Can Ultrawideband Antennas Be Miniaturized Effectively by Dielectric Loading?

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Abstract – A novel approach for miniaturization of disc monopole antennas is presented. The physical size of the antenna has been miniaturized by loading a dielectric material of high dielectric constant around the antenna in an intelligent manner. In order to maintain the impedance bandwidth characteristics, a spatial quarter wave transformer was applied. Simulations of the structure showed that the impedance bandwidth was conserved while the physical size of the structure was reduced by 58.4%.

1 INTRODUCTION

Antennas for ultrawideband (UWB) applications have been extensively studied by others for decades. UWB antennas based on disc monopole have been proposed, for example, in [1]–[3]. Recent studies of this group of antennas have focused on variations of the shape of the radiator and were designed to enhance the impedance bandwidth of the antenna [4]-[6]. Many UWB applications require an antenna with a compact physical size, which may preclude disc monopole antennas due to the large dimensions of the ground plane and radiator.

In this paper, we present a novel method for wideband antenna miniaturization through, what we call, intelligent dielectric loading. The method reduces the size of the disc monopole antenna by applying a hemispherically shaped material of high dielectric constant above the ground plane and around the radiator. In order to avoid the accompanied degradation of the antenna characteristics due to impedance mismatch, a layer of another dielectric material is applied. The thickness and dielectric constant of this added layer are designed so that it acts as a spatial quarter wave transformer. A particular example will be presented to show the size reduction potential afforded by this method. The linear dimensions of the antenna that will be presented are reduced by 58.4% by using the proposed method in simulation. Simulation in CST Studio Suite shows a 78.7% relative impedance bandwidth is achieved. We expect that wider bandwidths may be achievable by using a wider bandwidth matching layer.

2 DISC MONOPOLE ANTENNA

The Disc Monopole Antenna (DMA) is known to provide a very large impedance bandwidth. By following the design procedure in [2], a DMA was constructed as shown in Figure 1. A perfect electrical conducting (PEC) radiator is orthogonally mounted on a circular PEC ground plane, and their geometric dimensions are shown in Figure 1.

As presented in [2] an edge of the radiator is fed by a 50-Ω SMA launcher. The launcher itself is flush-mounted to the center of the cylindrical PEC ground plane. The lower portion of the radiator has been cut away with a cut angle (a = 20°) to remove excess capacitance between the radiator and the ground plane, which improves the broadband impedance match.

Figure 1: Original DMA structure.

3 MINIATURIZATION OF THE ANTENNA

One of the most common antenna miniaturization techniques is dielectric loading, which was demonstrated in [7]. This work showed that the well known biconical antenna may be miniaturized by applying dielectric loading of relatively low dielectric constant, with other techniques, while maintaining impedance matching and radiation pattern stability over frequency.

Our proposed approach to reduce the size of the DMA is to add a hemispherically shaped material of high dielectric constant above the ground plane. In this design, the relative permittivity of the loading material was chosen to be 9.00, therefore the linear dimensions of the DMA were reduced to one third of their original sizes according to scaling theory in electromagnetism.

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Unfortunately, the impedance bandwidth is degraded by such an approach. It is our interpretation that this degradation is due to two primary effects. One is the impedance mismatch at the feed of the antenna due to the high dielectric loading. For the type of antenna in Figure 1, this effect can be compensated by adjusting the antenna height above the ground. The second effect is the wave impedance mismatch at the outer boundary of the high dielectric constant hemisphere of the loading material.

4 OPTIMIZATION OF FEED REGION

The miniaturized DMA in a high dielectric loading material gives us two geometric degrees of freedom for compensating the loss of impedance bandwidth: the distance between the edge of the radiator and the ground plane (H), and the cut angle (\( \alpha \)), as shown in Figure 2. Using CST Studio Suite, we conducted parameter studies to ascertain the effect of each geometric parameter and to determine an optimal value for the feed region of the miniaturized DMA.

The size of the ground plane and radiator were reduced to one third of its original size while holding the size of the 50-\( \Omega \) SMA launcher unchanged. In order to investigate the changes of input impedance with distance (H) and cut angle (\( \alpha \)), the mismatch at the outer boundary was intentionally disregarded. For this purpose, the simulation was conducted in an infinite \( \varepsilon_r = 9.00 \) space.

![Figure 2: DMA structure in an infinite \( \varepsilon_r = 9.00 \) space.](image)

The process of optimization begins with the choice of distance H while holding constant the cut angle \( \alpha \) at 10°. The simulated VSWR is shown in Figure 3. As this distance is swept from 0.0 mm to 1.0 mm the impedance match across the band progressively improves. After 1.0 mm the match across the band deteriorates. From this simulation data, it is known that the impedance mismatch caused by dielectric loading can be compensated if distance H is chosen to be 1.00 mm for cut angle \( \alpha = 10^\circ \).

After optimizing the distance H at cut angle \( \alpha = 10^\circ \), similar processes of parameter study were conducted at different cut angle setups as shown in Figure 4, 5, 6, and 7 for the purpose of determining an optimal combination of cut angle \( \alpha \) and distance H, where the impedance mismatch at the feed due to the dielectric loading which adds excess capacitance is optimally compensated.

![Figure 4: Simulated VSWR in \( \varepsilon_r = 9.00 \) space, while the cut angle \( \alpha \) is held constant at 20°, and the distance H is varied from 0.0 mm to 1.2 mm.](image)

![Figure 5: Simulated VSWR in \( \varepsilon_r = 9.00 \) space, while the cut angle \( \alpha \) is held constant at 30°, and the distance H is varied from 0.0 mm to 1.0 mm.](image)
Figure 6: Simulated VSWR in $\varepsilon_r = 9.00$ space, while the cut angle $\alpha$ is held constant at 40°, and the distance $H$ is varied from 0.0 mm to 1.0 mm.

Figure 7: Simulated VSWR in $\varepsilon_r = 9.00$ space, while the cut angle $\alpha$ is held constant at 50°, and the distance $H$ is varied from 0.0 mm to 1.0 mm.

As shown in Figure 4, 5, 6, and 7 the parameter studies at the feed have now been completed. The first impedance degradation effect at the feed region is addressed by setting the angle $\alpha = 40^\circ$ and distance $H = 0.6$ mm, as shown in Figure 6.

4 SPATIAL MATCHING LAYER

With the impedance mismatch in the feed region due to dielectric loading having now been compensated, an additional impedance matching technique at the outer boundary of the dielectric hemisphere will be applied. Since the actual dielectric loading is a dielectric hemispherical cap around the radiator, there is wave impedance mismatch at the outer boundary of the hemisphere of dielectric loading material. To address this mismatch, the wave impedance of the dielectric loading needs to be matched to that of free space at the outer boundary of the loading region. One way to accomplish this is to apply a layer of dielectric material. The thickness and dielectric constant of this added layer can be designed so that the layer acts as a spatial quarter wave transformer.

As shown in Figure 8, the thickness of the matching layer was 6.2 mm and the relative permittivity was 3.00. These parameters were determined by following the design procedure of quarter wave transformer for TEM transmission lines at 7.0 GHz. Note that the distance $H$ and cut angle $\alpha$ were adjusted to 0.6 mm and 40° to incorporate the optimization of the feed region into the final antenna design, as determined in the previous section.

After implementation of these size reduction and impedance enhancement techniques, simulations in CST Studio Suite were performed to characterize the design and the results are shown in Figure 9. The miniaturized DMA exhibits a 78.7% relative impedance bandwidth centered at 7.0 GHz for VSWR < 2.0, while the diameter of the ground plane has been reduced by 58.4% when compared to an equivalent unloaded design. The fact that the impedance bandwidth of the miniaturized DMA is close to that for a quarter wave transformer for TEM transmission lines confirms the validity of our proposed method.

Figure 8: Miniaturized DMA structure.

Figure 9: VSWR of DMA in Figure 1 and miniaturized antenna in Figure 8. The green dashed area indicates the theoretical bandwidth of the quarter wave matching layer.
The simulated elevation gain patterns of the original and miniaturized antenna at 7.0 GHz were also computed and are shown in Figures 10 and 11. The pattern differences between two antennas are caused by the miniaturized antenna size due to the dielectric loading, as expected.

![Figure 10: Simulated gain patterns at 7.0 GHz of the original DMA and the miniaturized DMA. This cut is the pattern in the xz plane shown in Figure 8.](image)

![Figure 11: Simulated gain patterns at 7.0 GHz of the original DMA and the miniaturized DMA. This cut is the pattern in the yz plane shown in Figure 8.](image)

5 CONCLUSION

A novel approach for miniaturization of DMA based on dielectric loading has been proposed. When compared to an unloaded DMA, the diameter of the ground of miniaturized DMA has been reduced by 58.4%. From our simulations, a 78.7% relative impedance bandwidth is obtained. The enhancement for impedance bandwidth is limited by the electrical properties of single-layer wave impedance transformer. In principle, a multiple-layer structure could be used if a larger impedance bandwidth was desired.

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References


