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ABSTRACT

A Moxon antenna is a special case of Yagi-Uda antenna with folded dipole and single folded reflector. It is a simple antenna with no side or back lobes. It has a moderate gain and a high front-to-back ratio. It can be designed for different frequency bands, starting from HF up to centimetric and even millimetric bands. It can be built as a wire antenna or printed on a dielectric substrate. In this paper we are going to study the development of Moxon antenna from simple dipole antenna and the design and optimization of printed Moxon antennas on different substrates, trying to investigate the effects of substrate material on the antenna performance.

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A Design Study of Printed Moxon Antenna

Aladdin Assisi, MTC, Cairo

ABSTRACT

A Moxon antenna is a special case of Yagi-Uda antenna with folded dipole and single folded reflector. It is a simple antenna with no side or back lobes. It has a moderate gain and a high front-to-back ratio. It can be designed for different frequency bands, starting from HF up to centimetric and even millimetric bands. It can be built as a wire antenna or printed on a dielectric substrate. In this paper we are going to study the development of Moxon antenna from simple dipole antenna and the design and optimization of printed Moxon antennas on different substrates, trying to investigate the effects of substrate material on the antenna performance.

I. INTRODUCTION

The Yagi-Uda antenna is a widely used radiating structure for a variety of applications in commercial and military sectors [3]. The Moxon antenna was created by British Ham Radio operator Les Moxon, as a means of reducing the size of a typical 2 element Yagi [5]. It is a special case of Yagi-Uda antenna with folded dipole and single folded reflector, where the horizontal spans of the reflector and the dipole are equal. The main advantage of the Moxon antenna is its high front-to-back ratio. Moreover, it has no side lobes. A Moxon antenna can be a wire antenna or a printed antenna. It is difficult to find published papers about Moxon antennas. Chougale et al designed a simple UHF Moxon antenna [5]. Q. Lui et al proposed a printed UHF Moxon antenna with miniature size using meanderline structures in the dipole and the reflector. They achieved a 70 x 150 degrees beamwidth, a 4.48 dB gain and a 17.7 dB front to back ratio at 900 MHz with 80 x 60 mm antenna dimensions [10]. and a 4. . The first published Moxon antenna array was proposed by Suad Başbuğ [11]. He has synthesized

a four element array pattern of Moxon elements, using a proposed hybrid method [11].

In this paper we apply some numerical optimization techniques to get the best possible antenna design in different cases. We have selected the Trust Region Framework Algorithm recommended by CST electromagnetic simulator. This technique was discussed and explained by Yuan [7]. In most antenna optimization problems, several goals must be satisfied simultaneously in order to obtain an optimal solution. As these objectives are often conflicting, no single solution may exist that is best regarding all considered goals [6]. Solving antenna optimization problems is a conflicting problem where fast methods only carry local guarantees while robust methods are prone to have very slow convergence [6]. X. L. Travassos, D. A. G. Vieira and A. C. Lisboa introduced an excellent study of antenna design optimization with solved examples [6]. Fortunately, optimizing Moxon antenna design with a single objective function has been successful as we shall see in this paper.

A single director, or even multiple directors, may be inserted in front of the dipole to increase the antenna gain and decrease its beamwidth. If there is a director, its geometrical parameters affect the antenna gain and radiation pattern. They may also affect the frequency response. Therefore, the antenna design should be re-optimized after adding a director. This case will not be studied in this paper.

In the following sections we shall study the following:

- a. Developing a Moxon antenna, starting from a simple printed dipole.
- b. The electric field flux lines of a Moxon antenna in free space and on different substrates to see the effect of dielectric constant on electric flux.

- c. Study and optimization of main antenna performance parameters; namely insertion loss, bandwidth, gain, radiation efficiency, total efficiency and front-to-back ratio on different substrates.

II. A FREE SPACE DIPOLE ANTENNA

Figure 1a shows a simple printed dipole antenna in free space with dipole length = 212 mm. It resonates at 653.23 MHz as shown in Figure 1b.

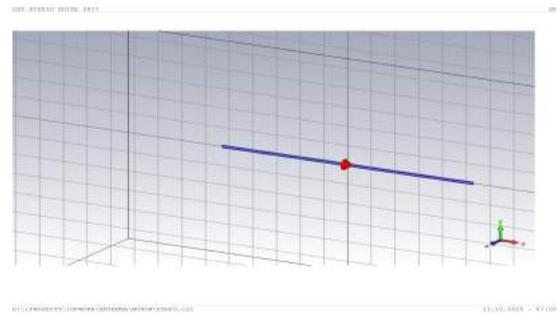


Figure 1a:

A dipole antenna resonates at frequency f_0 , given by:

$$f_0 = \frac{3 \times 10^8}{\text{wavelength}} \cdot K \quad (1)$$

where K is a correction factor < 1 due to the end effect of the dipole. It depends on the dipole cross section area and the frequency band.

Driven element is usually kept 0.475 times of wavelength because only 95% of the dipole antenna radiates [4]. The theoretical resonance frequency would be:

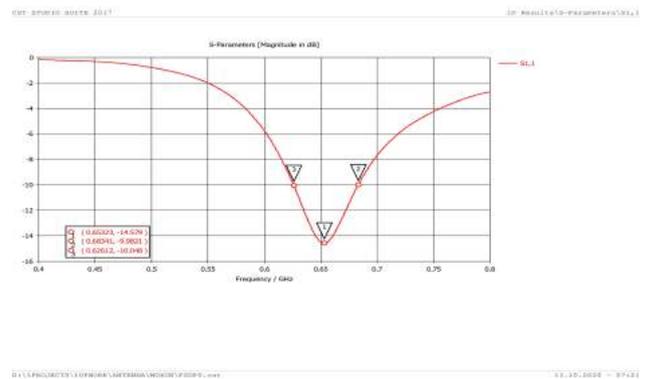


Figure 1b:

$$f_{0th} = \frac{3 \times 10^8}{\text{wavelength}} = \frac{3 \times 10^8}{0.424} = 707.55 \text{ [MHz]}$$

The ratio K between the actual and theoretical resonance frequencies is $653.23/707.55 = 0.9232$.

The electric field intensity vector of an electric dipole in polar coordinates is give by [1]:

$$\mathbf{E} = \frac{Qd}{4\pi\epsilon_0 r^3} (2 \cos \theta \mathbf{a}_r + \sin \theta \mathbf{a}_\theta) \quad (2)$$

where Qd is the dipole moment
 θ is the vertical angle measured from the z axis
 r is the distance from coordinates origin

\mathbf{a}_r and \mathbf{a}_θ unit vectors in the r and θ directions, respectively.

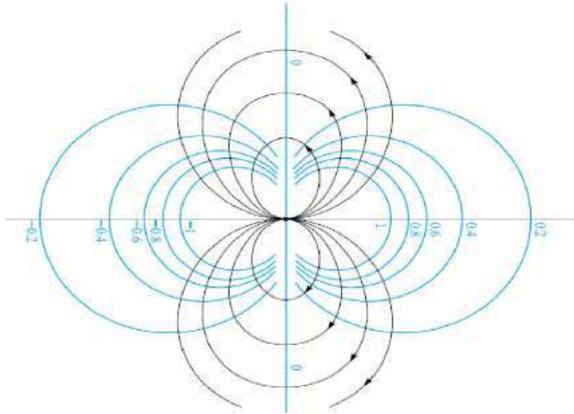


Figure 2a

Figure 2a shows the calculated electric flux lines (black) of an electrostatic dipole, while Figure 2b shows the simulated 3D electric flux lines of the free space dipole antenna. The blue lines in figure 2a are the equipotential surfaces of the electrostatic dipole. The simulated radiation pattern is a symmetrical omni-directional pattern with 2.28 dB gain and very high radiation efficiency at 653.23 MHz.

III. A PRINTED DIPOLE ANTENNA

Figure 3a shows a simple UHF printed dipole antenna with dipole length = 212 mm.

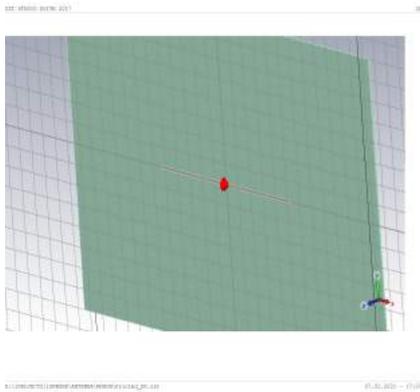


Figure 3a

Due to the substrate dielectric constant, a 210 mm dipole resonates at this frequency. Therefore, we can estimate the effective dielectric constant as

$$\sqrt{\epsilon_{eff}} = (\lambda_0/\lambda_g) = \frac{573}{459.27} = 1.2477 \text{ and } \epsilon_{eff} \approx 1.1557.$$

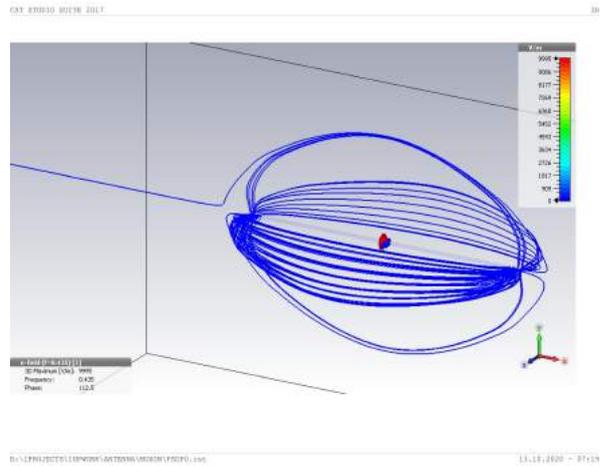


Figure 2b

If we consider that the dipole length $L = k\lambda_G/2$; the guided wavelength is

$$\lambda_G = \frac{2L}{k} = \frac{2 \times 212}{0.9232} = 459.27 \text{ mm.}$$

Figure 3b shows the S11 of the printed dipole antenna. It resonates at 567.2 MHz with a 56.89 MHz bandwidth.

Since the dipole resonates at 0.5672 GHz; its free space wavelength is

$$\lambda_0 = \frac{300}{0.5671k} = 573 \text{ mm.}$$

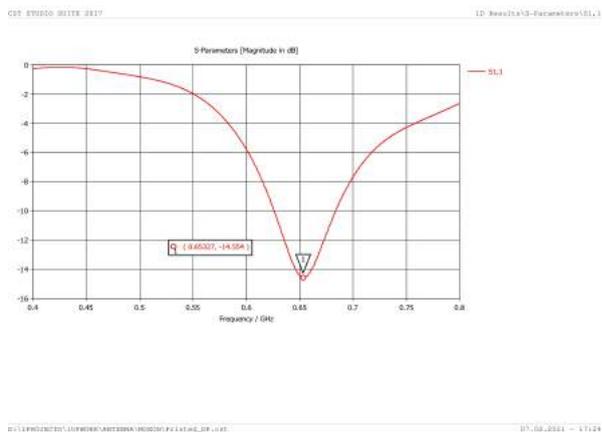


Figure 3b

Figure 4 shows the omni-directional antenna radiation pattern of the simple printed dipole at 567.2 MHz with a 2.237 dB gain

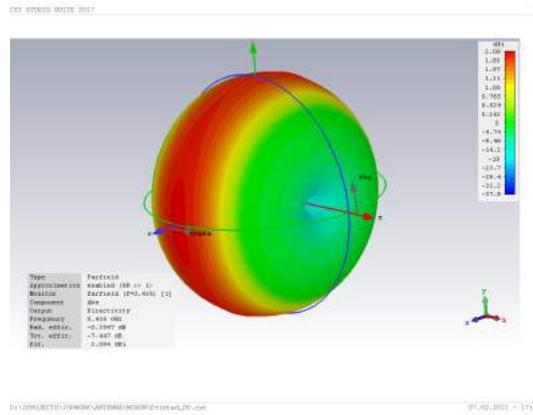


Figure 4

IV. FOLDED PRINTED DIPOLE ANTENNA

Figure 5a shows the same dipole antenna after the addition of two 31 mm perpendicular extensions.

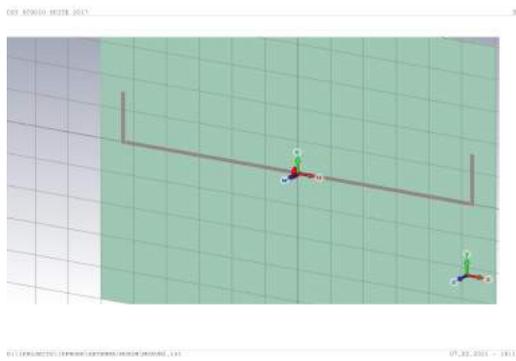


Figure 5a

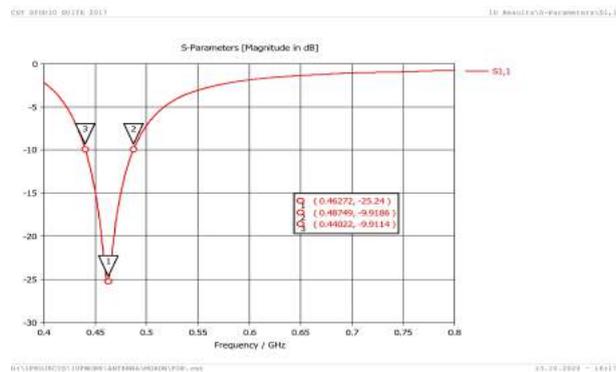


Figure 5b

As the dipole length is extended, the resonance frequency decreases to 462.72 MHz, as it appears in Figure 5b. The electric flux lines of the folded

dipole antenna are shown in Figure 6, while the 3D antenna pattern is shown in Figure 7. They are similar to those of the unfolded dipole.

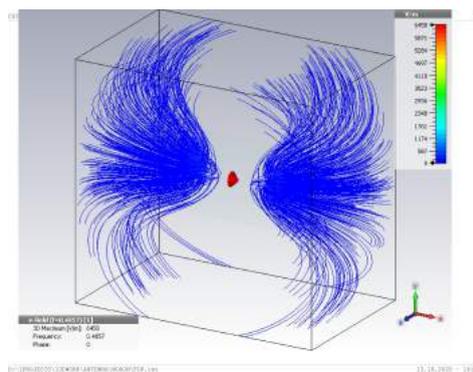


Figure 6

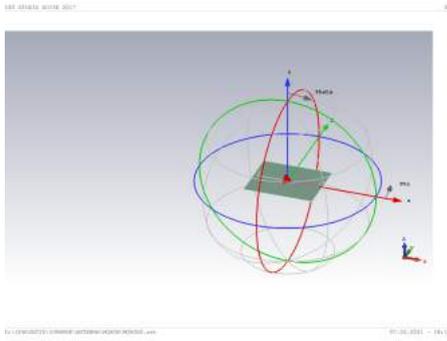


Figure 7a

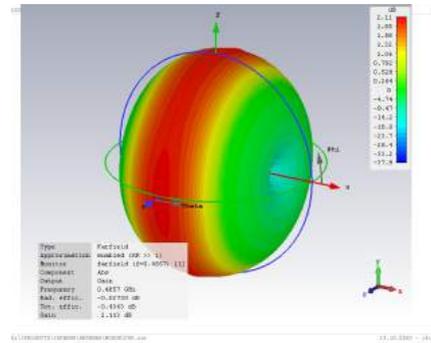


Figure 7b

V. FOLDED DIPOLE WITH REFLECTOR

A simple dipole has an omnidirectional toroidal radiation pattern. It can be directed by placing a reflector parasitic element. A rod of equal or slightly longer length is placed a quarter wave away from a half wavelength long vertical antenna. The current induced in it will be in phase or lag behind. This effect will make this rod a 'wave reflector' [4]. Figure 8 shows the same folded dipole with a reflector. A folded dipole with

such a reflector is called Moxon Antenna. The reflector has the same lateral length of the original dipole (212 mm) with folded arms such that there is a certain gap between each arm of the reflector and the corresponding arm of the folded dipole. This gap is subject to control and optimization; since it affects the Moxon antenna performance. Perhaps the most critical dimension is the gap [5].

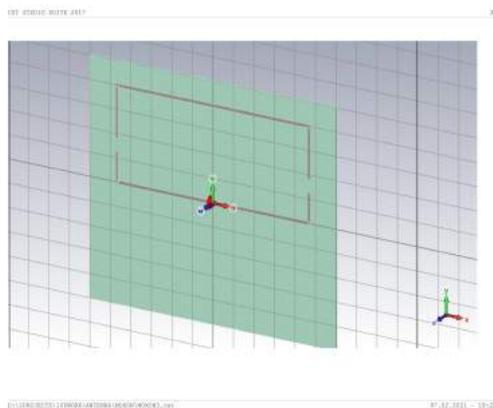


Figure 8a

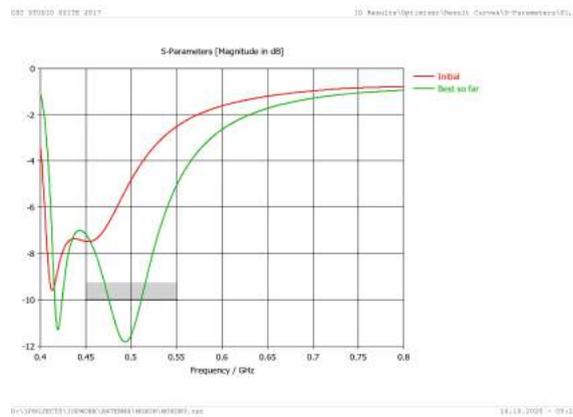


Figure 8b

Figure 8b shows the S11 of this Moxon antenna. It resonates at a smaller frequency with distorted frequency response. Its parameters need optimization.

Figure 9a shows the 3D antenna pattern of this Moxon antenna. It is evident that the reflector directed the pattern in the negative y direction.

The pattern is no more omni-directional. The maximum gain has been increased from 2 dB to 4.87 dB. The total efficiency is increased from -1.789 dB (66.237%) to -0.7617 dB (83.9%) and the radiation efficiency from -0.53 dB (88.5%) to -0.01761 dB (99.6%).

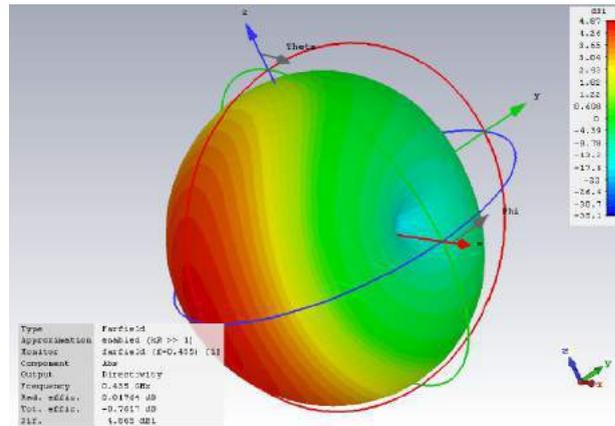


Figure 9a

Figure 9b shows the 2D antenna pattern of the same Moxon antenna. It is evident that the pattern has neither a back lobe nor side lobes. The front-to-back ratio is $5.698 + 7.841 = 13.539$ dB.

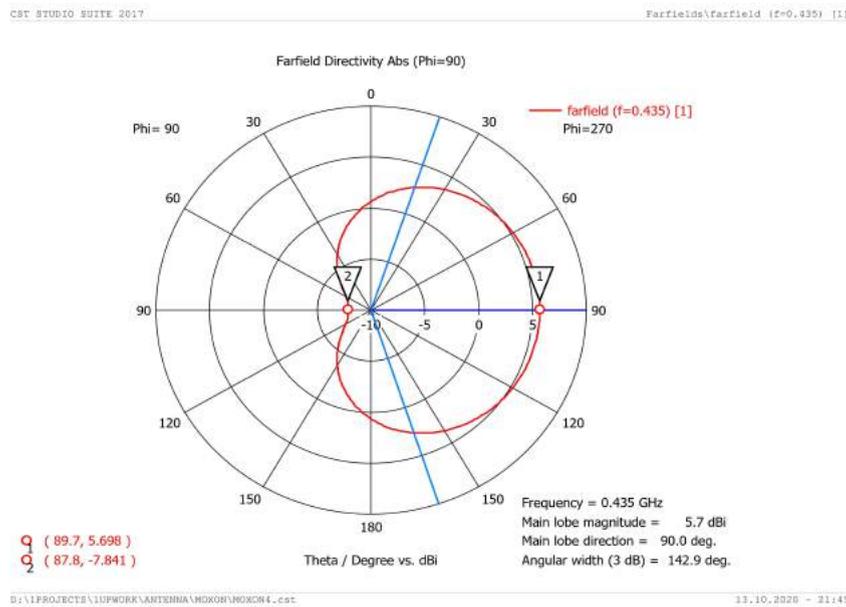


Figure 9b

VI. A 2.4 GHz FREE SPACE MOXON ANTENNA

The total length of a dipole antenna at 2450 MHz is estimated as

$$L_o [\text{mm}] = \frac{150k}{f_{\text{GHz}}} = \frac{150 \times 0.9232}{2.45} = 56.52 [\text{mm}].$$

The Moxon antenna was modeled as 0.036 mm thick copper lines in free space. Figure 10 shows the designed antenna. Let us start with a 0.2

folding ratio and optimize the antenna dimensions to maximize the insertion loss at 2450 MHz. Being a time / frequency domain electromagnetic simulator that indirectly extracts radiation patterns from simulation results, the CST Microwave Studio cannot take radiation pattern parameters as optimization goals. We have optimized for maximum insertion loss around the resonance frequency. The optimization variables were the dipole arm width, the dipole arm length, the folding ratio, the gap

between the dipole arm and the reflector and the reflector depth. The optimization for maximum resonance insertion loss enhanced all the antenna performance parameters. The S11 of the optimized antenna is shown in Figure 11.

Figure 12a shows the electric field intensity distribution of the free space Moxon antenna. In this figure we can see that the field peaks lie at the dipole edges and that the electric field is

minimum at the dipole center. The same phenomenon can be observed at the reflector: The electric field intensity is minimum at the reflector center. When the electric field display is animated, it is noted that the field starts from the dipole, travels to the reflector where it is reflected back and radiated to the negative y direction. In this way the reflector enhances the front radiation and, consequently, the radiation efficiency, and the main lobe antenna gain.

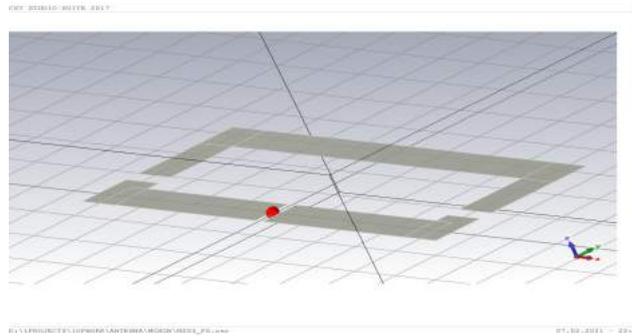


Figure 10

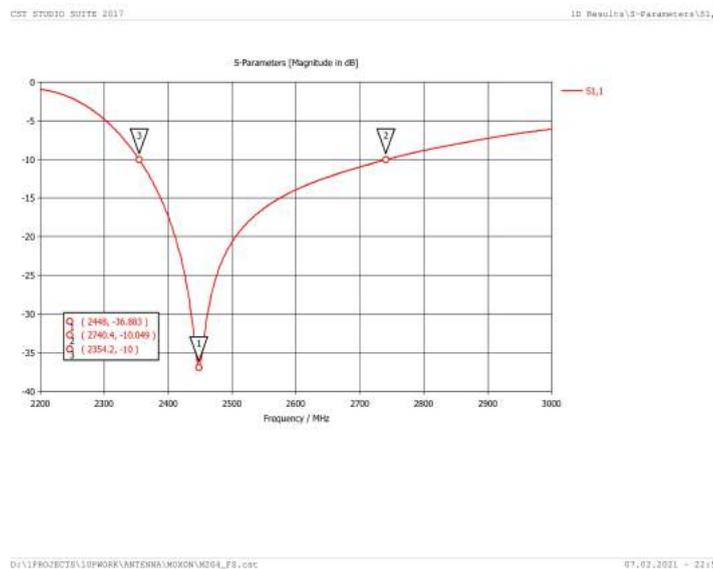


Figure 11

If we observe the electric flux lines in Figure 12b, we can see that they start at one dipole edge and end at the other edge as expected. Another group of flux lines start at the dipole edge and ends at the reflector edge, while a third group of flux lines go through the gap between the dipole and the reflector. It can be noted that the 3D electric field flux lines pass outside the horizontal plane where the metallic lines of the antenna lie. The most

important remark is that no flux lines pass at the geometric centerline of the antenna.

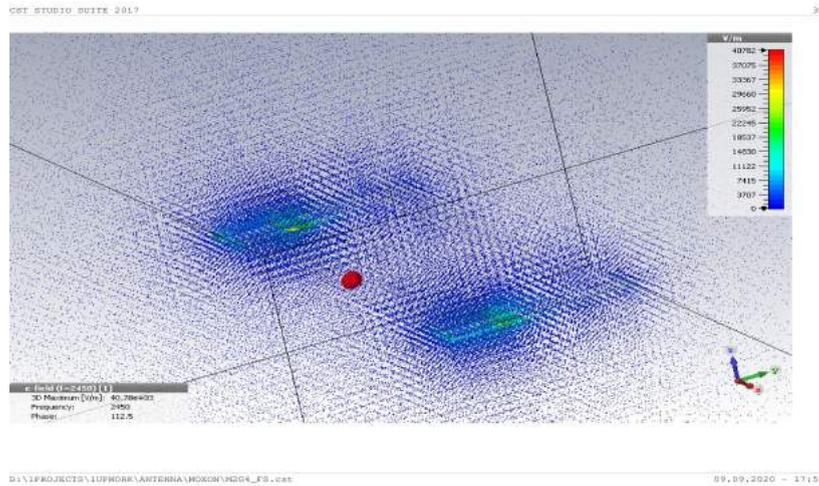


Figure 12a

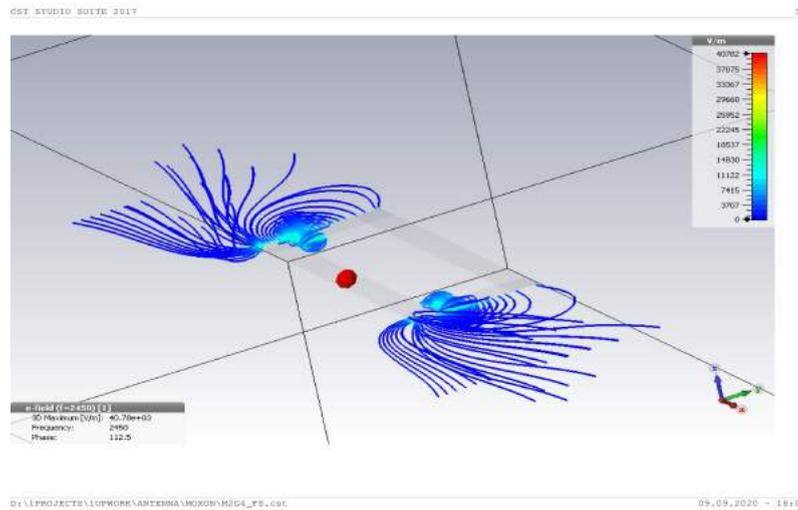


Figure 12b

Figure 13a shows the 3D antenna gain pattern of the optimized free space 2.4 GHz Moxon antenna at 2.5 GHz. We can note that the antenna gain in the negative y direction is 5.562 dB, while in the positive y directions it decreases to about -11 dB. This will be seen more clearly in the 2D antenna plot (Figure 5). The antenna has a good radiation efficiency (-0.01011 dB) and an excellent total efficiency (-0.008993 dB). Figure 13b shows the 2D radiation pattern plot; where it is very clear the absence of any back or side lobe. We can measure the front-to-back ratio = $5.562 - (-11) = 16.562$ dB.

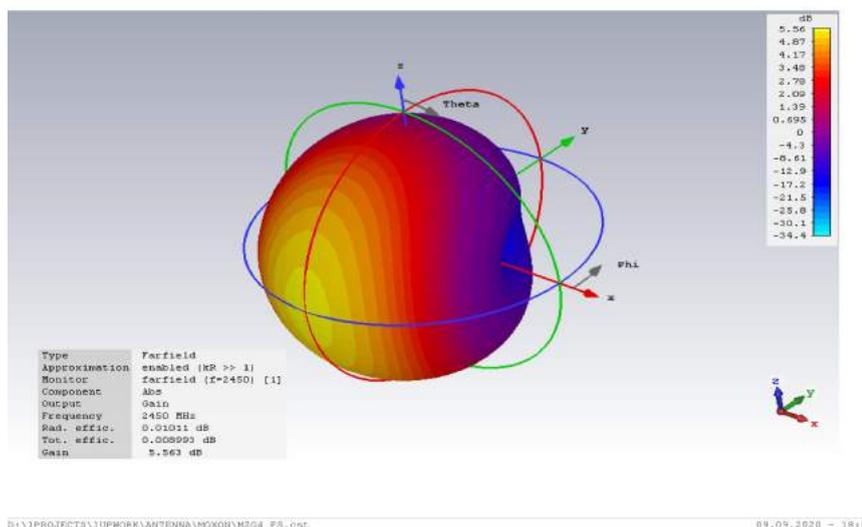


Figure 13 a

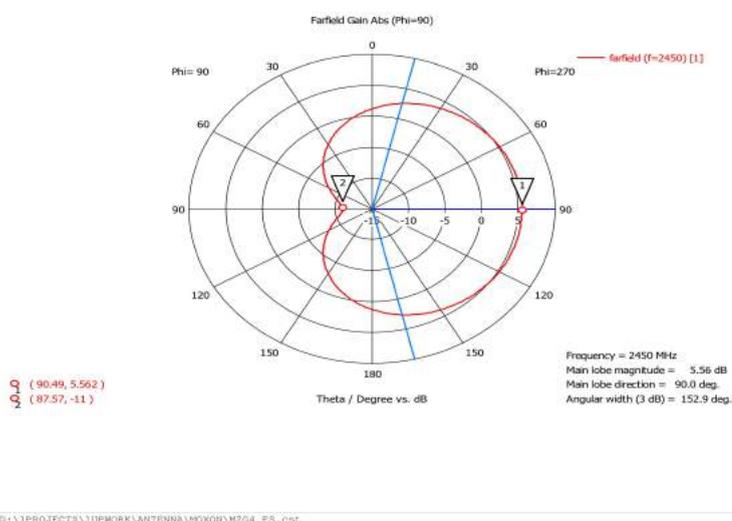


Figure 13 b

VII. 2.4 GHz MOXON ANTENNAS ON TWO DIFFERENT SUBSTRATES

A Moxon antenna was designed as printed copper lines on a 1.6 mm thick TACONIC HT-1.5 substrate with a 2.35 dielectric constant and a 0.0025 dissipation factor.

The first simulation showed an acceptable match and a shifted resonance frequency. The optimization resulted in a well matched antenna,

resonating at 2440.5 MHz with a peak return loss of 42 dB and 366 MHz bandwidth. The S11 of the original and optimized antenna are shown in Figure 14. The Moxon antenna was re-designed and optimized as printed copper lines on a 1.6 mm thick FR4 with a 4.3 dielectric constant and a 0.025 dissipation factor. The frequency response of the optimized FR4 antenna is shown in Figure 15.

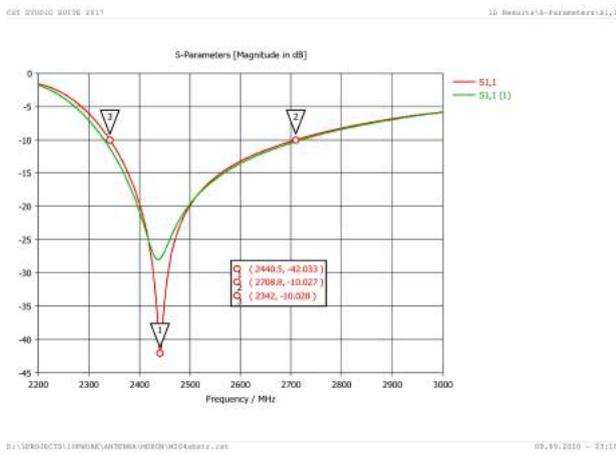


Figure 14

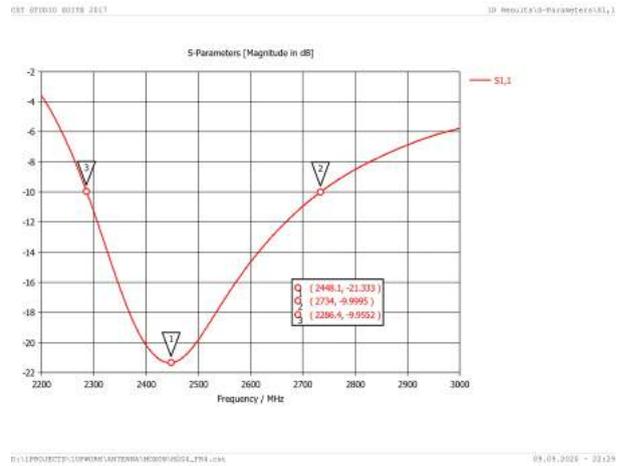


Figure 15

The far field 3D patterns of the two antennas are shown in Figures 16 and 17 respectively, while the 2D patterns are shown in Figures 18 and 19.

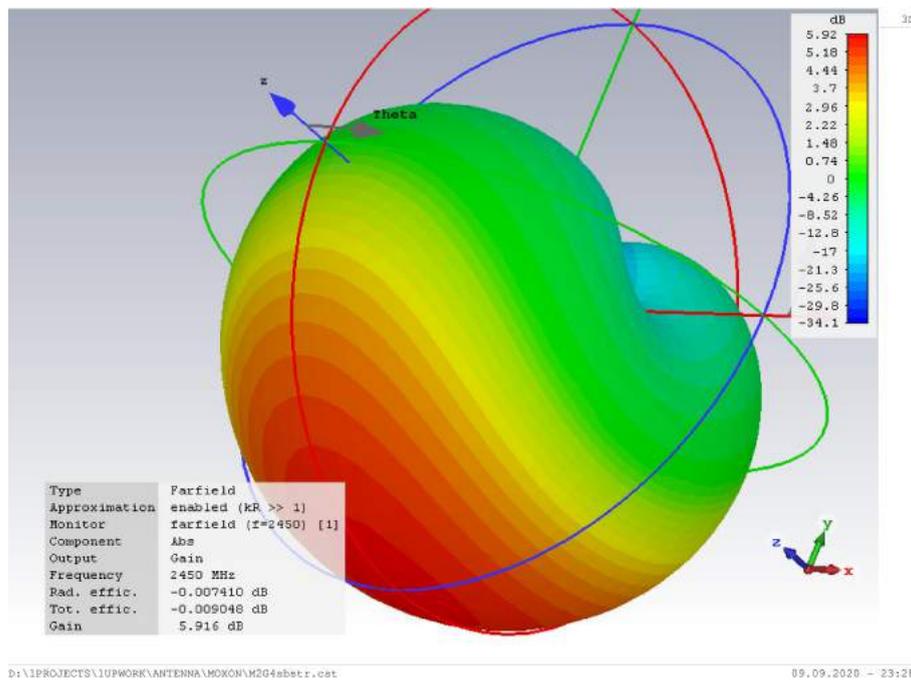


Figure 16: 3D Pattern of the HT-1.5 antenna

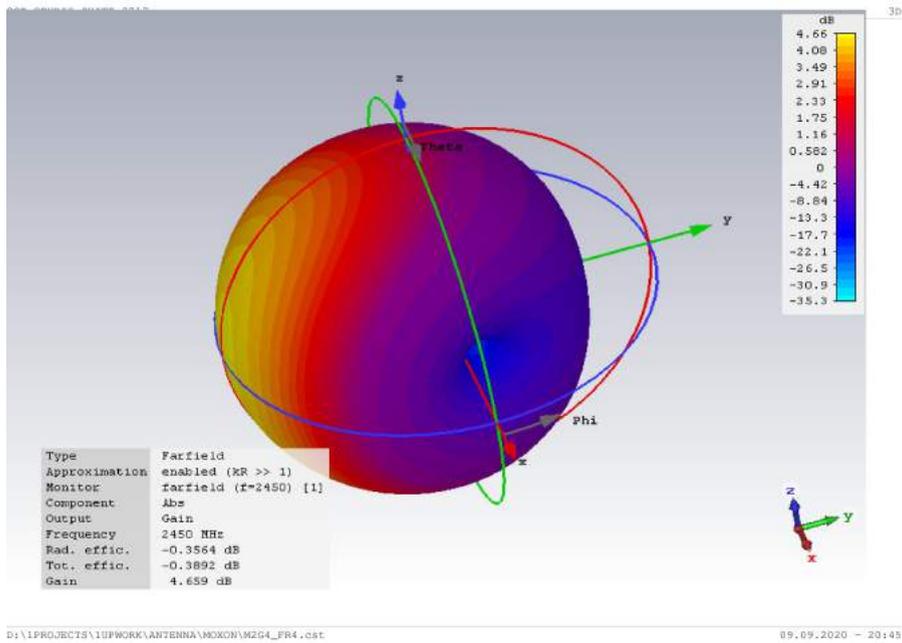


Figure 17: 3D Pattern of the FR4 antenna

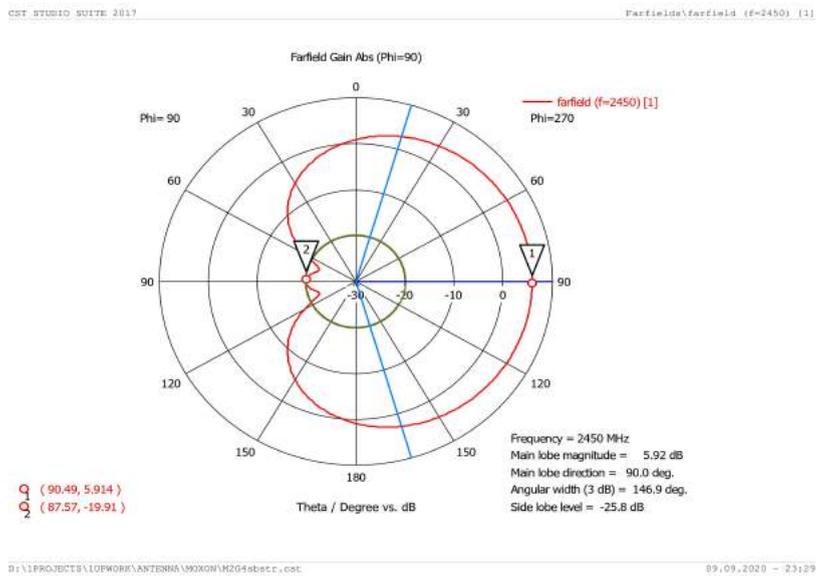


Figure 18: 2D Pattern of the HT-1.5 antenna

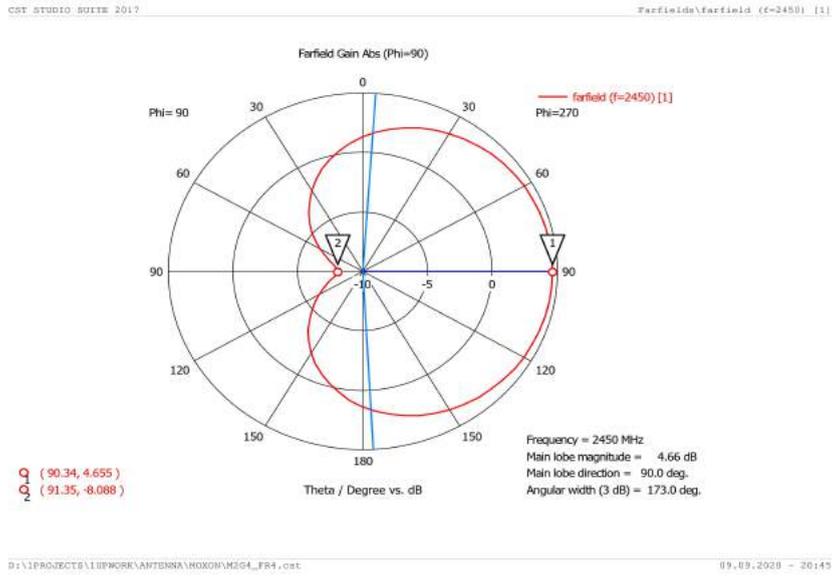


Figure 19: 2D Pattern of the FR4 antenna

VIII. EFFECT OF DIELECTRIC CONSTANT ON THE ELECTRIC FLUX

The electric field flux lines of printed Moxon antenna for three different dielectric constant values are displayed with equal scales in Figure 20 (a for free space, b for TH-1.5 with $\epsilon_r = 2.35$ and c for FR4 $\epsilon_r = 4.3$).

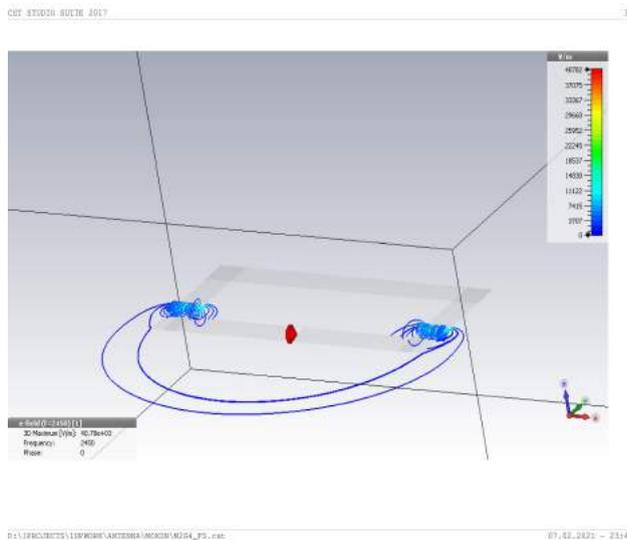


Figure 20a.

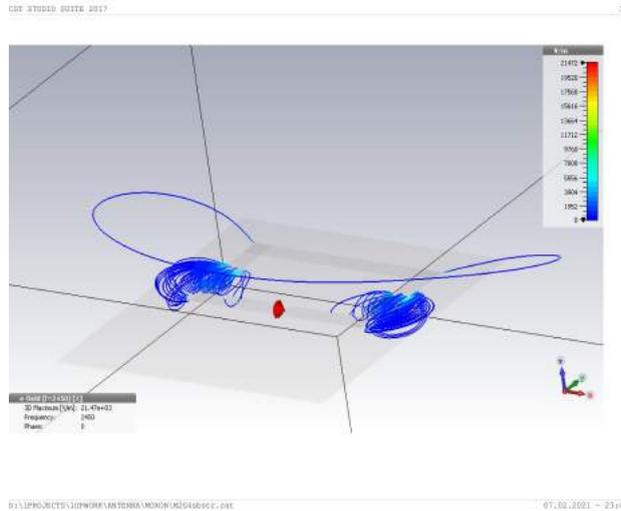


Figure 20 b

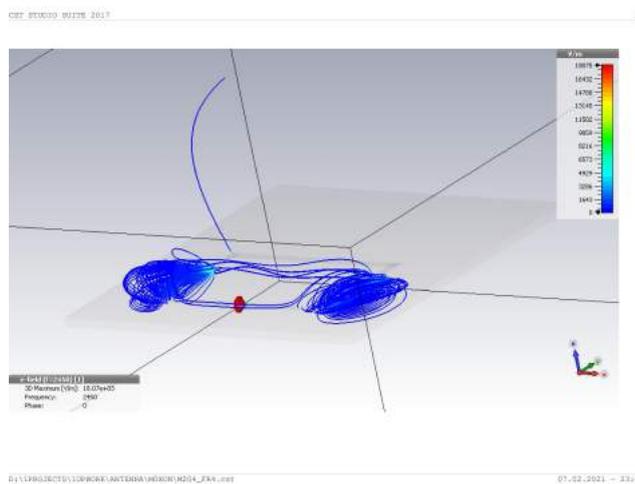


Figure 20 c

it can evidently be seen that increasing the dielectric constant concentrates electric flux lines in a smaller volume. We can expect that a 10.2 dielectric constant substrate would shrink the electric field to a smaller volume than that of the FR4 Moxon antenna. This conclusion will help to locate metallic bodies in the vicinity of a printed Moxon antenna without affecting its performance.

IX. COMPARISON OF ANTENNAS ON DIFFERENT SUBSTRATES

The following table summarizes the antenna performance parameters of 2.4 MHz Moxon

antennas designed and optimized on different substrate materials.

The free space Moxon antenna with 0.036 mm copper thickness is only considered for reference. It cannot be practically implemented. The actual comparison is between the HT-1.5 and FR4 substrates.

TABLE 1

DIELECTRIC		FREE SPACE	TACONIC HT-1.5	FR4
Dielectric constant		1	2.35	4.3
Resonance frequency	GHz	2.45	2.4405	2.48
Bandwidth	MHz	386	366	448
Radiation Efficiency	dB	-0.01011	-0.0047	-0.3564
	%	99.77	99.89	92.12
Total Efficiency	dB	-0.008993	-0.009	-0.3892
	%	99.79	99.79	91.428
Maximum Gain	dB	5.562	5.916	4.655
Front-to-back Ratio	dB	16.562	25.826	12.743

Although the optimized HT-1.5 antenna has a higher radiation efficiency, a higher total efficiency, a higher maximum gain and a much higher front-to-back ratio than the optimized FR4 antenna, the corresponding performance parameters of the optimized FR4 antenna are still very good. If we consider its wider bandwidth and much smaller price, we would recommend the FR4 for building printed Moxon antennas in the ISM 2.4 GHz frequency band.

X. CONCLUSION

The front-to-back ratio is mainly affected by the dipole-reflector separation. The antenna resonance frequency is mainly controlled by the total length of the folded dipole. However, it can be affected by the reflector dimensions. Special attention should be paid to adjust the resonance frequency and maximize the in-band return loss, the bandwidth and the radiation and total efficiencies. All these performance parameters can be affected by the geometric parameters of the reflector and the folding ratio of the dipole. Optimizing the antenna dimensions for maximum resonance return loss may enhance all its performance parameters, such as bandwidth, beamwidth, radiation and total efficiencies, gain and front-to-back ratio.

In a printed Moxon antenna, the substrate parameters also affect the antenna performance.

Increasing the dielectric constant compresses the electric flux lines to smaller volumes and makes it easier to locate metallic bodies in the antenna vicinity without degrading its performance.

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