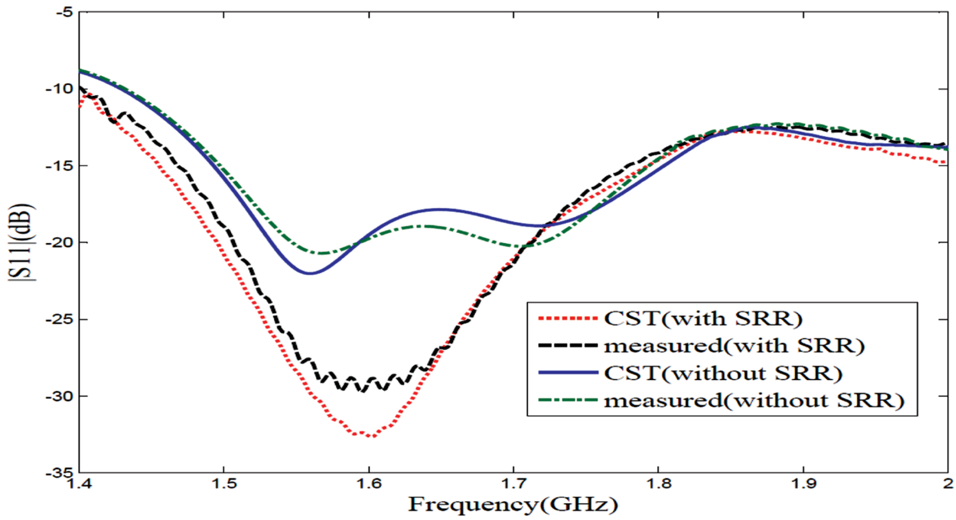


Figure 2. Measured and simulated input reflection coefficients of antenna array with and without SRR structures. (color figure available online)

at 1.575 GHz; however, only results without the SRR structures are considered in here. Figure 3 depicts the measured and simulated ARs versus the elevation angle at 1.575 GHz (both helices are oriented along the y-axis), and it can be seen that they have a low value for a large angular envelope. It is perceived that the measured and simulated angular envelope of an AR below 3 dB is 76° and 77°, respectively, which is about half of the upper half-space and can generate CP radiation. Both simulated and measured 3-dB AR bandwidths are found to be close to 15.8%.

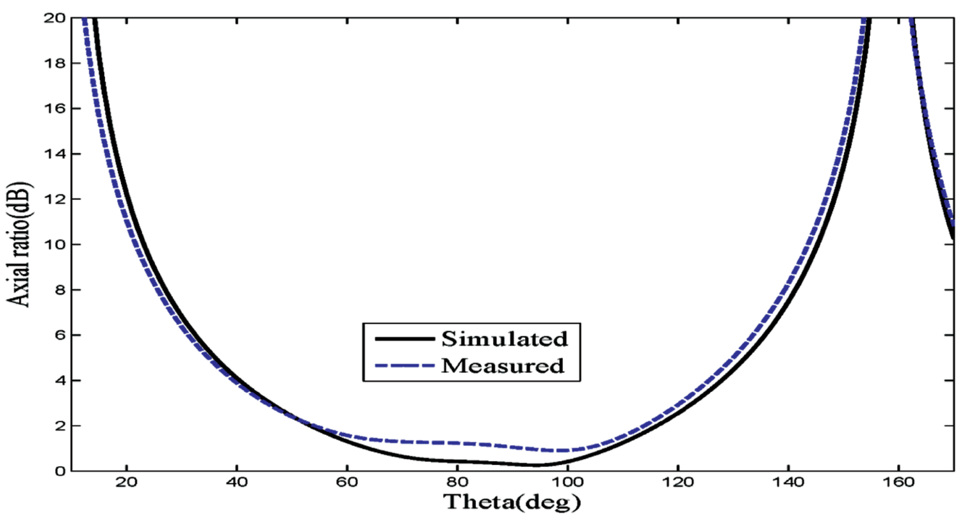
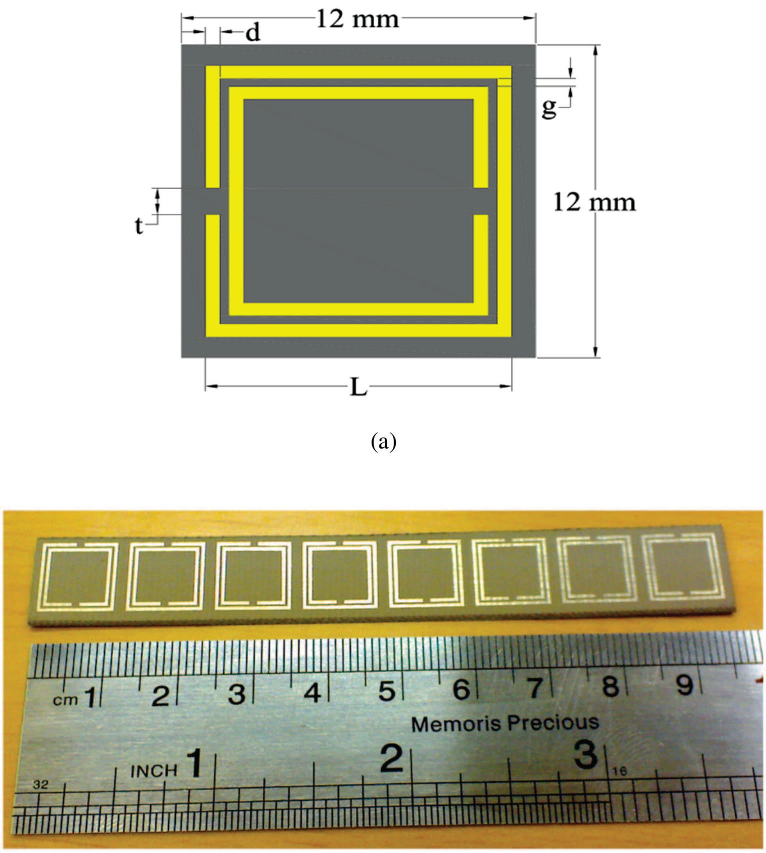


Figure 3. Measured and simulated ARs versus the elevation angle at frequency of 1.575 GHz. (color figure available online)

4. Reduction of the Mutual Coupling

As previously mentioned, for reducing mutual coupling between two antennas, SRRs are designed and inserted between two elements. An SRR contains two concentric copper square rings with gaps on the opposite sides. They are printed on one side of a dielectric substrate (Taconic RF-35, Republic of Korea; $\varepsilon_r = 3.5$, $\tan\delta = 0.0018$) with a thickness of 0.762 mm. They produce an effective negative permeability over the desired frequency band.

Figure 4(a) schematically represents the SRR. The dimensions of its structure are calculated using CST. Each simulation model consists of a two-port waveguide formed by two pairs of perfect electric conductor (PEC) walls and perfect magnetic conductor (PMC) walls (Ziolkowski, 2003). A unit cell SRR is positioned at the center of the waveguide. The SRR structure is parallel to the PMC walls. To calculate the S-parameters of an SRR, two ports are used to excite a quasi-TE mode. The final dimensions of an SRR as obtained from CST are included in Figure 4(a). Dimensions of the dielectric substrate for one unit cell are 12 mm × 12 mm, which is smaller than the wavelength at the operation



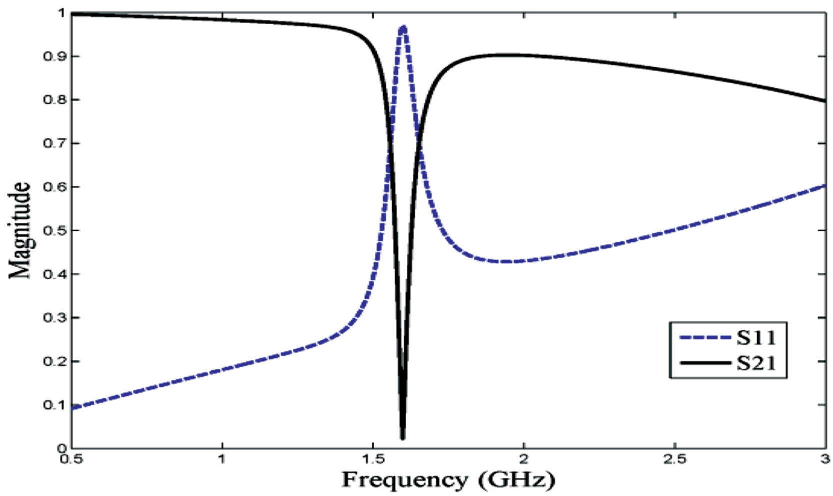
(a)

(b)

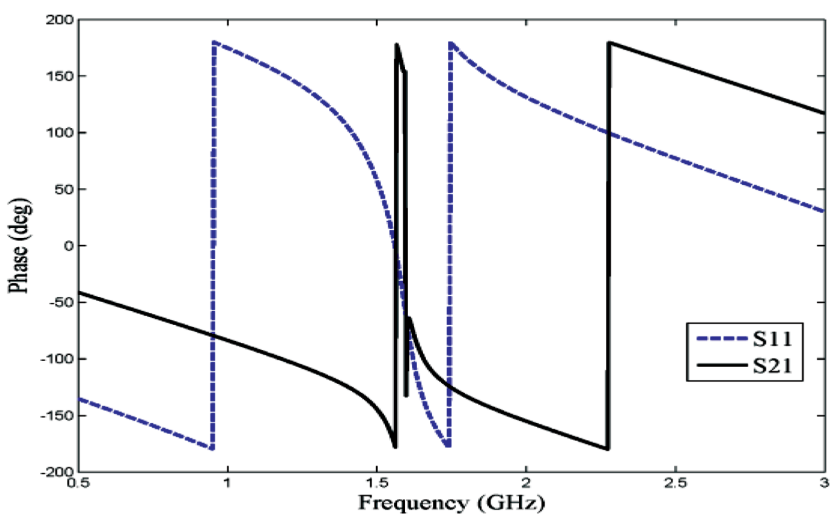
Figure 4. (a) Dimensions of the SRR unit cell and (b) array consisting of eight SRRs. (color figure available online)

frequency of 1.575 GHz. Also, to realize a stopband at 1.575 GHz, the parameters of the SRR are chosen as $L = 10.4$ mm, $t = 1$ mm, $d = 0.5$ mm, and $g = 0.3$ mm. The simulated magnitude and the phase of the S-parameters of the waveguide in the operating frequency band is plotted in Figures 5(a) and 5(b).

An array consisting of eight SRRs are printed on the dielectric substrate, as shown in Figure 4(b). To reduce the mutual coupling between the two antennas, four arrays with identical gap spacing of 10 mm are placed horizontally between two short helical



(a)



(b)

Figure 5. (a) Magnitude of S parameters and (b) phase of S parameters. (color figure available online)

Figure 6. Fabricated short helical antenna array with SRRs installed between the elements. (color figure available online)

antennas (see Figure 6). Note that the spacing between the arrays is half the height of the PEC-PMC waveguide by which the unit cell SRR was evaluated. Figures 2 and 7 show the measured and simulated scattering parameters of the antenna array with and without SRR structures, respectively. Figure 2 shows the antenna with SRR structures, which provides better impedance matching. Figure 7 shows the mutual coupling $|S21|$ between two short helical antennas. In the frequency range of 1.56 GHz to 1.74 GHz, it is observed that by placing the SRR structures between two antennas, $|S21|$ is reduced to a low value and equals −25 dB at the resonance frequency of 1.61 GHz. As can be seen,

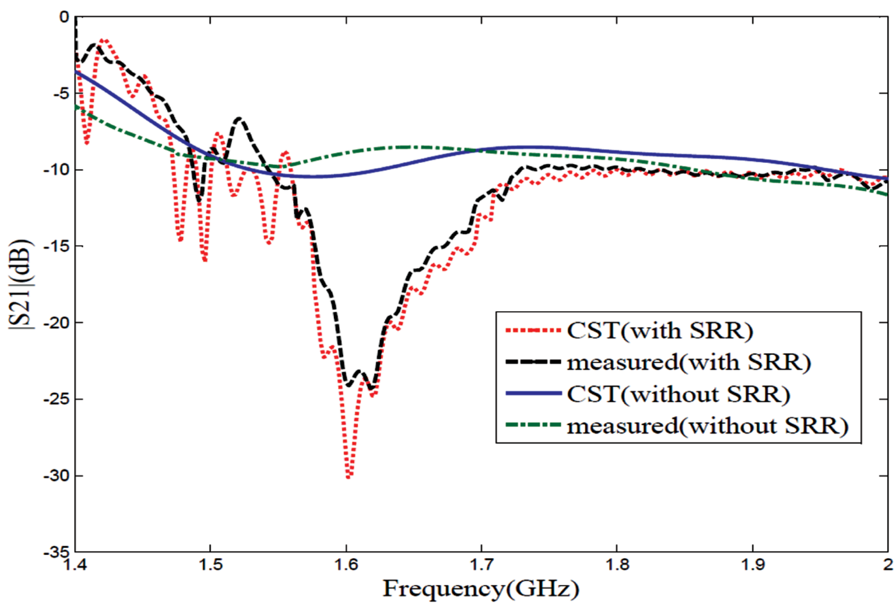
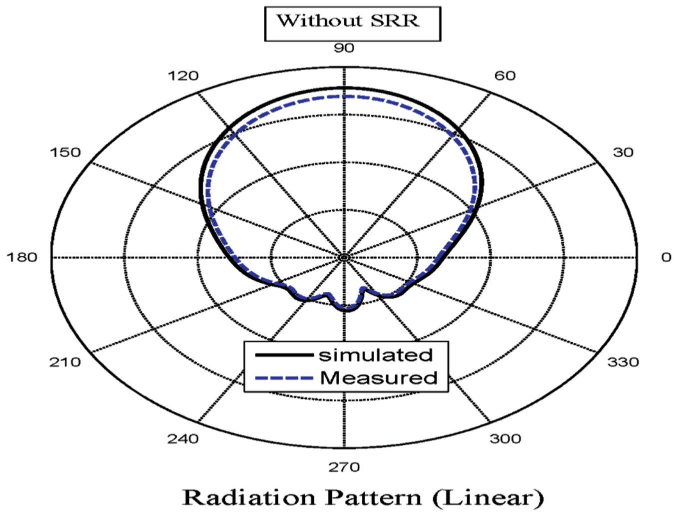
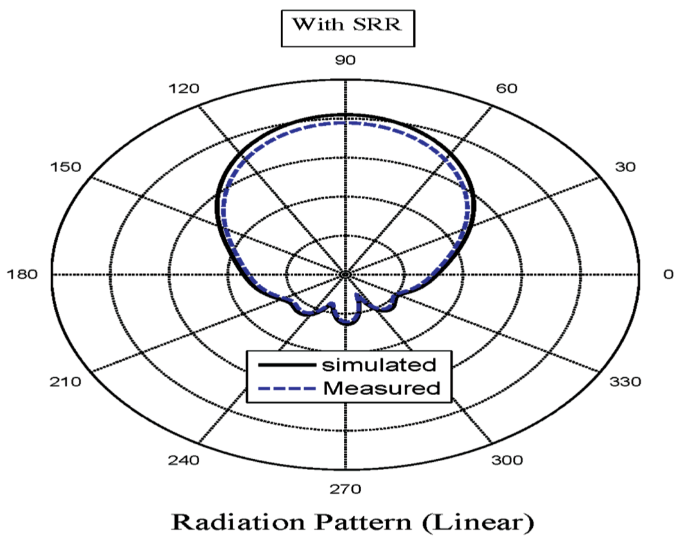


Figure 7. Measured and simulated mutual coupling of antenna array with and without SRR structures. (color figure available online)



(a)



(b)

Figure 8. Far-field radiation pattern of the antenna array at the resonance frequency: (a) without SRR structures and (b) with SRR structures. (color figure available online)

the simulation results and measurements are in good agreement. The radiation pattern of the array at the resonance frequency is simulated and measured with and without SRR structures, and the results are shown in Figure 8. It is noticed that the maximum gain is increased from 11.5 dB without SRR structures to 12.9 dB with SRR structures between two helical antennas.

5. Conclusion

The design, simulation, and realization of an L-band axial-mode 1×2 short helical antenna array are presented. It is found that reduced mutual coupling, high gain, enhanced AR, and good matched input impedance can be reached at the same time. Experimental and simulated results show that by optimizing the helix wire radius and the feed length, a good impedance matching can be achieved. Additionally, by adding an appropriate incorrect turn at the end of the helix (0.19 turn), the measured angular envelope of an AR below 3 dB is 76°, and 3-dB AR bandwidths are close to 15.8%. It is observed that AR has a low value for large angular envelope. Finally, by placing SRR structures between two antennas, the value of $|S21$ is reduced in the frequency range of 1.56 GHz to 1.74 GHz. The maximum gain is increased from 11.5 dB (without SRR) to 12.9 dB (with SRR).

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