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Research Article

An Optimized Circuit in Plastic Meander Line Antenna for 2.45 GHz Applications

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Researchers seek to design electrically small planar antennas for RFID applications. Using multiparameter optimization, various meander line antennas were designed for the lowest resonant frequency and maximum radiation efficiencies for a fixed grid size. One such design for highest radiation efficiency was optimized for microwave frequencies by including an impedance matching structure. The antenna was printed with silver ink on a plexiglass substrate using the circuit in plastic (CiP) technique of embedded electrical components. The measured scattering parameter (S_{11}) was −18.43 dB at resonance. The radiation efficiency of the antenna measured using simple and improved Wheeler cap method was 74.4/74.1%. The radiation pattern of electrically small CiP antenna was doughnut-shaped with main lobe magnitude of 0.453 dB and an angular width of 84.2° in elevation plane. The measured 10 dB fractional bandwidth of the antenna was 18.98%. The results are compared with silver/copper in air antennas optimized for achieving the highest radiation efficiency for a fixed grid size. Plastic antennas are viable at microwave frequencies.

1. Introduction

Optimized antenna design has now become an indispensable research area because many applications demand space reduction, good impedance match, higher antenna efficiencies, and other antenna parameters. These antennas can be used for various RFID applications including swimmer communications, tidal monitoring, wireless communications, autosensing doors, and remote controlled toys. Electrically small antenna theory was first introduced by Wheeler [1] for antennas enclosed in a sphere of radius r such that $kr \leq 1$, where k is the wave number at the frequency of interest. Small antennas have performance limits in terms of efficiency, gain, and bandwidth and usually have small resistance and large reactance, resulting in poor impedance match to commonly used transmission lines [2]. Marrocco [3] provided the survey of various size reduction and impedance matching techniques for UHF RFID antenna design.

Printed circuit boards (PCB) produced by traditional methods of manufacturing are not readily recyclable. Copper is a pollutant in the environment, although it is one of the most highly conductive materials. Some research is focused on the development of new materials that can replace copper. Circuits in plastic (CiP) introduced in [4] is a technique of manufacturing completely waterproof circuits inside their enclosure in one thermal process step. Transparent plastic substrates are required for use in wet, dusty, and high-impact environments. This technology suggests using silver ink conductors instead of copper to reduce the environmental impacts of the manufacturing process. Another option is to use conductive polymers to achieve optical transparency, which makes it possible to integrate antennas to interfaces without losing transparency [5–8]. Recently, a comprehensive study of the impact of reduced conductivity on antenna performance was highlighted in [9], as it directly influences the impedance, radiation, and scattering (e.g., absorption and extinction cross sections) performance of an antenna. Lewis et al. [10–12] used the ant colony algorithm to optimize small meander line antennas in a fixed area and found the highest and lowest resonant frequency structures for the fixed grid size. Shahpari et al. optimized various meandered "wire in air" antennas on a fixed grid size for highest radiation efficiency and lowest resonant frequency [13].

The radiation efficiency (η_r) of an antenna can be measured by various methods such as Wheeler cap [14], the ratio of directivity to gain, and the ratio of the measured Q factor to ideal Q factor [15, 16]. The Wheeler cap method which is considered to be the most accurate method is based on inserting the antenna into a sealed metallic container, to separate the radiation resistance (R_{rad}) and loss resistance (R_{loss}) of the antenna. The radiation efficiency of the antenna using Wheeler cap method is calculated using

$$\eta_r = \frac{R_{\text{rad}}}{R_{\text{rad}} + R_{\text{loss}}}. \quad (1)$$

Here, R_{rad} is the resistive part of the antenna impedance measured inside Wheeler cap, while $R_{\text{rad}} + R_{\text{loss}}$ is the resistance of the antenna measured in free space. The Wheeler cap method known to be the simplest efficiency measurement method is not reliable in all possible scenarios [17, 18]. Johnston and McRory [19] proposed repeating Wheeler cap measurements in a waveguide with a sliding cap for at least another three times with various additional conducting objects inside the container. Sliding of the cap results in Wheeler cap measurements of scattering parameter (S_{11}) of the antenna, which can be used to draw a circle on the Smith chart to determine the antenna efficiency. The radiation efficiency of the antenna at resonance was calculated from the points on the circle with minimum ($\Delta s_{\min}$) and maximum ($\Delta s_{\max}$) distance from the S_{11} measurement of the antenna in free space using

$$\eta_r = \frac{2}{\left(1/\Delta s_{\min} + 1/\Delta s_{\max}\right)\left(1 - \left|S_{11}\right|^2\right)}. \quad (2)$$

This improved Wheeler cap method although requires more computations and time but is more reliable.

Yaghjian and Best [20] defined the matched VSWR bandwidth of the antenna as

$$\text{FBW}\left(f_0\right) = \frac{f_+ - f_-}{f_0}. \quad (3)$$

Here, f_+ and f_- are the frequencies on either side of resonant frequency (f_0) for a fixed VSWR value. Equation (3) can be used to measure the fractional bandwidth (3 dB or 10 dB) of any tuned antenna under the sufficient condition that first-order derivatives of real and imaginary part of antenna impedance do not change significantly over the measured bandwidth.

This article reports design strategies and experimental measurements on a proposed wire meandered dipole antenna optimized for highest radiation efficiency for a fixed grid size, using multiparameter optimization [13]. The original optimized design for highest radiation efficiency [13] was modified with the inclusion of a matching structure for improved impedance matching to commonly used transmission lines [21]. The design was printed with silver ink on a 3 mm transparent plexiglass substrate using circuit in plastic (CiP) technology of embedded electrical components. The transparent plexiglass was used as a substrate for integrating the antenna with the surfaces without losing transparency.

2. Circuit in Plastic (CiP) Design and Fabrication Process

A circuit in plastic (CiP) antenna design was optimized using a 3 mm plexiglass substrate (permittivity: $\varepsilon = 3.6$; loss tangent: $\tan\delta = 0.038$) at microwave frequencies. A matching structure (track width = 0.2 mm) was included for improved impedance matching with a 50 ohm reference transmission line which changes the dimensions of the original design [13] optimized for highest radiation efficiency slightly. Silver ink was chosen as a conductor with conductivity (σ_s) of 4.3×10^6 S/m (see "Electrodag 479SS technical data sheet"). A 50 ohm discrete port was used for feeding the antenna in CST simulations (Figure 1(a)). The dimensions of the optimized antenna including the matching structure are shown in Figure 1(b). The largest dimension of the antenna was 35.6 mm being 29% of the free space wavelength λ_0.

Figure 2 shows the silver ink printing process: the plexiglass substrate (Figure 2(a)), a screen with a mesh count of 90 threads per square centimeter (Figure 2(b)), application of silver ink (Figure 2(c)), and final product (Figure 2(d)). The printed design was cured at elevated temperatures (93°C) for 15 minutes to achieve the conductivity σ_s of silver ink. The printed antenna was directly glued to a 20.2 cm long coaxial cable with the help of conductive epoxy for measurement purposes (see Figure 3). Another coaxial cable with connectors at both ends (shown in Figure 3) having exactly the same length and specifications was calibrated (short, match, and open) using standard calibration kit. The calibrated cable was then replaced by the cable having the mounted (glued) antenna. This procedure eliminates the effect of coaxial cable glued to antenna from impedance and scattering parameter measurements of the antenna. The method is suitable for proposed design having resistance matched to the characteristic impedance (50 ohms) of feeding coaxial cable.

3. Results and Discussion

3.1. Impedance of CiP Antenna. The simulated and measured resistance ($R_{\text{rad}} + R_{\text{loss}}$) of the antenna across the frequency range 2-3 GHz are shown in Figure 4. The resistance of the fabricated antenna at resonant frequency (f_0) is very close to 50 ohms (i.e., matched to commonly used transmission lines). Wheeler cap (WC) measurement of the resistance (R_{rad}) of the antenna used for Wheeler cap radiation efficiency measurement in Section 3.3.1 is also shown in the figure. The simulated and measured (free space and Wheeler cap) reactance of the antenna across the frequency range 2-3 GHz is shown in Figure 5. The graph indicates that the free space antenna resonance occurs at 2.45 GHz.

3.2. Scattering Parameter of CiP Antenna. Figure 6 is a plot of simulated and measured scattering parameter S_{11} (dB) of the CiP antenna. The antenna resonates at 2.45 GHz with measured $S_{11} = -18.43$ dB. The result was in good agreement with the simulation. The 10 dB fractional VSWR bandwidth FBW(f_0) of the CiP antenna calculated using (3) was 18.98%.

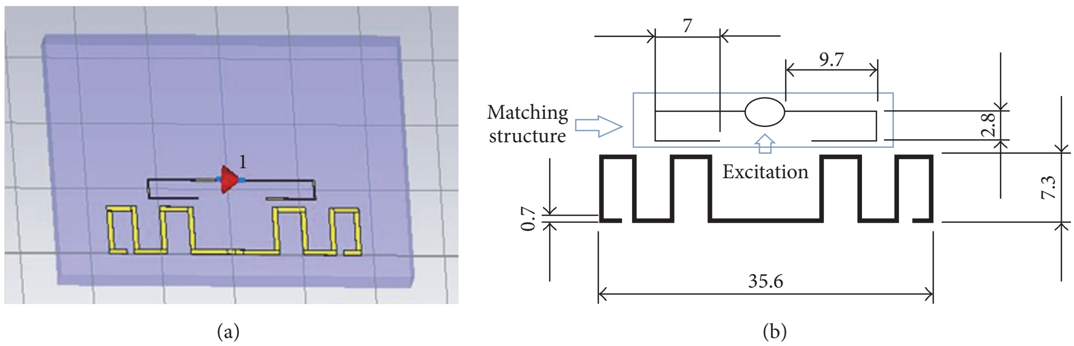

FIGURE 1: (a) CST simulated design with 50 ohm discrete port (used for excitation); (b) dimensions (in mm) for the optimized CiP design including the matching structure.

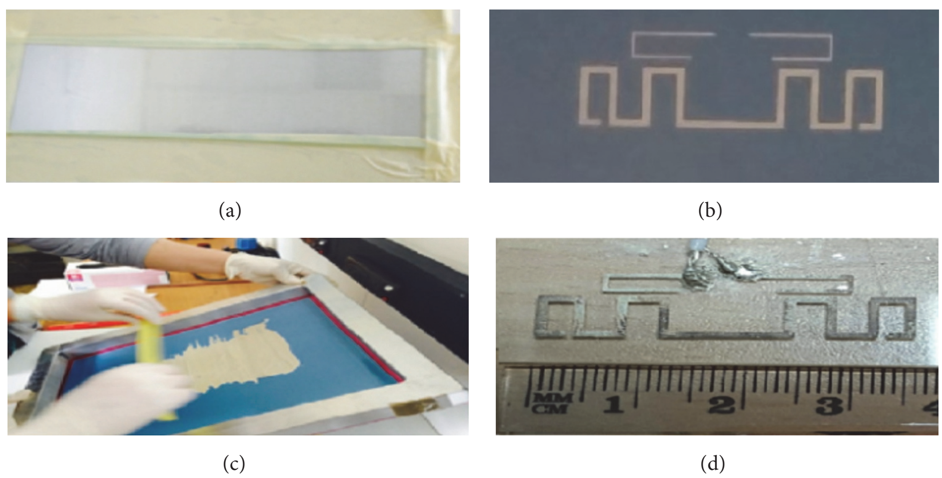

FIGURE 2: Silver ink printing process steps showing the plastic substrate (a), the screen (b), the application of the silver paste (c), and the final result (d).

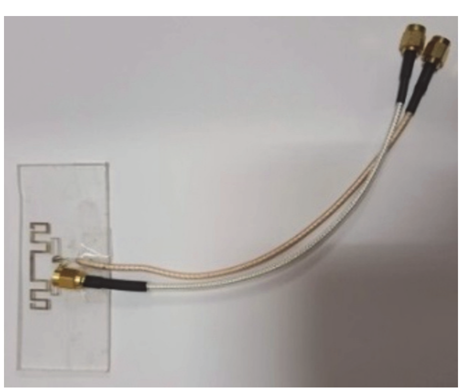

FIGURE 3: Silver ink printed antenna connected to a 20.2 cm long coaxial cable (with conductive epoxy) along with another unconnected coaxial cable of same length having connectors at both ends used for calibration purpose.

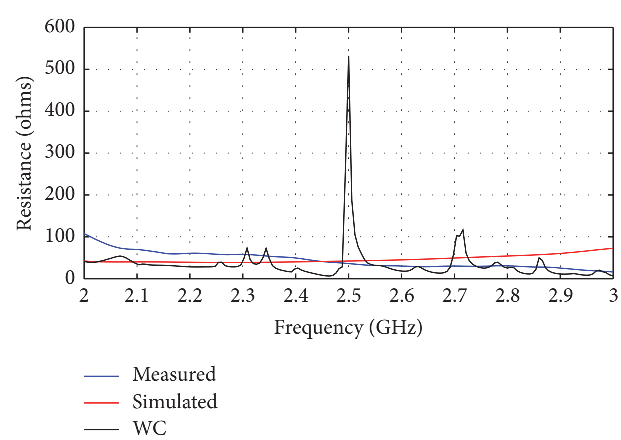

FIGURE 4: Resistance of CiP antenna (simulation versus measurement (free space and Wheeler cap (WC))) over the frequency range 2-3 GHz.

Figure also includes S_{11} measurements (WC1–WC3) obtained by placing the antenna in Wheeler cap along with insertion of various conducting objects and sliding the cap position. This data was used for efficiency measurement of the antenna using improved Wheeler cap method [19] presented in Section 3.3.2.

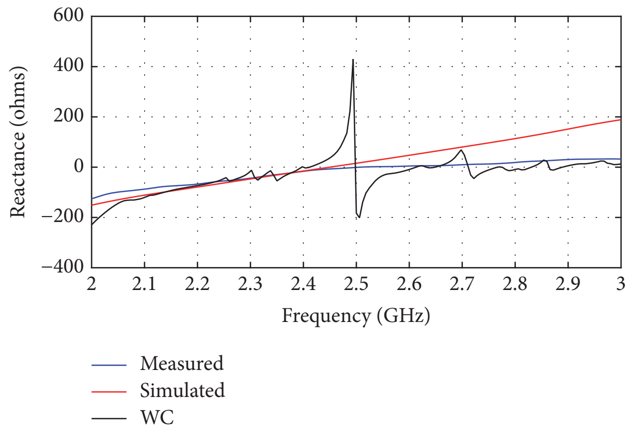

Figure 5: Reactance of CiP antenna (simulation versus measurement (free space and Wheeler cap (WC))) over the frequency range 2-3 GHz.

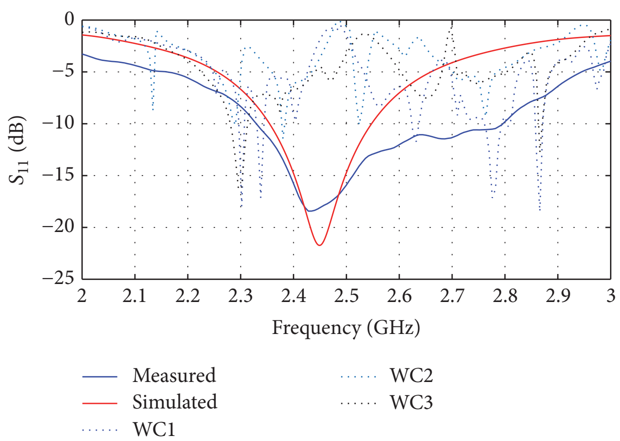

Figure 6: S_{11} (dB) of CiP antenna (simulation versus measurement) over the frequency range 2-3 GHz.

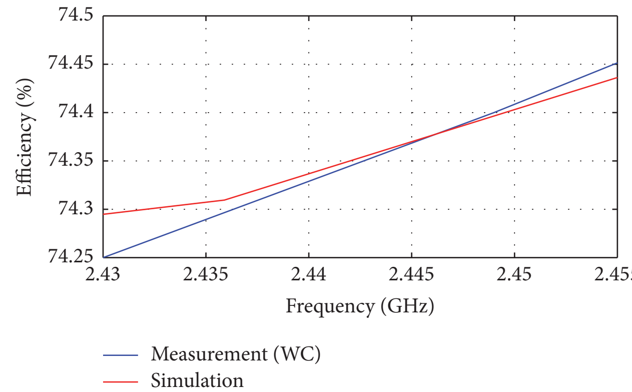

Figure 7: Radiation efficiency (η_r) of CiP antenna (simulation versus Wheeler cap (WC) measurement).

3.3. Radiation Efficiency of CiP Antenna

3.3.1. Wheeler Cap (WC) Method. Equation (1) was used to calculate the radiation efficiency (η_r) of the antenna near resonance ($f_0 = 2.45$ GHz), based upon free space and Wheeler cap (WC) resistance (Figure 4) of the antenna. The measured result ($\eta_r = 74.4\%$) was in good agreement with simulated radiation efficiency of the antenna (see Figure 7).

3.3.2. Improved Wheeler Cap (IWC) Method. The radiation efficiency of the antenna was further verified by using an improved Wheeler cap (IWC) method [19]. The method [19] suggests inserting different conductive objects inside the Wheeler cap (copper wire, foam, copper wrap, etc.) for improved matching. The antenna was inserted in a conducting cylinder (diameter 5.5 cm) and the opening was sealed using a movable plastic cap (red) covered with aluminum foil (Figure 8). The cap was moved to different positions along the cylinder to obtain varied Wheeler cap measurements WC1–WC3 of S_{11} (dB) (Figure 6). This data was plotted on the Smith chart (Figure 9) at resonant frequency (f_0), such that a circle could be drawn through the WC measurements which enclose the free space data (blue dot). The radiation efficiency at resonant frequency of the antenna was calculated with (2) using points on the circle with minimum ($\Delta s_{\min}$) and maximum ($\Delta s_{\max}$) distance from the free space measurement (blue dot) of the antenna. The radiation efficiency of the antenna at resonance using IWC method was 74.1% which verifies the results presented in Section 3.3.1.

3.4. Radiation Pattern of CiP Antenna. The simulated and measured radiation pattern (realized gain) of the CiP antenna in elevation plane is shown in Figure 10. The measured data was taken at the intervals of 15° by rotating the CiP antenna over the angular range of 360° in an anechoic chamber. Horn antenna was used as a source of excitation for the CiP antenna. The CiP antenna was placed in the far field region of the horn antenna at a distance of $R = 1$ meter, satisfying the far field relation $R = 2D^2/\lambda_0$, where D is the largest dimension of the antenna. Since electrically small antennas are well known for small gain [2], the main lobe magnitude of the radiation pattern of the antenna was 0.453 dB with an angular width of 84.2°.

3.5. Scattering Parameter of Optimized Antenna in Air (No Substrate). A comparison of simulated scattering parameter S_{11} (dB) and resonant frequency (f_0) *of* the optimized antenna design “in air” including matching structure has been shown in Figure 11 for two different metals: silver ink ($\sigma = 4.3 \times 10^6$ S/m) and copper ($\sigma = 5.8 \times 10^7$ S/m). Both of these antennas, having no substrate, provide the resonance at $f_0 \approx 3.53$ GHz with an excellent impedance matching to the 50 Ω reference transmission line. So the proposed antenna design can be used with either silver ink or copper as a conductor to produce good impedance matching with commonly used transmission lines, at resonance. The 10 dB fractional bandwidth FBW(f_0) for silver ink/copper antenna in air (without substrate) calculated using (3) was 7.93/7.91%.

3.6. Radiation Efficiency of Optimized Antenna in Air (No Substrate). The radiation efficiencies of the optimized silver ink/copper antennas without substrate were compared over

(a)

(b)

FIGURE 8: Antenna efficiency measurements using a conducting cylinder as a Wheeler cap with insertions: copper wire wrap, foam, and so on (a). The cylinder was sealed using an aluminum foil coated movable red plastic cap (b).

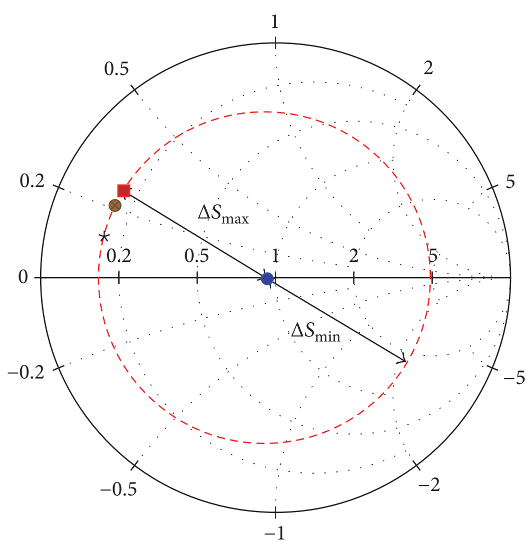

FIGURE 9: Smith chart representation of the CiP antenna at resonant frequency $f_{(0)} = 2.45$ GHz (free space versus Wheeler cap data (WC1–WC3)). The red dashed circle passing through Wheeler cap data points. The blue dot represents the free space measurement of CiP antenna. Δs_{min} and Δs_{max} are minimum and maximum distanced points on circle from the free space measurement (blue dot) of the antenna.

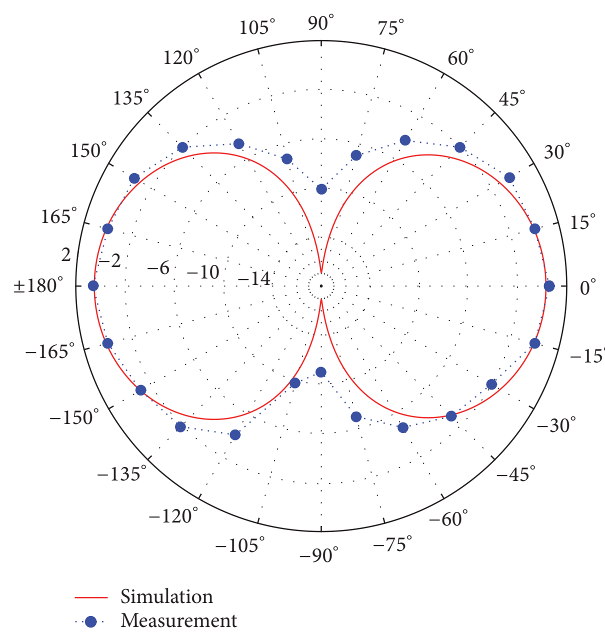

FIGURE 10: Simulated versus measured radiation pattern (realized gain) of CiP antenna in elevation plane.

the frequency range 3.2–4 GHz (see Figure 12). It can be seen that, at resonance, that is, $f_0 \approx 3.53$ GHz, the radiation efficiency of the silver ink antenna is 96.2%. A copper antenna with similar dimensions produces a radiation efficiency of 99% at resonance. It can be concluded that the optimized "in air" meander line antenna can provide the highest radiation efficiency ($\eta_r > 96\%$), when either silver ink or copper was chosen as a conductor.

3.7. A Comparative Study of Optimized Antennas. Table 1 provides a comparison of resonant frequency, radiation efficiency, and 10 dB fractional bandwidth of the 3 modelled antennas optimized for highest radiation efficiency. The copper antenna in air (i.e., having no substrate) resonates at 3.53 GHz with η_r of 99% and 10 dB FBW(f_0) = 7.91%. The silver ink antenna without a substrate shows a reduction in radiation efficiency by 2.8% as compared with copper antenna in air with 10 dB FBW(f_0) = 7.93%. However, when the silver ink antenna was printed on 3 mm thick plexiglass substrate

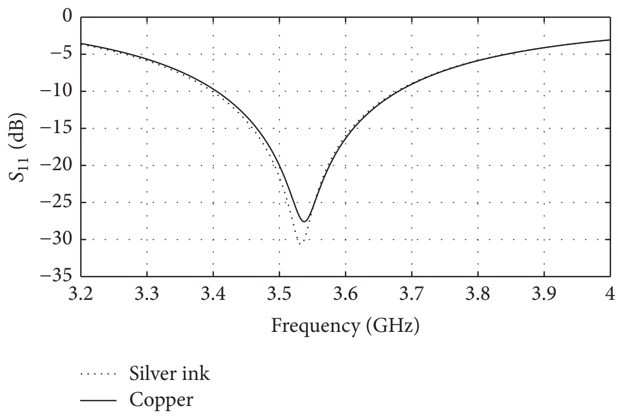

Figure 11: S_{11} (dB) of silver ink/copper antenna (without substrate) over the frequency range 3.2–4 GHz.

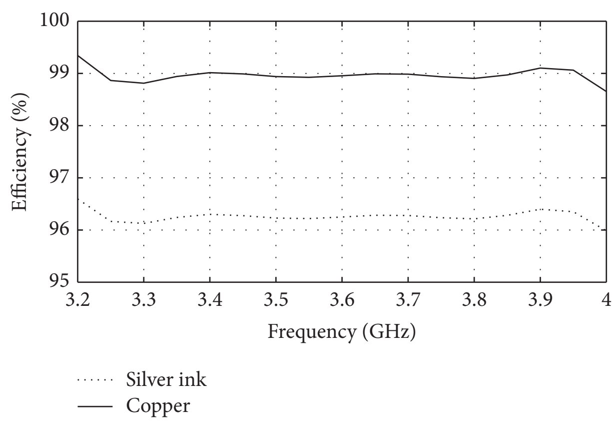

Figure 12: Radiation efficiency (η_r) of silver ink/copper antenna (without substrate) at resonance (3.53 GHz).

Table 1: A comparison of resonant frequency, radiation efficiency, and 10 dB fractional bandwidth of three modelled antennas optimized for highest radiation efficiency.

Antenna	Resonant frequency (f_0) (GHz)	Radiation efficiency (η_r) (%)	Fractional bandwidth FBW (f_0) (%)
Copper (in air) (simulation)	3.53	99	7.91
Silver ink (in air) (simulation)	3.53	96.2	7.93
CiP (measurement)	2.45	74.4 (WC method)	18.98
CiP (measurement)	2.45	74.1 (IWC method)	18.98

using CiP technique of embedded electrical components, the antenna was resonant at 2.45 GHz with η_r of 74.4% and 10 dB FBW(f_0) = 18.98%. Due to its higher thickness, the plexiglass substrate helps in improving the bandwidth of antenna. However, the radiation efficiency of the printed antenna is reduced on the cost of improving bandwidth.

4. Conclusion

An electrically small CiP antenna was designed for highest radiation efficiency for 2.45 GHz RFID applications. The original "in air" antenna design (optimized for highest radiation efficiency for a fixed grid size) was modified with the inclusion of a matching structure for better matching to commonly used transmission lines. This changes the dimensions of original optimized design slightly; however, the modified design still provides highest radiation efficiency (η_r > 96%) at resonance, when either silver ink or copper was chosen as a conductor. When the design was printed on 3 mm plexiglass substrate using CiP technique, the measured radiation efficiency of the antenna reduces to 74.4% with an improvement in fractional 10 dB bandwidth of antenna to 18.98%. The substrates with larger thickness help in improving the antenna bandwidth for RFID applications. The transparent plexiglass substrate can be used in the antenna applications where transparency is an important concern. The CiP antenna can be used to replace the traditional printed circuit board (PCB) antennas in wet, dirty, and high-impact environments. The screen printing process with curing and lamination can be highly automated for high volume manufacture. The printed antenna can be sealed in a thin plastic lamination making the design viable for a broad range of applications, including swimmer communications, and tidal monitoring.

Competing Interests

The authors declare that they have no competing interests.

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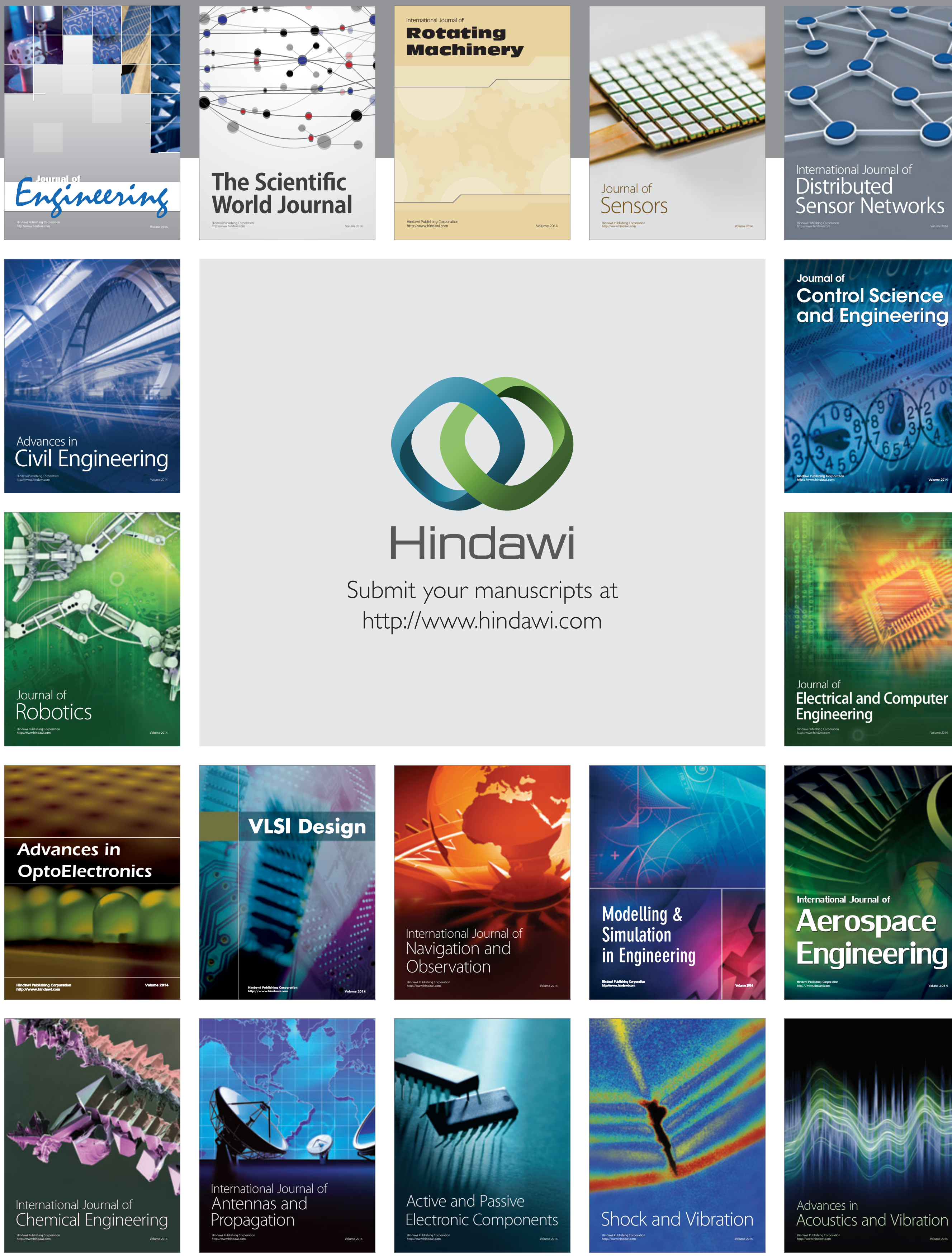
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