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DESIGN OF A UWB COMBINED ANTENNA AND AN ARRAY OF MINIATURIZED ELEMENTS WITH AND WITHOUT LENS

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Abstract—In this paper, the design of an array of wideband combined antenna elements is presented. A TEM horn antenna is combined with magnetic dipoles to obtain a wideband element with a bandwidth from 180 MHz to 30 GHz. The element is then miniaturized in order to be placed in a two by two array, and then the optimized values of the horizontal and vertical spacings are calculated. To enhance the array bandwidth, a lens is placed in front of each element. This leads to an increase in the bandwidth from 0.2 to 10 GHz while no grating lobes appear over the bandwidth. The combined element is fabricated and the simulation results are verified by the measured data. Furthermore, simulation results for the return loss, radiation patterns and antenna gain for the 2×2 array are presented.

1. INTRODUCTION

Techniques of generation and transmission of narrow time-width pulses are developing rapidly since they have various applications in radar systems for discovering hidden objects beneath the earth [1]. In addition, in radar systems with wide bandwidth and high accuracy, short-width pulses are utilized [2]. Wideband antennas are capable of transmitting narrow-width pulses. They are used in standard antenna measurements, broadband communication systems, satellite tracking systems and reflector feeding [3]. Theses antennas are highly demanded in the measurement equipments, since the technicians do not need to stop the measurement test in order to replace the standard antenna when working in another frequency band [4]. For this purpose, many antennas have been designed such as TEM horn, Vivaldi and shark

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antennas [5–8]. In [9], a Double Ridged Horn Antenna (DRGH) has been presented which is not able to radiate at low frequencies because of the DR cutoff frequency. Furthermore, its radiation patterns are divided at high frequencies. For employing a wideband antenna in an array structure, the antenna dimensions should be small in comparison with the wavelength because a distance between elements greater than the wavelength creates grating lobes.

In this paper, a wideband TEM horn antenna is chosen as the array element. In order to radiate at low frequencies, the dimensions of this element are large. Therefore, this antenna is not appropriate for low frequency radiation of the array. The idea of combined antenna is used to increase the antenna bandwidth towards low frequencies. In [10], the electric and magnetic energies around an electric dipole placed in a lossless environment have been analyzed. It is observed that the electric energy is larger than the magnetic energy. The difference between these energies is called reactive energy, which determines the imaginary part of the antenna input impedance. It plays no role in the antenna radiation and acts as a loss. Thus, the reactive energy around the antenna can be minimized by equalizing electric and magnetic energies. In this case, the imaginary part of the input impedance tends to zero and the input impedance becomes real resulting in a wide impedance matching.

One approach to reduce the reactive energy around the antenna is to position electric and magnetic dipoles near each other [11]. A combination of electric and magnetic dipoles reduces the reactive energy and gives impedance matching at low frequencies. Various designs are given in [12–14] for combined antennas.

Here, the idea of combined antenna is utilized to enhance the bandwidth of a TEM horn antenna. First, using this idea, TEM horn fields are combined with those of magnetic dipoles and an element with a bandwidth from 180 MHz to 30 GHz is obtained. A step by step design procedure is presented. Next, the antenna is fabricated to validate the simulation results. This antenna cannot be used as an element in a planar array, since its height is large which creates grating lobes at high frequencies in an array structure. Hence, the element is miniaturized and its height is optimized. The miniaturized element is placed in a two by two array. The structure gives appropriate bandwidth and radiation patterns. To have better patterns at high frequencies, a lens is used in front of each element. The lenses focus the radiation pattern of the elements and prevent grating lobes at higher frequencies. This extends the bandwidth up to 10 GHz. The next section presents the wideband design steps. Then the element is miniaturized and placed in a two by two array. Finally, the array structure with lenses is presented.

2. ANTENNA DESIGN

Our goal is to design a small size wideband antenna. It is important that it has a small size especially at lower frequencies where the antenna dimensions are several wavelengths larger than those at higher frequencies. The TEM horn antenna is one of the wideband antennas with TEM propagating mode in which, the propagation velocity does not depend on frequency. This means different frequencies of the applied pulse spectrum reach the antenna aperture simultaneously which prevents pulse distortion. To extend the antenna bandwidth at the lower side of the band, the idea of combined antenna is used.

2.1. Design and Fabrication of Wideband Combined Antenna

In fact, the TEM horn antenna is a parallel plate line with the characteristic impedance of 50 Ω at one end and free space impedance (377 Ω) at the other end. Therefore, it acts as an impedance taper between 50 Ω and free space impedance. This impedance taper can be implemented in linear, exponential, sinusoid and other forms. The characteristic impedance of a microstrip line is given as [15]:

$$Z_0 = \begin{cases} \frac{60}{\sqrt{\varepsilon_{eff}}} Ln\left(\frac{8h}{W} + \frac{W}{4h}\right) & \text{for } W/h \leq 1 \\ \frac{120\pi}{\sqrt{\varepsilon_{eff}}[W/h + 1.393 + 0.667 Ln(W/h + 1.444)]} & \text{for } W/h \geq 1 \end{cases} \quad (1)$$

In which,

$$\varepsilon_{eff} = (\varepsilon_r + 1)/2 + (\varepsilon_r - 1) \Big/ \left(2\sqrt{1 + 12h/W}\right) \quad (2)$$

where w, d and ε_{eff} are strip width, the distance between the strip and the ground plane, and effective permittivity of the substrate, respectively. If we apply the image theory to a microstrip line, a parallel plate line is obtained by omitting the ground plane. The distance between the two plates is 2d in the equivalent parallel plate line. By using image theory, it is proved that the characteristic impedance is twice the microstrip line impedance. To achieve a proper taper between the two impedances, the width of the strips and the distance between them are optimized. In our design, the dielectric is air, i.e., $\varepsilon_{eff} = 1$. Figure 1(a) shows the basic design of the TEM horn. W and d are calculated as follows:

$$W = 30 + 0.283z \qquad 0 \leq z \leq 300 \quad (3)$$

$$d = 5e^{0.0142z} \qquad 0 \leq z \leq 300 \quad (4)$$

Since coaxial cable can be better matched to the microstrip line than parallel plate, the width of the lower strip is designed equivalent to 100 mm to act as a ground plate for the upper strip. Figure 1(b) indicates the proposed structure.

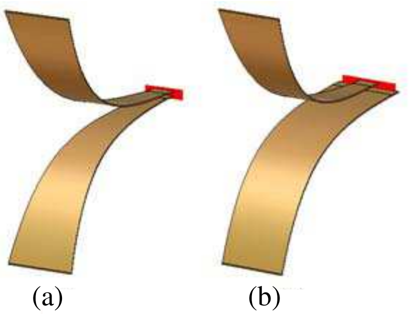

Figure 1. (a) Basic design of the TEM horn, structure (1). (b) Modified TEM horn, structure (2).

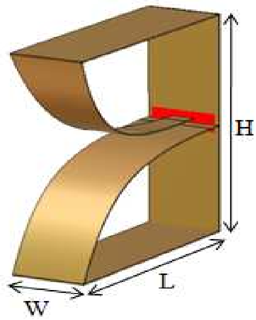

Figure 2. Combined antenna, structure (3).

In [10], the fields around a dipole placed in a lossless environment are studied. It is observed that the electric energy is greater than magnetic energy, which difference is called antenna reactive energy, calculated as below [10]:

$$\bar{W}_r = \int\limits_{V_a} \pi \left(\bar{W}_m - \bar{W}_e\right) dV \tag{5}$$

where V_a is the volume surrounding the antenna, and $\bar{W}_e$ and $\bar{W}_m$ are averages of the electric and magnetic energy densities, respectively. The reactive energy has no role in antenna radiation and acts as a loss in the antenna. It creates the imaginary part of the antenna input impedance. A more suitable impedance matching to the feed line is achieved when the antenna input impedance is real. Hence, we attempt to reduce the reactive energy around the antenna in order to minimize the imaginary part of the input impedance. A magnetic dipole is modeled by a current flowing in a ring. Its fields can be controlled by the ring area and current magnitude. To reduce the antenna reactive energy, three plates are placed over, beneath and behind the antenna. These plates create rings of current which act as magnetic dipoles. The combination of these dipoles with TEM horn antenna radiating fields minimizes the reactive energy and consequently a better matching is achieved. Figure 2 shows the proposed structure added to the horn antenna. The height and length of the antenna are 350 mm and 320 mm respectively. A waveguide port at the beginning of the microstrip line is positioned with a small gap behind the back plate for antenna excitation. Return loss of three structures is shown in Figure 3. It is seen that the addition of the rings has improved the return loss at low frequencies. The inner conductor of the coaxial cable has crossed a hole created in the back plate and has been connected to the upper strip. In travelling wave antennas, every discontinuity the propagating wave faces causes reflection and deteriorates impedance matching. To mitigate this issue, a transition is used between the coaxial cable and the antenna. Figure 4 illustrates the transition structure. The inner conductor is lofted to the upper strip in an appropriate distance. This enhances the antenna matching. An N-type 50 Ω coaxial cable is used for the antenna excitation.

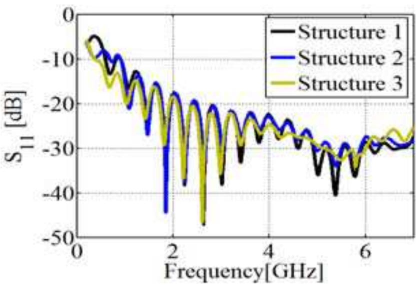

Figure 3. Return loss of three proposed structures.

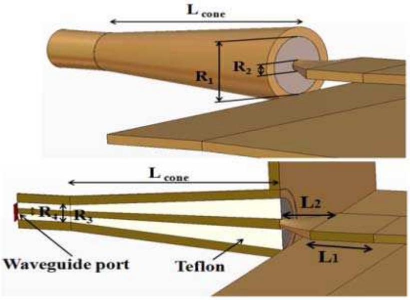

Figure 4. Transition between the coaxial cable and antenna.

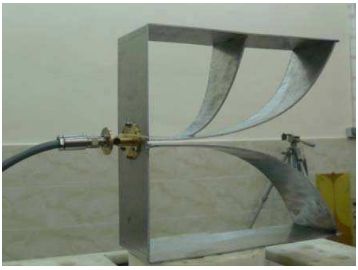

Figure 5. Fabricated antenna.

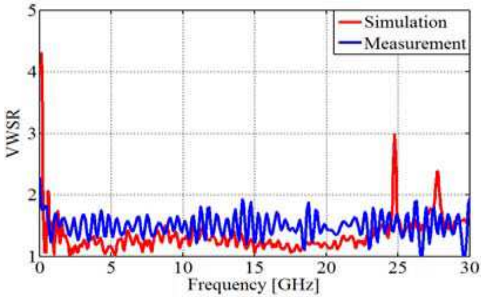

Figure 6. Simulated and measured VSWR.

The inner and outer conductors of the cable are tapered to improve the matching. This taper acts like a transmission line with a proper taper. The optimized parameters for the appropriate impedance

Table 1. Designed parameters for the appropriate impedance matching.

Variables	R_1	R_2	R_3	R_4	L_{cone}	L_1	L_2
Values (mm)	12	2.4	4	1.2	40	20	12

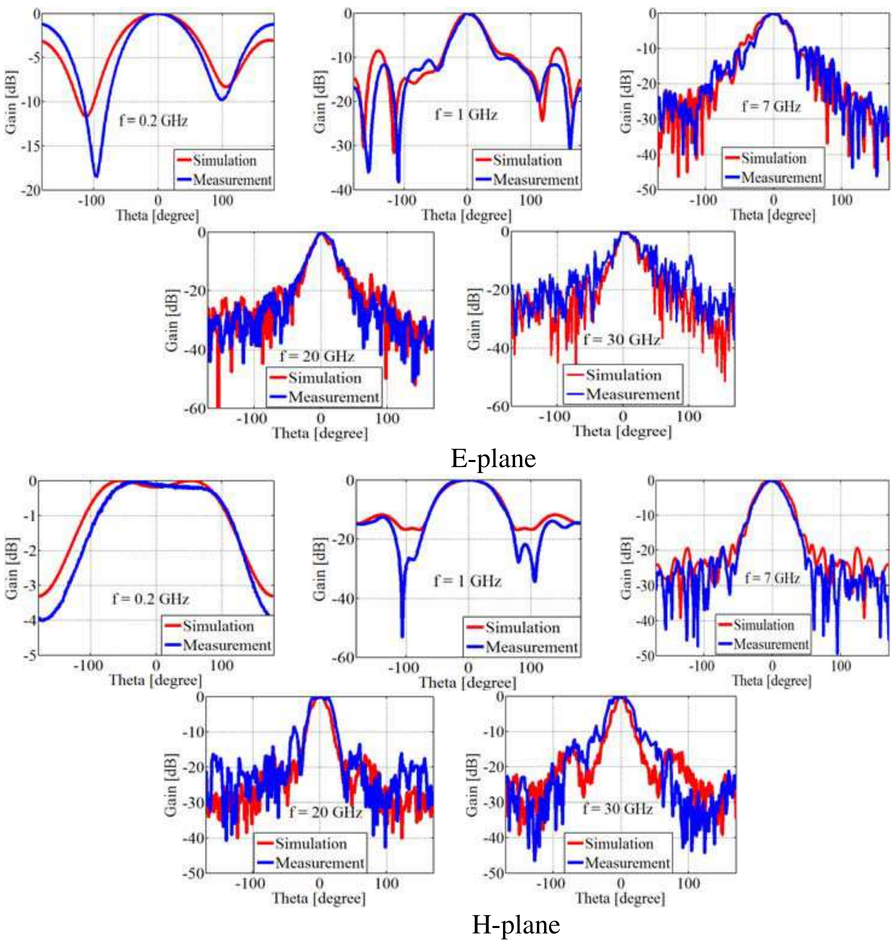

Figure 7. The simulated and measured radiation patterns of combined antenna.

matching are given in Table 1. To control the magnetic energy around the antenna, a plate is placed on top of the antenna. The antenna matching can be improved by optimizing the position and shape of this plate. The fabricated antenna is illustrated in Figure 5. The comparison between simulated and measured VSWR is plotted in Figure 6. The results are not exactly similar because of the fabrication tolerance. However, the matching is appropriate over the desired band. The simulated and measured radiation patterns of the element at specific frequencies are plotted in Figure 7.

2.2. Miniaturization of the Element of the Array

The height of the designed element is large for a planar array structure. This can worsen the array performance since a distance greater than a wavelength between the array elements creates grating lobes in the patterns and decreases antenna gain. If we decrease the height of the element, its performance in low frequency degrades. To compensate this effect, the element width is increased to $W = 120\,\mathrm{mm}$ which causes the lower frequency to start from 0.2 GHz. The optimized parameters for the miniaturized antenna are given in Table 2.

Table 2. Designed parameters for the miniaturized antenna.

Variables	R_1	R_2	R_3	R_4	L_{cone}	L_1	L_2	L	H
Values (mm)	11	3.2	4	1.2	60	4	5	300	200

2.3. Miniaturized Element in the Two by Two Array Structure

By using the idea of combined antenna, a wideband antenna was designed with dimensions smaller than the wavelength in low frequencies. This feature makes it possible to use this element in a planar array structure. The array structure is two by two. The distance between the elements should be as small as possible to prevent grating lobes in high frequencies. But, the small distance between elements increases the coupling between them which degrades the impedance matching. Thus, a tradeoff must be done for the distance values between the elements in the horizontal and vertical directions. Figure 8 shows the two by two array. Each element is fed by a coaxial cable. The distance in the horizontal and vertical directions are given as $d = 40\,\mathrm{mm}$ and $h = 0$, respectively. The elements are excited simultaneously with identical signals to obtain the return loss at each port. Since the array structure is symmetrical, the return loss for upper

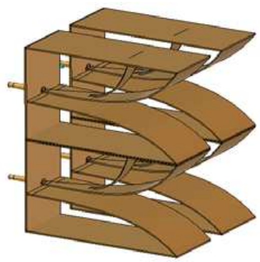

Figure 8. Two by two array.

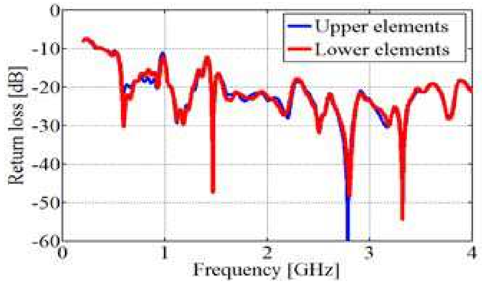

Figure 9. Total return loss of array elements without lens.

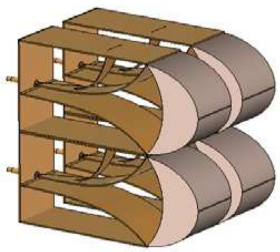

Figure 10. Array of elements with lens.

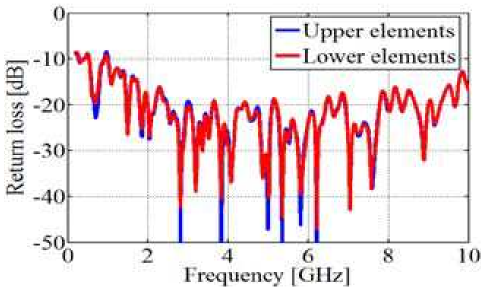

Figure 11. Total return loss of array elements with lens.

elements is equal to lower elements. Figure 9 shows the total return loss for array elements. The element was designed for a broadside radiation pattern in order to prevent grating lobes in the array radiation pattern. Up to 4 GHz the main lobe of the array is in the broadside direction and the grating lobes are about 13 dB and 7 dB smaller than the main lobe in H-plane and E-plane, respectively.

2.4. Addition of a Wideband Lens to Each Array Element

In the element design, it was attempted to prevent beam tilt in the radiation pattern but the pattern tends to top at high frequencies because of the element asymmetry. To compensate this issue, a wideband dielectric lens is placed in the aperture of each element. This focuses the element radiation pattern which leads to a decrease in the grating lobes of the array. The array bandwidth extends to 10 GHz by using the lenses. The lens is made of Teflon with permittivity of 2.1. The inner and outer surfaces of the lens are circular and hyperbolic, respectively. The thickness of lens is 70 mm at its centeral part. It is noted that the lens reduces the coupling between the elements. Therefore, it is possible to decrease the distance between the elements in the array.

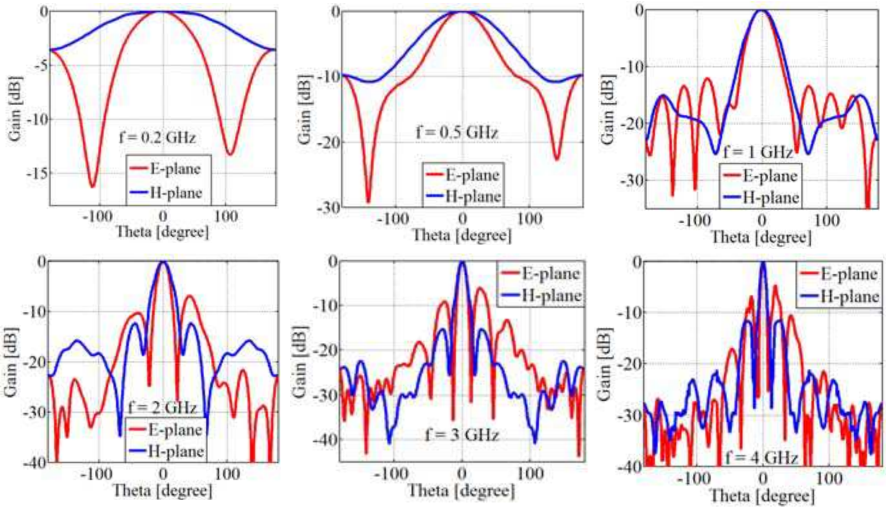

Figure 12. Simulated radiation patterns for array of elements without lens.

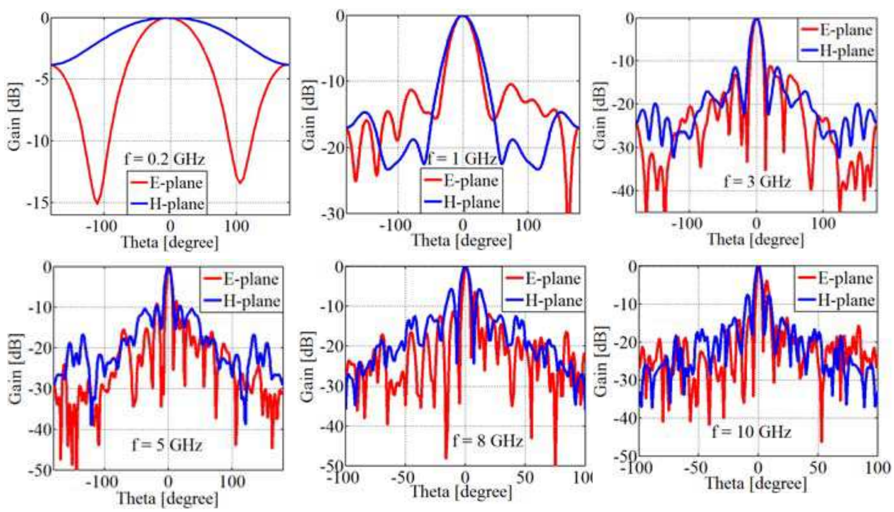

Figure 13. Simulated radiation patterns for array of elements with lens.

3. SIMULATION RESULTS AND DISCUSSION

CST Microwave Studio was used for the array simulation. Radiation patterns of the array without and with a lens at specific frequencies over the bandwidth are plotted in Figure 12 and Figure 13, respectively. It can be seen that the addition of lenses has decreased the grating lobes up to 10 GHz. This has also enhanced the antenna gain. Figure 14 shows the array gain with lens. It is observed that the gain increases over the bandwidth in case of the array with lens whereas, the gain decreases in the broadside direction in the case of the array without lens which is because of the grating lobes.

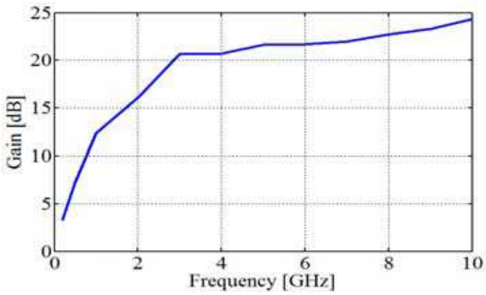

Figure 14. Array gain of elements with lens.

4. CONCLUSION

In this paper, design and implementation of a wideband combined antenna with a bandwidth from 180 MHz to 30 GHz was presented. The simulation results were compared with measurement results of the element. There was excellent agreement between the results. In order to extend the array element bandwidth, the radiation fields of a TEM horn antenna were combined with magnetic dipoles. Then, the element was miniaturized to be utilized in a two by two array structure. The bandwidth of 0.2 to 5 GHz was obtained for the array. To prevent grating lobes in the array radiation pattern, wideband dielectric lenses were placed in front of each element. A bandwidth up to 10 GHz was achieved by the addition of the lenses. Furthermore, the array gain increased up to 10 GHz. The results of the array structure were also simulated with CST which showed satisfying performance in terms of impedance matching and radiation patterns.

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