TELKOMNIKA, Vol.16, No.6, December 2018, pp.2588~2596
ISSN: 1693-6930, accredited First Grade by Kemenristekdikti, Decree No: 21/E/KPT/2018
DOI: 10.12928/TELKOMNIKA.v16i6.10193

Different Multilayer Substrate Approaches to Improve Array Antenna Characteristics for Radar Applications

N. Chater*, T. Mazri, M. Benbrahim
Laboratory of Electrical and Telecommunication Engineering,
National School of Applied Sciences, Kenitra, Morocco
*Corresponding author, e-mail: nadiachater1992@gmail.com

Abstract

The aim of this paper is to investigate deeply in multi-layer substrate technique as a way of improving the characteristics of patch array antenna for electronic scanning radar application. The basic array antenna consists of 8 patches mounted on a FR-4 substrate and operating at 3 GHz frequency. The feeding technique is microstrip technology. This structure has some disadvantages as a poor gain and a narrow bandwidth. In fact, the obtained gain value does not exceed 7 dB which could be explained by the lossy nature of the FR4 substrate. On the other side, the narrow bandwidth is caused by the microstrip limitations. For this reason, the technique of multi-layer substrate is proposed in this paper. Many approaches are investigated and the distance between the layers is studied. The design and simulations of each approach are performed under the tool Advanced Design System of Keysight Company. A comparison between simulation results of all approaches including simulation results of the basic array antenna will be analyzed.

Keywords*: multi-layer substrate, patch array antenna, electronic scanning radar, advanced design system, gain, bandwidth*

1. Introduction

Existing mechanical scanning methods are inherently slow and require large amounts of power in order to deal with high speed maneuvering targets. With electronic scanning, the radar beams are positioned almost instantaneously and completely without the inertia, time lags, and vibration of mechanical systems [1]. Electronic scanning radars use array antennas which by combining their radiation properties help to increase gain value in a particular direction. In many applications it is desirable to use phased array antennas, especially in aviation and spatial applications. The antenna type could be radiating slots, dipoles, horn antennas, patch antenna, etc. In our case, for electronic scanning radar application operating at 3 GHz frequency, we are based on an array antenna using microstrip technology which is already presented in a previous work [2]. In fact, microstrip antennas have attractive features of low profile, light weight, easy fabrication, and conformability to mounting hosts which make this type of antennas vastly used in the literature [3].

Besides the advantages of microstrip antennas, they inherently have a narrow bandwidth knowing that bandwidth enhancement is usually demanded for practical applications [3]. In addition to that, the choice of the substrate has a big impact on the antenna efficiency. In our work, the low cost but lossy substrate FR-4 is used. To overcome these disadvantages, a number of techniques have been proposed. A previous work investigates some of the different techniques and makes the comparison between them. In order to improve the array antenna characteristics, this paper will focus on using multilayer substrate technique. Different approaches will be investigated along this article. The paper is organized as follows: section 2 presents briefly the basic array antenna design and simulation results. Section 3 is divided into 3 parts. The first part introduces the first approach of multi layers substrate which is composed of 2 layers of FR-4 separated by air gap. The second part presents the approach of using 2 layers of FR-4 separated by foam material and the third part describes a single layer of FR-4 superposed on a foam dielectric. Section 4 presents a comparison between the approaches and finally section 5 draws the conclusion and the future works.

Received June 3, 2018; Revised August 28, 2018; Accepted October 24, 2018

Related works

The bandwidth and the gain are considered as important characteristics of the antenna. They can be improved significantly by applying techniques already mentioned in the literature [4]. This section presents some of the interesting papers which deal with the improvement of the antenna characteristics by using the multilayer substrate technique. In [5], a multiple metal back reflector is proposed for a wideband slot antenna. In [6], a metallic cavity shaped is used as a reflector with a magnetoelectric dipole antenna; the proposed antenna exhibits a high gain with high F/B in the operating frequency range with relatively large dimensions. But in [7], replacing metal with substrate as a reflector is presented to improve the F/B radiation with aperture coupled antennas. In [8], the antenna is constructed using double-stacked substrate with low dielectric constant. In [9], a second flame retardant layer (FR-4), coated with an annealed copper of 0.035 mm at both sides is applied for a single microstrip antenna, with an air gap separating both layers. In [10], an air gap is inserted between radiating element and the ground plane in order to increase the efficiency and to decrease the high substrate loss.

In this paper, the multilayer substrate technique will be developed by using different approaches mainly inspired from the propositions mentioned above. First, an extra layer of FR-4 will be added separated by an air gap. Afterwards, in order to facilitate the manufacturing process, a layer of foam will replace the air gap and thus avoids the use of vias. The last proposition consists of keeping only one FR-4 layer superposed on a foam dielectric. It permits to reduce the number of layers. The multilayer substrate technique will be developed in this paper into many approaches in order to optimize the performance of the basic array antenna.

2. Basic Array Antenna

2.1. Design

The basic array antenna is already presented in a previous work [2]. The design consists of eight patches using microstrip feeding. This technique permits to get the feed etched on the same substrate than the structure and get as a consequence a planar design. The radiating elements are equipped with notches for impedance matching and are mounted in parallel on FR-4 substrate with the following characteristics: (epsilon=4.3, h=1.55mm, Tgδ=0.02, copper thickness=0.035mm).Quarter wave transformers are used to ensure the division of power between patches. They are $\frac{\lambda}{4}$ microstrip impedance transformers used for impedance matching in order to minimize the reflected energy. Figure 1 shows the array antenna design and Table 1 presents its dimensions.

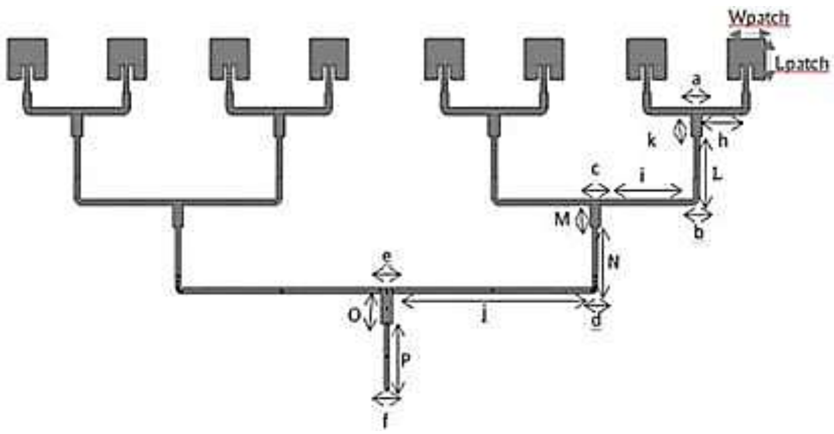

Figure 1. Array antenna design

2.2.1. Simulation Results

The simulation results that will be studied in this paper are focused on the S11 parameter and the gain value. In our case, as illustrated in Figure 2, the S11 parameter and the bandwidth are equal successively to -17.23 dB and 160 MHz.

Table 1. Array Antenna Dimensions

Parameters	Values (mm)	Parameters	Values (mm)
a	7	I	52
b	3.5	J	115
c	6.5	K	13
d	3.5	L	29
e	6.5	M	13
f	2.5	N	39
H	25	O	15
P	45	Wpatch	20.9579
Lpatch	16.215		

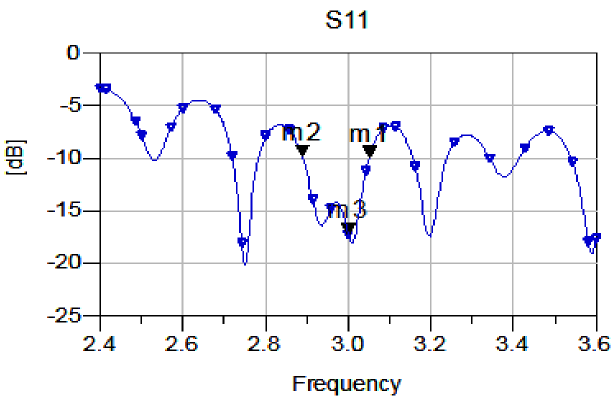

Figure 2. Array antenna S11 parameter and bandwidth

The radiation pattern form is illustrated in Figure 3. The gain and directivity values according to theta angle are illustrated in Figure 4. The gain is the product of the antenna's efficiency $E_{antenna}$ and directivity D according to (1).

$$G = Eantenna.D \qquad (1)$$

The gain and the directivity values are successively equal to 6.11dB and 15.6dB at theta 4°.

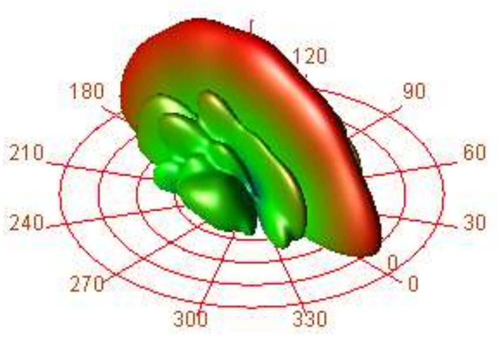

Figure 3. Array antenna radiation pattern

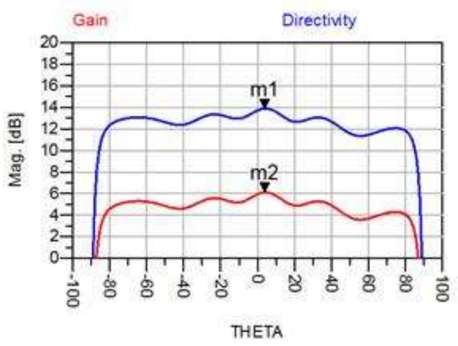

Figure 4. Array antenna gain and directivity

Based on simulation results, this design shows some weaknesses in terms of gain and impedance bandwidth. This is the main reason to think of a way to improve our structure. In this paper, the proposed solution will be using the multi-layer substrate technique. This solution will be improved by proposing many approaches and is going to be developed in the rest of the paper.

3. Multilayer Substrate
3.1. Theory of Multilayer Substrate Structure
In many applications and specifically in Radar, wide band antennas are required. The most straightforward way to improve the bandwidth is to increase the separation between the patch and the ground plane by using a thicker substrate. However, it results in the lowering of the gain due to dielectric height. In fact, the losses in a dielectric are due to the surface wave excitation resulting in lower gain and thereby reducing the efficiency. Surface waves propagate from the patch downward to the substrate and are reflected from the ground plane. More surface wave's modes exist as substrate becomes electrically thicker. A major drawback of these waves is the coupling introduced between the antennas.

Therefore, an alternative approach would be introducing an air gap between the antenna and the ground without lowering the gain. In order to calculate the total structure thickness h, we perform the sum of substrate thicknesses hd_i including the air layer; $h = \sum_{i=1}^{n} hd_i$, with n equals to the number of layers. The assumptions of Lee et al. [11] are respected in this analysis. The equivalent dielectric constant of the medium below the structure is given by Abboud et al. [12] and is illustrated in Formula 2, where ε_{re} is the equivalent dielectric constant, ε_r is the dielectric constant of FR-4 layer, H_A is the thickness of the air gap and H is the thickness of the FR-4 layer.

$$\varepsilon_{re} = \frac{\varepsilon_r\,(H+H_A)}{(H+H_A\varepsilon_r)} \qquad (2)$$

In case of air gap or foam dielectric, the relative permittivity is almost equal to one. On the other hand, instead of using a patch array antenna with low–loss expensive dielectric materials such a Teflon or Ceramic, the idea is to keep using low cost substrate and improve the gain. Meanwhile, it is known that in order to increase the gain value, a reflector plane could be used. This reflector is introduced at the back side of the antenna to reduce the back lobe. It is placed at a distance from the ground plane which creates an air gap between the substrate and the reflector. The same air gap could be a used as a way to improve the bandwidth as described above. Hence, since the use of air gap leads to a wider bandwidth and the use of the reflector at the back side of the antenna helps to improve the gain, the multilayer substrate technique seems to be a good way to improve both the bandwidth and the gain. In our work, we proposed different types and dispositions of multilayer substrate techniques. The next sections will present in detail the different propositions.

3.2. First Proposition of Multilayer Substrate
This first approach is detailed in a previous work [13]. It consists of using two layers of FR-4 separated by air gap. In fact, the second layer of FR4 acts as a reflector. It helps to get higher gain and higher front to back ratio by redirecting the propagation density from back lobe to main lobe. The FR-4 layers are spaced by vias made of Teflon PTFE (polytetrafluoroethylene). Teflon permittivity is 2.1. The equivalent dielectric constant of the medium below the structure according to the formula in the theoretical section is ε_{re}=2.38. Figure 5 shows the side view of the multilayer substrate.

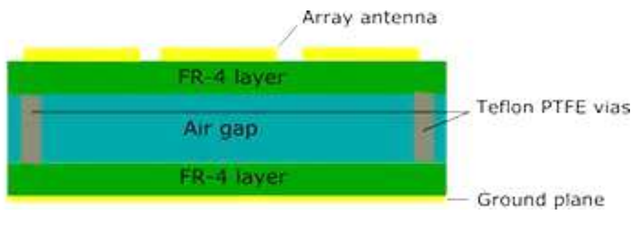

Figure 5. Multi layer substrate side view

In order to choose the air gap thickness, the structure is implemented using a variety of distance separation from the bottom FR-4 layer to the top FR-4 layer. The gap thickness is gradually varied from 0.1 mm to 10 mm. The simulation results of the gain corresponding to each air gap thickness are illustrated in Table 2.

Table 2. Air Gap Vs Gain

Air gap thickness (mm)	0.1	1	2	3	4	7	10
Gain (dB)	2.16	9.22	13.94	15.84	16.62	17.29	17.21

We deduced from Table 2 that by increasing the air gap thickness, the gain increases as well. For air gap thicknesses 7 mm and 10 mm, the gain remains the same, for this reason we will keep the smaller air gap thickness (7 mm). From the thickness 2 mm, the gain starts to represent an accurate value for an array antenna in general.In other terms, the air gap thickness value will be chosen starting from 2 to 7 mm. As a tradeoff between the design volume and the gain value, we chose to work with the air gap thickness 4 mm which corresponds to 0.04xλ_0 and which gives us a gain value of 16.62 dB. The corresponding directivity is 17.85 dB.

3.2.1. Simulation Results

Figure 6 shows the simulation results of S11 parameter and impedance bandwidth corresponding to the chosen air gap thickness 4 mm. The results show that S11 parameter at operating frequency and the impedance bandwidth are equal successively to -17 dB and 440 MHz. These results reflect that the bandwidth has increased by 278 MHz comparing to the basic array antenna.

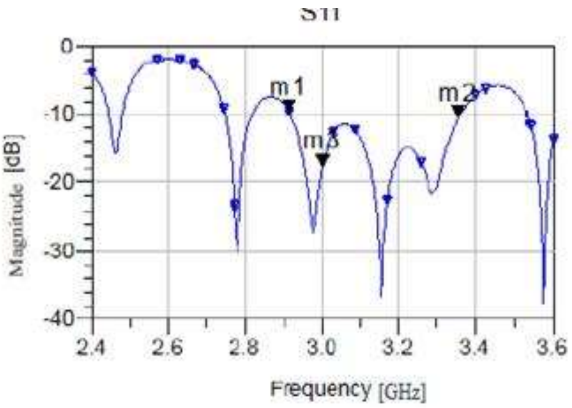

Figure 6. S11 parameter and bandwidth of the first proposition

The Figure 7 presents radiation pattern form at operating frequency for air gap thickness 4 mm.The Figure 8 shows that the gain and the directivity values are equal successively to 16.63 dB and 17.85 dB at theta 30°. The gain value has increased by 10.5 dB comparing to basic array antenna.

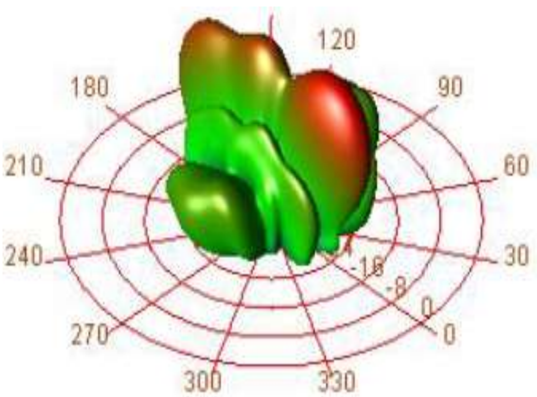

Figure 7. Radiation pattern of the first proposition

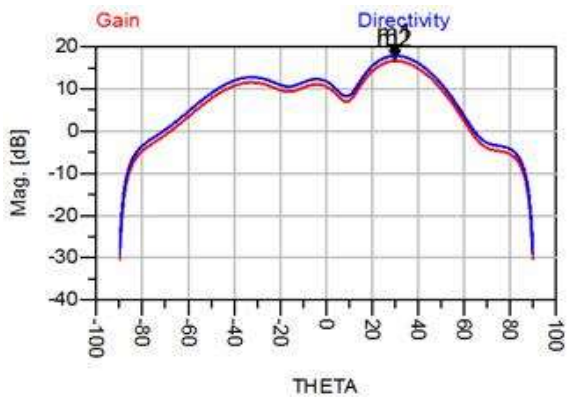

Figure 8. Gain and directivity of the first proposition

3.3. Second Proposition of Multilayer Substrate

The second approach is similar to the first one, but in this case, the air gap is replaced by another dielectric with a permittivity of 1.05. This dielectric is the foam. Another advantage of this proposition is the fact that there is no need to use vias made of teflon since a solid substrate separates the FR-4 layers. The foam material has the particularity to offer low dielectric constant (close to 1). This allows designing antennas with high efficiency. This kind of foam is composed of basic initial PVC material into which air is injected or special gas [14]. Foam-like materials are, due to their intrinsic structure, very lightweight. These materials typically exhibit low dielectric constant and loss tangent. Such properties make foams very attractive to be used as substrates for the fabrication of antennas in applications requiring light-weight, low-loss, reduced bill of materials, less mechanical complexity while preserving the electromagnetic performance [15]. The foam thickness chosen in this section has the same value as the air gap thickness 4 mm chosen in the previous section. The equivalent dielectric constant of the medium below the structure according to the formula in the theoretical section is ε_{re} =2.38

3.3.1. Simulation Results

Figure 9 shows the simulation results of both S11 parameter and impedance bandwidth. It shows a value of S11 parameter and a bandwidth which are equal successively to -12 dB and 428 MHz.

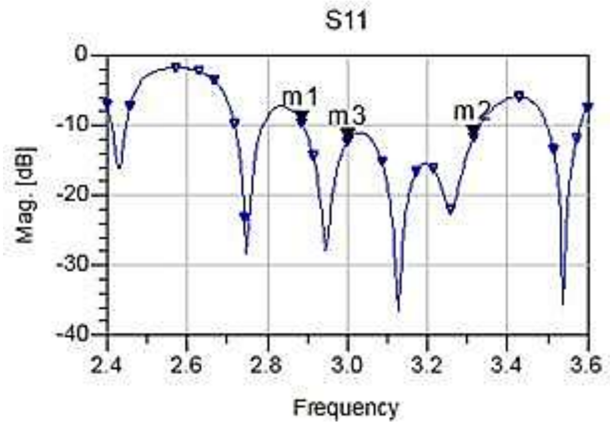

Figure 9. S11 parameter and bandwidth of the second proposition

Figure 10 shows the form of the radiation pattern at 3 GHz. Figure 11 illustrates both the gain and the directivity values. The gain is equal to 16.5 dB and the maximum directivity is equal to 17.76 at theta 31°.

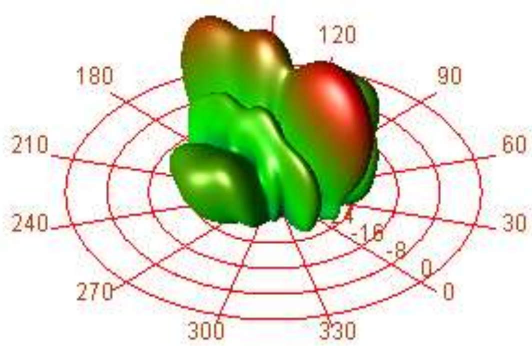

Figure 10. Radiation pattern of the 2nd proposition

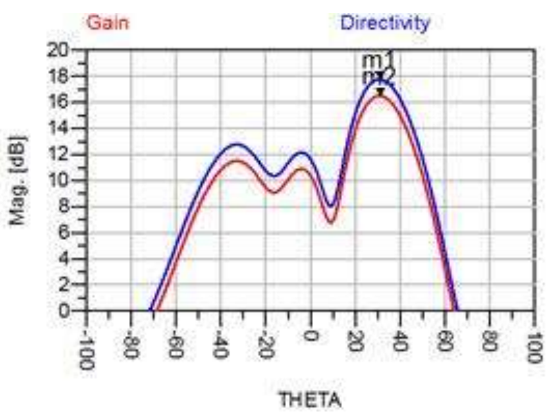

Figure 11. Gain and directivity of the 2nd proposition

3.4. Third Proposition of Multilayer Substrate

This section proposes a different disposition of multi-layer substrate technique in terms of number of layers. In fact, this proposal presents only 2 layers; the first one consists of FR-4 substrate and the second one consists of foam material. The thickness of foam layer remains the same as the previous paragraph (4 mm).

The advantage of this proposal is the number of layers which is reduced while keeping the use of low cost substrates. This time, the equivalent dielectric constant of the medium below the structure according to the formula in the theoretical section is ε_{re}=1.64. The array antenna dimensions have been slightly modified in order to realize impedance matching and antenna tuning.

3.4.1. Simulation Results

The simulation results in Figure 12 show that the S11 parameter is equal to -11.525 dB and the bandwidth is equal to 375 MHz.

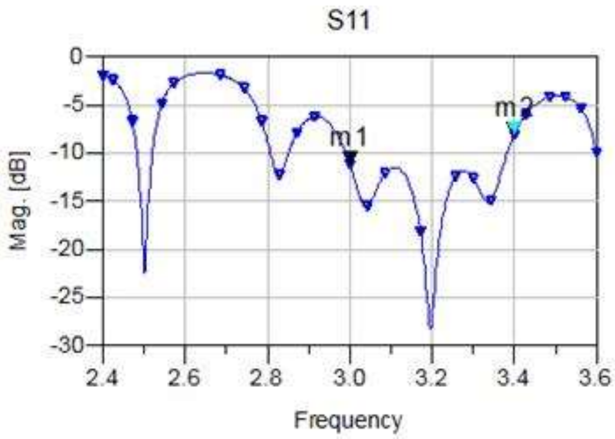

Figure 12. S11 parameter and bandwidth of the 3rd proposition

The radiation pattern form is shown in Figure 13. The gain and directivity are shown in Figure 14 The gain is equal to 16.3 dB and the maximum directivity is equal to 17.86 dB at theta 25°.

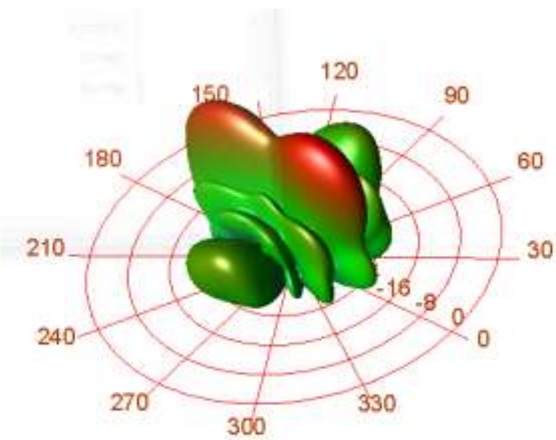

Figure 13. Radiation pattern of the 3rd proposition

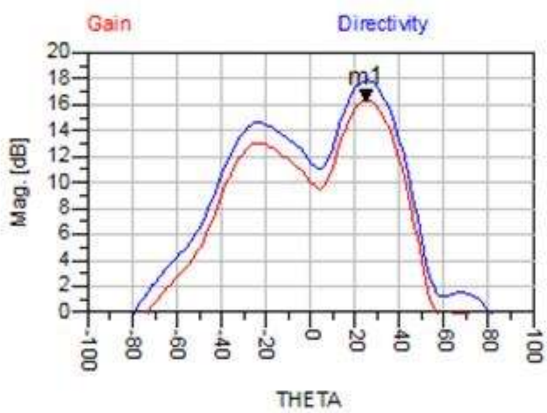

Figure 14. Gain and directivity of the 3rd proposition

4. Comparison And Discussion

The previous sections present different propositions to improve array antenna characteristics using multilayer substrate technique. The design and simulations are done under ADS tool. Table 3 compares the different simulation results related to the gain and the bandwidth for the basic array antenna and also the proposition of multi layer substrate technique.

Table 3. Comparison between Different Propositions

Design	Gain (dB)	Bandwidth (MHz)
Basic array antenna	6.11	160
FR4 layer+ air gap+ FR4 layer	16.62	440
FR-4 layer + foam+ FR4 layer	16.5	428
FR4 layer +foam	16.17	375

Three dispositions were investigated. The first one consists of using two FR-4 layers spaced by Vias made of Teflon, the second one consists of using 2 FR-4 layers separated by a layer of foam and the third one consists on using a single layer of FR-4 superposed on a foam layer. Among these propositions, the optimized technique in terms of number of layers and industrial process is the third one. From Table 3, we can notice that the gain and the bandwidth values remain almost the same for all the three propositions since the difference could be neglected. In general, the gain has improved by 10 dB and the bandwidth has increased by minimum of 215 MHz.

To sum up, for all approaches, good results in terms of gain and bandwidth were obtained with small differences and meanwhile, the third approach proposes an optimized number of layers. The available evidence seems to suggest that the best disposition to be adopted is the third one which consists of using a layer of FR4 superposed on a layer of foam. Nevertheless, in the third approach, S11 parameter is equal to -11 dB at resonance frequency. This value is less than -10 dB which ensures the resonance. Nevertheless, it is preferable to optimize this value to ensure the resonance after the realization of the structure. The value could be explained by the fact that a decrease in the dynamic permittivity as calculated in each proposition, results in an upward shift in the resonance frequency. This flaw will be improved in a future work.

5. Conclusion

In this paper, the multilayer substrate technique was applied on a microstrip array antenna in order to enhance its characteristics. Different approaches were proposed by taking into consideration the number of layers and the nature of substrate material. The first section described briefly the basic array antenna and its simulation results. A theoretical section illustrated the reason of choosing the multilayer substrate technique and highlighted the benefits of using a layer with dielectric constant close to 1. The second section investigated the first proposition of multilayer substrate which consisted of two FR-4 layers separated by air gap and using vias as spacers. The third section described the second proposition which consisted also of two FR-4 layers but separated this time by a foam dielectric. The fourth section described the last proposition which consisted of using only a single FR-4 layer superposed on a dielectric foam. The simulation results of all these propositions have been presented and a comparison between them has been illustrated. We decided to consider the last proposition since it used reduced number of layers while keeping almost the same simulation results as the previous methods. The inconvenience of this proposition was the return loss S11=-11 dB which should be improved to get better resonance.

References

[1]. Payne, Craig M., ed. Principles of naval weapon systems. Naval Institute Press, 2006.
[2]. Chater, N., T. Mazri, and M. Benbrahim. *Design and simulation of microstrip patch array antenna for electronic scanning Radar application*. In Wireless Technologies, Embedded and Intelligent Systems (WITS), 2017 International Conference on. IEEE. 2017: 1-5.

[3]. Vijayalaxmi, S. W., and A. Sreenivasan. *Design and simulation of ircular Microstrip patch antenna*. In Innovative Mechanisms for Industry Applications (ICIMIA), 2017 International Conference on. IEEE, 2017: 548-551.
[4]. Lakrit, Soufian, Hassan Ammor, Soufiane Matah, Radouane Karli, Adil Saadi, Jaouad Terhzaz, and Abdelwahed Tribak. A new small high-gain wideband rectangular patch antenna for X and Ku bands applications. *Journal of Taibah University for Scien*ce 12. 2018; 2: 202-207.
[5]. Gao, Xueyi, Yihong Qi, and Yong-Chang Jiao. Design of multiplate back-reflector for a wideband slot antenna. *IEEE Antennas and Wireless Propagation Letters 12.* 2013: 773-776.
[6]. Ge, Lei, and Kwai Man Luk. A low-profile magneto-electric dipole antenna. *IEEE Transactions on Antennas and Propagation 60*. 2012; 4: 1684-1689.
[7]. Rao, Qinjiang, Tayeb A. Denidni, and Ronald H. Johnston. Dielectric reflector backed aperture-coupled antennas for reduced back radiation. *IEEE transactions on electromagnetic compatibility 48,* 2006; 2: 287-291.
[8]. Santosa, Cahya Edi, Josaphat Tetuko Sri Sumantyo, Katia Urata, Ming Yam Chua, Koichi Ito, and Steven Gao. Development of a Low Profile Wide-Bandwidth Circularly Polarized Microstrip Antenna for C-Band Airborne CP-SAR Sensor. *Progress In Electromagnetics Research* 81. 2018: 77-88.
[9]. Mekki, Anwer Sabah, Mohd Nizar Hamidon, Alyani Ismail, and Adam RH Alhawari. "Gain enhancement of a microstrip patch antenna using a reflecting layer. *International Journal of Antennas and Propagation*. 2015.
[10]. Singh, Surya Sevak, and Sheetal R. Bhujade. Design and evaluation of high gain microstrip patch antenna using double layer with air gap. *International Journal on Recent and Innovation Trends in Computing and Communication* 3. 2015; 3: 1678-1681.
[11]. Lee, Kai-Fong, K. Ho, and J. Dahele. Circular-disk microstrip antenna with an air gap. *IEEE Transactions on Antennas and Propagation* 32. 1984; 8: 880-884.
[12]. Abboud, F., J. P. Damiano, and A. Papiernik. A new model for calculating the input impedance of coax-fed circular microstrip antennas with and without air gaps. *IEEE Transactions on Antennas and Propagation* 38. 1990; 11: 1882-1885.
[13]. Chater, Nadia, Tomader Mazri, and Mohammed Benbrahim. *Array antenna characteristics enhancement for electronic scanning radar application: Parasitic patches and multi layer techniques*. In Intelligent Systems and Computer Vision (ISCV), 2018 International Conference on, IEEE, 2018: 1-5.
[14]. Bor, Jonathan, Olivier Lafond, Hervé Merlet, Philippe Le Bars, and Mohamed Himdi. Technological process to control the foam dielectric constant application to microwave components and antennas. *IEEE Transactions on Components, Packaging and Manufacturing Technology 4*. 2014; 5: 938-942.
[15]. Anguera, Jaume, Jean Pierre Daniel, Carmen Borja, Josep Mumbru, Carles Puente, Tiphaine Leduc, Khalid Sayegrih, and Peter Van Roy. Metallized foams for antenna design: application to fractal-shaped sierpinski-carpet monopole. *Progress In Electromagnetics Research* 104. 2010: 239-251.