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Research Article

Miniaturization of UWB Antennas on Organic Material

Symeon Nikolaou and Muhammad Ali Babar Abbasi

Department of Electrical Engineering, Frederick University, 7 Y. Frederickou Street, Pallouriotisa, 1036 Nicosia, Cyprus

Correspondence should be addressed to Symeon Nikolaou; s.nikolaou@frederick.ac.cy

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Three planar, CPW-fed, UWB antennas with increasingly reduced size are presented and the miniaturization method is discussed. The first antenna is a CPW-fed elliptical slot with an uneven U-shaped tuning stub, the second antenna is a cactus shaped monopole, and the third one is a miniaturized version of the cactus shaped monopole antenna. All presented antennas have a simulated and measured return loss below −10 dB over the 3.1 to 10.6 GHz UWB frequency range and mostly omnidirectional radiation patterns. The proposed antennas are fabricated on liquid crystal polymer (LCP). The CPW-fed slot antenna requires an overall board dimension of 38 mm × 40 mm, and the evolved cactus monopole is confined in a 28 mm × 32 mm board, while the final miniaturized cactus monopole is printed on 28 mm × 20 mm board, resulting in a 41% and 63% size reduction, respectively. Using both simulations and measurements, the paper analyzes the response of all three antennas and discusses and demonstrates the effectiveness of the implemented miniaturization method.

1. Introduction

The ultrawideband protocol that covers the frequency range from 3.1 to 10.6 GHz was released from the FCC in 2002 [1], partly as an attempt to meet the demand for high data rate communications in short distances for mobile and personal applications. Consequently, there is an increasing need for compact sized, low cost, and high efficiency antennas with omnidirectional radiation patterns. The combination of these characteristics in a wide frequency range such as the UWB band is a challenging problem and several design concepts and different materials have been used in an attempt to provide a satisfactory solution. The challenge associated with the miniaturization of antennas has been the tradeoff between the reduction of the physical size of the antenna and its operational bandwidth [2] and radiation efficiency. Some researchers have adopted the use of substrates with relatively high dielectric constant to reduce the antenna’s resonant frequency because permittivity is inversely related to the resonant frequency [3, 4]. However, bandwidth reduction is inevitable in this approach because bandwidth is also inversely proportional to the permittivity [2]. In an attempt to increase the bandwidth of an antenna and cover the whole UWB frequency range, configurations like planar monopoles [5–8], slot fed IF (inverted F) [6], CPW-fed monopole [7, 9–12], U-shaped elliptical slot [13], patch array with energy band gap (EBG) structures [3], and CPW-fed fractal antenna [14] have been proposed. Also, the effects of printed UWB antenna miniaturization on transmitted time domain pulse fidelity and pattern stability have been recently discussed in [15]. In several papers [2, 4, 16, 17], it has been demonstrated that, by following certain miniaturization guidelines, compact planar UWB antennas can be made. Numerous planar UWB antennas and band-notch UWB quasi-monopole antennas have illustrated symmetrical shapes [12, 15, 18]. In these structures, two symmetrical halves exhibit two identical strong current paths. It has been noted that the current distribution patterns in these structures replicate the conditions of magnetic mirror symmetry. Chopping off half of the symmetrical monopole antenna provides straightforward miniaturization. It has also been explored that, by having one strong current path, antenna exhibits an even wider bandwidth [15, 18, 19]; however, not all half-cut UWB structures can achieve suitable impedance matching over a wide bandwidth. A further modification to the feeding structure is required for better impedance
2. Antenna Design and Fabrication

2.1. Fabrication. The proposed antennas are presented in Figure 1. They are fabricated on low loss (tan δ = 0.002), low dielectric constant (εr = 3), LCP with a copper layer that is 18μm thick. The CPW-fed slot antenna is fabricated on a 350μm thick substrate while for the cactus antenna and the miniaturized cactus antenna a thinner 225μm thick substrate was used. At the early stages of the design procedure, it was observed that the 350μm thick paper substrate exhibits rigidness. To make the cactus antenna conformal as well as miniaturized, substrate thickness was reduced. By specifying the angle and rate of LCP extrusion while manufacturing, the coefficient of thermal expansion (CTE) can be controlled. With this unique characteristic, one can engineer the thermal expansion of LCP to match with many commonly used cladding materials like silver, copper, and so forth [32]. Standard photolithography was used for the fabrication. The size reduction of the cactus antenna and the miniaturized cactus is obvious from Figure 1 where the fabricated prototypes are presented and compared in size with a coin.

2.2. Schematic Discussion. The schematics of the compared antennas are presented in Figure 2 and the dimensions are summarized in Tables 1, 2, and 3. Three antennas are presented, which are the successive evolutions of the first antenna, namely, CPW-fed slot antenna. The second antenna, called cactus antenna, is a CPW-fed monopole UWB antenna with 41% (28×32mm² compared to 38×40mm²) size reduction, and finally the third version called miniaturized cactus is a monopole UWB antenna with even smaller RF ground patches which is 63% (28×20mm² compared to 38×40mm²) smaller than the original slot antenna. Full-wave EM simulators were used for the design of the presented prototypes and for the radiation pattern and the return loss optimization. All three antennas are well matched as can be seen from S11 plots presented in Figure 3.

For the CPW-fed slot, the stub dimensions and the linear tapering affect the matching, while the ellipse axes size has a small effect on the radiation patterns. The proposed antenna is fed by a CPW line with an inner conductor width, W, of 2.2mm and a gap, g, between the ground and the inner conductor of 0.3mm. At a distance S = 9.9mm from the board edge, the inner conductor is linearly tapered until its width becomes 0.9mm to improve the matching between the transmission line and the U-shaped stub. The U-shaped stub consists of a semiannular ring and two linear segments. The semiannular one has an outer radius R = 5.5mm and inner radius r = 2.5mm. The left linear segment has length...
\( S_1 = 5 \text{ mm} \) and width \( d = 3 \text{ mm} \) while the right linear segment has length 6 mm and width \( d = 3 \text{ mm} \). The center \( C \) of the semiannular ring is 4.1 mm from the ellipse center \( O \) and the ellipse center is 22 mm from the bottom edge. The ellipse has a major axis equal to \( L_1 = 30 \text{ mm} \) and secondary axis equal to \( L_2 = 20 \text{ mm} \). Overall board dimensions are 40 mm \( \times \) 38 mm.

The evolution of the cactus antenna was based on the observation that most of the radiated energy for the CPW-fed slot antenna was confined on the tuning stub. Therefore, a design was attempted without the elliptical slot. Impedance matching over the entire UWB range was not satisfactory with only the two linear segments of the \( U \)-shaped tuning stub, and to overcome this problem, a third linear segment was added in the feed line direction. The thinner LCP substrate used for the cactus antenna and the addition of the middle linear segment required the linearly tapered transition and the semiannular segment reoptimization. Consequently, for the cactus antenna, the CPW center conductor width \( W \) is 1.78 mm and length \( d_2 \) is 7.92 mm. A linear taper is used to reduce the center conductor width to \( d = 0.61 \text{ mm} \) and is connected to the cactus shaped stub at distance \( d_1 = 10.24 \text{ mm} \) from the board edge. The two rectangular ground patches have dimensions \( G_l \times G_w \) which correspond to 9.44 mm and 14.89 mm, respectively. For the primary radiator, a cactus shaped stub is used. It consists of a semiannular ring with inner radius \( r = 2.60 \text{ mm} \) and an outer radius \( R = 5.72 \text{ mm} \) and three linear segments of different

\[ \text{Figure 2: Schematic of (a) CPW-fed slot antenna, (b) cactus antenna, and (c) miniaturized cactus antenna.} \]
Figure 3: Comparison of simulated and measured $S_{11}$ for (a) CPW-fed slot antenna, (b) cactus antenna, and (c) miniaturized cactus antenna.

lengths. The middle linear segment is $L_2 = 13.00$ mm long and $W_2 = 2.08$ mm wide while the left and right segments are $L_1 = 7.28$ mm and $L_3 = 1.56$ mm long, respectively. Both of them are 3.12 mm wide. From the bottom part of the semiannular ring, a circular sector is detached leaving a chord of length $S = 2.73$ mm.

The third and final evolution of UWB antenna, the miniaturized cactus, is based primarily on the intermediate design, and the objective was to decrease the size of the two ground patches. Careful design allowed the decrease of the ground patches to an overall size of 9 mm $\times$ 8 mm which correspond to $G_l$ and $G_w$, respectively. The description of the miniaturized cactus design is similar to the presented description for the cactus antenna. As a result of the ground size reduction, further tuning was needed for the three stubs that consist of the cactus shaped radiating element, and the detailed dimensions are summarized in Table 3.

| Table 1: CPW-fed slot antenna dimensions. |
|-----------------|-----|-----|------|
| $D_1$           | 40.00 mm | $r$ | 2.50 mm |
| $D_2$           | 38.00 mm | $R$ | 5.50 mm |
| $W$             | 2.20 mm  | $S_1$| 5.00 mm |
| $g$             | 0.30 mm  | $S_2$| 6.00 mm |
| $v$             | 0.90 mm  | $D$ | 3.00 mm |
| $S$             | 9.90 mm  | $L_1$| 30.00 mm |
| $T$             | 2.50 mm  | $L_2$| 20.00 mm |
| $OC$            | 4.10 mm  | —   | —      |
The overall board dimensions for the cactus antenna are 32 mm × 28 mm, resulting in a 41% reduction in area compared to the CPW-fed slot, while the miniaturized cactus has overall board dimensions of 28 mm × 20 mm resulting in 63% size reduction compared to the slot antenna. For the summarized antenna dimensions in Tables 1, 2, and 3, the common variables' names are set independently for each antenna schematic and must not be related.

3. Miniaturization

3.1. Surface Current Distribution. The size reduction was envisioned by the investigation of the surface current distribution on the slot antenna. It was observed that the radiation was primarily caused by the current distribution on the U-shaped stub (Figures 4(a) and 4(b)), although the elliptical slot also contributes, to a lesser extent. The surface

Figure 4: Surface current (J) distributions on CPW-fed slot antenna at (a) 5 GHz and (b) 9 GHz, cactus antenna at (c) 5 GHz and (d) 9 GHz, and miniaturized cactus antenna at (e) 5 GHz and (f) 9 GHz.
current distributions on the two cactus antennas (Figures 4(c)–4(f)) have a similar form to the one on the U-shaped stub, something that explains the similarity in the resulting radiation patterns. Based on the surface current distribution observations, and trying to improve the matching, the even U-shaped stub (Ant1 from Figure 5) was replaced with an...
uneven U-shaped stub. The added perturbation on the tuning stub added one design degree of freedom that allowed the improvement of the matching as can be seen in Figure 6. The uneven U-shaped slot, which is presented in Figure 5 under the name Ant2, had improved matching as can be seen in $S_{11}$ plots of Figure 5. In the next iteration (Ant3), the slot was removed, and in order to further improve the matching for the remaining U-shaped stub, a third tuning stub was added, along the direction of the feed line, resulting in the cactus shaped radiator (Ant4) that evolved eventually, after some additional tuning, to the miniaturized cactus antenna. This third middle stub allowed for an additional design parameter and as a result of its bigger length the matching in the lower end of the UWB range, in the area around 3.1GHz, could be improved. The matching improvement in the lower frequency end is evident in Figure 5, and the presented frequency notch that can be seen in Figure 7 (red dotted line) as a result of the additional third stub can be easily suppressed with the careful selection of the stub size $L2$.

3.2. Ground Size Reduction. The miniaturization process so far led to the Ant4 structure shown in Figure 5. This structure was further optimized and the final structure is presented as cactus antenna in Figure 1(b). However, the overall antenna size could be further improved by attempting a ground patch reduction in addition to the removal of the elliptical slot. The idea was also based on the study of the surface current distribution of the cactus antenna (Figures 4(c) and 4(d)) where the current intensity along the outer edges of the rectangular ground patches is clearly lower than the current intensity on the edges closer to the signal line. Parametric study of the width of the ground patches (Gw) showed

$$\begin{align*}
S_{11} \text{ (dB)} \\
\text{Frequency (GHz)}
\end{align*}$$

Figure 7: $S_{11}$ with $L2$ variation.

$$\begin{align*}
S_{11} \text{ (dB)} \\
\text{Frequency (GHz)}
\end{align*}$$

Figure 8: $S_{11}$ with ground width (Gw) variation.
only little effect on $S_{11}$ plots (Figure 8) and the optimization steps resulted in the miniaturized cactus version depicted in Figure 1(c), with Gw equal to only 8 mm, and overall board dimensions 20 mm $\times$ 28 mm, which is equivalent to 63% size reduction compared to the original design of the CPW-fed slot antenna.

4. Discussion of Measurements and Simulation Results

4.1. Return Loss. For return loss and radiation pattern measurements, an SMA connector was soldered onto the board. An HP8530 Network Analyzer was used to measure the return loss, which is shown in Figure 3 with the simulated return loss. For the CPW-fed slot, two main resonances are observed in both the simulated and the measured return loss plots which are controlled by the two linear segments on the U-shaped stub. The simulated return loss is well matched from 3 GHz to over 12 GHz, but the measured return loss is slightly worse than $-10 \, \text{dB}$ around 8 GHz; however, it remains matched up to the frequency of 10.6 GHz, which is the upper bound for the UWB frequency range.

The simulated and measured return loss for both, cactus antenna (Figure 3(b)) and miniaturized cactus antenna (Figure 3(c)), are obviously better, especially at the two ends of the frequency range, with a better than $-10 \, \text{dB}$ return loss from 2.9 GHz to 12 GHz that overlaps the designated UWB range. Three resonances dominate the return loss; for the cactus antenna, these appear at 3.7, 5.1, and 6.4 GHz, one for each linear segment. Generally, the longer the stub is, the lower the corresponding resonance appears to be. This can be seen in Figure 7 where $S_{11}$ is plotted for three different length values ($L_2$) of the longest linear segment. The matching at the higher frequencies is affected by the rectangular ground patches’ width Gw as can be seen in Figure 8 where $S_{11}$ is plotted for three different Gw values.
for the miniaturized cactus antenna. It was concluded that the width of the ground patch cannot be smaller than 8 mm without compromising matching at higher frequencies and radiation patterns consistency, although it would be highly desired for an even more compact design.

For the presented $S_{11}$ plots, there is a small discrepancy between the simulated and measured results. This is partly due to the fact that the UWB range is large compared to the central frequency and it is difficult for the frequency domain simulation tools to give accurate results over the whole band. Moreover, the size of the SMA connector which is significant compared to the size of the antennas causes additional discrepancy between measurements and simulated results, for which a CPW mode excitation port was used.

4.2. Radiation Patterns and Gain. Measured and simulated radiation patterns for all three antennas at 5 and 9 GHz, which are representative of the patterns across the frequency range, are presented in Figures 9 and 10. Figure 9 presents the $E$-plane ($x$-$z$) copolarization, where $\theta = 0^\circ$ corresponds to the $z$-axis and $\theta = 90^\circ$ corresponds to the $x$-axis. It is seen that, for all three antenna designs, the $E$-plane has a null along the $x$-axis due to the feed line and a pattern that is nearly symmetric around the $x$-axis. The $H$-plane ($y$-$z$) copolarization plots are presented in Figure 10, where $\theta = 0^\circ$ is the $z$-axis and $\theta = 90^\circ$ is the $y$-axis. It is seen that the $H$-plane patterns for both cactus antenna designs are almost perfectly omnidirectional at 5 GHz and mostly omnidirectional at 9 GHz; however, particularly at 9 GHz, the slot antenna $H$-plane pattern flattens along horizontal axis. This somewhat directional behavior is verified by the gain measurements which are taken along the $z$-axis direction shown in Figure 11. As can be deduced from Figure 11(a), the gain at 5 GHz and 9 GHz for the slot antenna is 5 dBi and 4 dBi, respectively. The evident discrepancy between simulated and measured peak gain shown in Figure 11(a) can be explained by relatively
more directive measured $E$-plane pattern when comparing with the simulated $E$-plane pattern shown in Figure 9(a). A directive beam with maxima at 37° was observed in measured $E$-plane pattern resulting in a 2.2 dBi higher peak gain value when compared with the simulated predictions. This more directive measured pattern can be directly related to fabrication anomalies. Both cactus shaped antennas maintain almost perfectly omnidirectional radiation patterns which is also verified from the gain plot which is close to 0 dBi. Particularly, the miniaturized cactus antenna, in addition to its compact size, presents rather constant gain which improves the fidelity of transmitted time domain fast pulses [15]. The additional size of the slot antenna, as a result of the included elliptical slot, makes the antenna more directive, and for some applications this could be an advantage. However, considering that most applications involve mobile handheld devices, omnidirectional characteristics can be an overall advantage for a UWB antenna.

5. Conclusions

Three proposed antennas are fabricated on flexible, low loss, and low cost LCP organic material and a miniaturization method is discussed. All three antennas have a return loss better than $-10$ dB in the whole ultrawideband range and have close to omnidirectional radiation patterns. The evolved cactus antenna and miniaturized cactus antenna are developed based on the fact that the original slot antenna's operation depends primarily upon the current distribution on the $U$-shaped tuning stub. Based on this observation, regions with relatively lower surface current amplitude were removed to achieve more compact, size reduced device.
During this process, the U-shaped stub elliptical slot antenna was modified to form a cactus shaped radiator. The radiation characteristics of cactus were thoroughly investigated and the new antenna was optimized to be well matched in the whole UWB range. The bigger cactus antenna covers only 59% of the area of the original CPW-fed slot antenna whereas the miniaturized cactus antenna covers only 37% of the initial area. As a consequence of the removal of the elliptical slot, the monopole cactus antennas became more omnidirectional. The good agreement between simulated and measured results verifies the good performance of the proposed antennas and validates the success of the proposed miniaturization method.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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