Instrumental test of patch antennas manufactured for C-Band applications

Prueba instrumental de antenas de parche fabricadas para aplicaciones en la banda C

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Keywords

Antennas; communication technology; electronic equipment; engineering education; experimental methods.

Abstract

In free space, the calculated wavelength of a 5,2 GHz signal is 57,7 mm, this gives us an idea of the volume required to be occupied by a patch type antenna intended for C-band applications and some of the limitations of relying on a traditional manufacturing process. Considering the interest of competing in the current technological market, it is important to obtain experimental results of the performance of the product that can be obtained with the suggested minimum of resources. Patch antenna prototypes require experimental verifications regardless of the manufacturing process that was carried out, so this work presents a clear methodology that includes calculations, design parameters such as characteristic impedance, acid-based manufacturing, experimental setup with a signal generator and a spectrum analyzer, tests with their respective measurements considering quantitative and qualitative approaches, compatibility with commercial C-band equipment and evaluation of results, providing an experimental comparison of different prototypes of designs based on simple patch antennas and array antennas.

Palabras clave

Antenas; tecnología de comunicación; equipos electrónicos; educación en ingeniería; métodos experimentales.

Resumen

En el espacio libre, la longitud de onda calculada de una señal de 5,2 GHz es de 57,7 mm. Esto nos da una idea del volumen requerido para ser ocupado por una antena tipo parche destinada a aplicaciones en la banda C, y algunas de las limitaciones de depender de un proceso de fabricación tradicional. Considerando el interés de competir en el mercado tecnológico actual, es importante obtener resultados experimentales del rendimiento del producto que se puede obtener con el mínimo de recursos sugerido. Los prototipos de antenas de parche requieren verificaciones experimentales independientemente del proceso de fabricación que se haya llevado a cabo, por lo que este trabajo presenta una metodología clara que incluye cálculos, parámetros de diseño como la impedancia característica, fabricación basada en ácido, configuración experimental con un generador de señales y un analizador de espectro, pruebas con sus respectivas mediciones considerando enfoques cuantitativos y cualitativos, compatibilidad con equipos comerciales de la banda C y evaluación de resultados, proporcionando una comparación experimental de diferentes prototipos de diseños basados en antenas de parche simples y antenas de matriz.

Introduction

Nowadays, digital communications require greater bandwidths and operating bands in the order of GHz. Fortunately, this allows the use of compact antennas, even the ones that take advantage of designs that improves the gain and width of the basic antenna by applying stacked patch topology with printed circuit boards or PCBs [1]. Mass production ensures profitability in this type of product, but there are also prototyping stages that can require less complex and expensive methods: alternatives that may be attractive to researchers and engineers from

Central American countries. The research questions arise, what models and design rules must be respected as a minimum for the basic functional designs of patch antennas? what kind of experimental results can be obtained with this type of products?

Methodology

The applied methodology consists of the typical steps to follow for any electronic or telecommunications prototype:

a) Calculation and theoretical design.
b) Verification of the design using software simulators.
c) Manufacture of prototypes.
d) Experimental results: experimental set-up and commercial compatibility tests.

Calculation and theoretical design

The basic design of a patch antenna like the one in Figure 1 consists of calculating its width *W* and length *L*, slots methods with x_0 and y_0 dimensions are used for impedance matching.

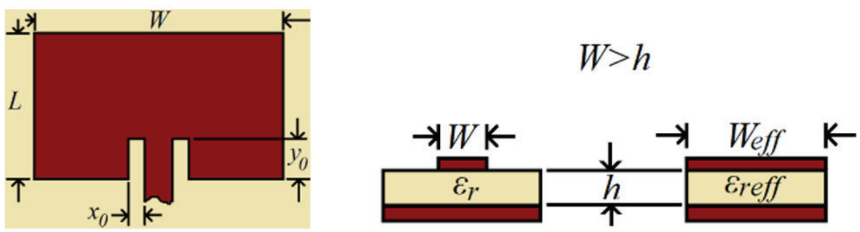

Figure 1. Patch antenna with an inset feed and its planar waveguide model.

Two models are considered here for the design: transmission line model and cavity model [2], [3]. For an efficient radiator, a practical *W* that leads to good radiation efficiencies [2] is given by (1) where *fr* is the resonance frequency, *c* is the free-space velocity of light and ε_r is the relative dielectric constant of the substrate, considered 4.5 for FR4.

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{1}$$

By the cavity model shown in Figure 1, the effective width W_{eff} and the effective relative dielectric constant ε_{reff} are calculated for its planar waveguide model. The constant ε_{reff} can be calculated by (2), where *h* is the height of the substrate, considered 1.6 mm for the local PCBs. The patch length *L*, suggested that $1 < W/L < 2$ [3], is given by (3). Figure 2 summarizes the sizing that would be obtained at different f_r.

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{w}\right]^{-1/2} \tag{2}$$

$$L = \frac{c}{2f_r\sqrt{\varepsilon_{reff}}}$$ (3)

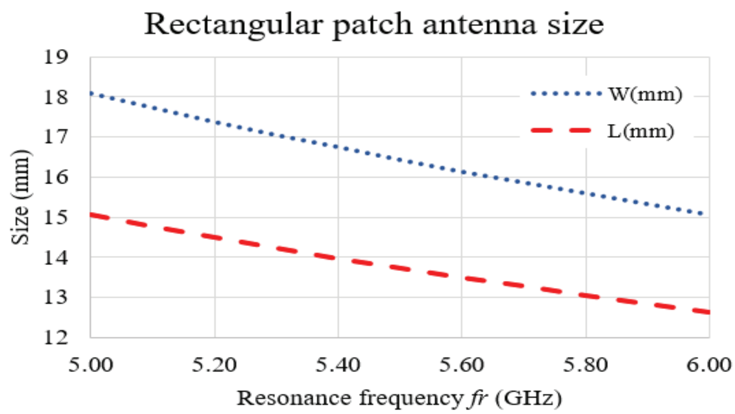

Figure 2. Calculated rectangular patch antenna sizing for h = 1.6 mm and ε_r = 4.5.

For inset feed, the input characteristic impedance of the patch antenna Z_{in} should match to the microstrip line characteristic impedance that feeds the patch. If we don't take into account mutual effects between slots and only a real resonant input impedance R_{in}, we can calculate it from the slots conductance G_1 and G_2 [2] as shown in (4) where λ_0 is the wavelength and k_0 is the phase constant ($k_0 = 2\pi/\lambda_0$), both in free space and at the resonant frequency.

$$Z_{in} = R_{in} = \frac{1}{(G_1 + G_2)} = \frac{1440\lambda_0}{W(24 - (k_0 h)^2)}$$ (4)

So, the inset feed point distance y_0 is obtained by (5) and Z_c is the characteristic impedance of the microstrip that will feed the patch antenna.

$$y_0 = \frac{L}{\pi} arccos\left(\sqrt{\frac{Z_c}{R_{in}}}\right)$$ (5)

From the single patch antenna, patch antenna arrays can be formed. This array can be fed by microstrips and λ/4 impedance microstrip transformers or even connecting one patch in series with another using microstrips [4].

Software design verification and microstrip line

Software-aided design is also considered for the fabrication of patch antennas. One of the software considered is: Matlab R2022b Update 4 (9.13.0.2166757), 64-bit (win64), January 11, 2023. The simple patch antenna design suggested by this software tool, to be operated at 5.2 GHz, consists of $W = L$ = 26 mm, that is $W = L \approx \lambda_0/2$; this leads to y_0 = 8 mm for a Z_c = 50 Ω, but the effects of the substrate FR4 are not considered yet.

Evaluating (2) using, for example, W = 15 mm leads to ε_{reff} = 3.91 but with a W = 30 mm leads to ε_{reff} = 4.11. In both cases, the effective relative dielectric constant is not affected as much by the value of these W. Wavelength has a larger impact as a function of the dielectric constant: at 5.2 GHz in free space λ_0 = 57.7 mm but λ = 28.5±0.5 mm when we use the previous W and ε_{reff}. In fact, re-evaluating (4) and (5) using the W values of 15 mm or 30 mm and ε_{reff}, keeping $W = L$, gives y_0 = 3.75±0.3 mm for Z_c = 50 Ω. The calculator included in the software KiCad ((c)1992-2022 KiCad Developers Team, version 6.0.6) indicates that a 3 mm width microstrip would be appropriate to obtain a characteristic impedance Z_c = 50 Ω at 5.2 GHz.

Prototyping

The use of local commercial PCBs with FR4 substrate, provides a low-cost but compatible alternative even to mmWave antennas [1]. Although a CNC machine allows a more reliable process, is not useful for removing considerable amounts of copper, so the prototype patch antennas were manufactured with the help of a solution of muriatic acid with hydrogen peroxide to remove copper from the PCB. The limitations of this process consist mainly in the fact that too narrow microstrip cannot be manufactured and a micrometer precision cannot be achieved. The manufactured prototype patch antennas appear in Figure 3 and Figure 4, their dimensions appear in the Table 1.

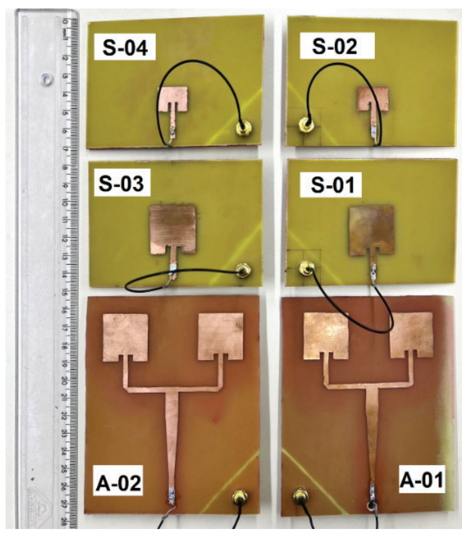

Figure 3. Manufactured patch antennas, simple (S-01, S-02, S-03, S-04) and in arrangement of two (A-01, A-02).

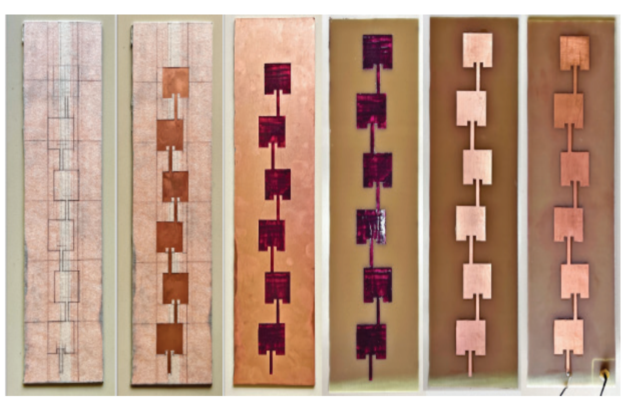

Figure 4. Manufacturing sequence shown for the A-03 patch antenna array (from left to right): drawing, cutting of the adhesive tape for the mold, varnish on the mold and remove the rest of the tape, use of the acid, remove the varnish.

Table 1. Prototype antenna sizes.

Antenna design	Measured patch dimensions				Number of patches
	W(mm)	L(mm)	x_0(mm)	y_0(mm)	
S-04, S-02	16.5	13.5	1.5	5	1
S-03, S-01	26	26	3	4	1
A-02, A-01	26	26	2.5	3.5	2
A-03	26	26	3	4	6

Experimental results

Experimental set-up

The methodology consists in design, simulation, manufacturing, tests, measurements and comparison of experimental measurements [5], [6], [7], [8]. The results of the tests in this work may be considered mostly from a qualitative approach as they are not carried out in an anechoic chamber. The Figure 5 and Figure 6 visually explain the set-up.

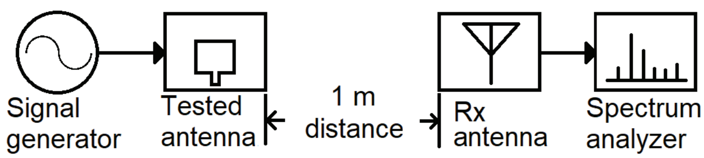

Figure 5. Scheme of the experimental set-up for the frequency sweep and the radiation pattern.

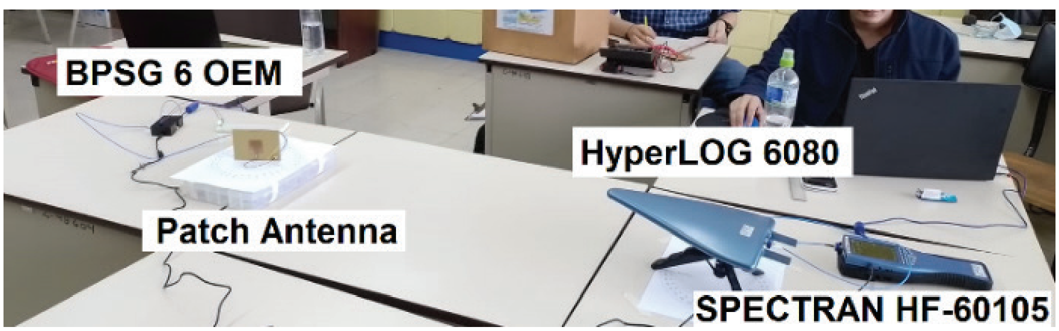

Figure 6. Experimental set up of measurements for the frequency sweep and the radiation pattern.

To empirically verify a functional distance between antennas for the tests, the AARONIA signal generator BPSG 6 OEM is used with a 5.2 GHz carrier and AM tones around 250 Hz, transmitting an AM signal through the S-03 antenna. This signal is received, demodulated, and the tones reproduced through the speaker of the AARONIA spectrum analyzer SPECTRAN HF-60105. By this way it is verified that the intensity of the signal transmitted is within the sensitivity of the spectrum analyzer. All these tests done at 5 dBm by the signal generator.

For the frequency sweep test, the patch antennas are pointed directly at the HyperLOG 6080 antenna of the spectrum analyzer. Using digital data logging, thousands of samples are taken to plot each of the curves shown in Figure 7 and Figure 8.

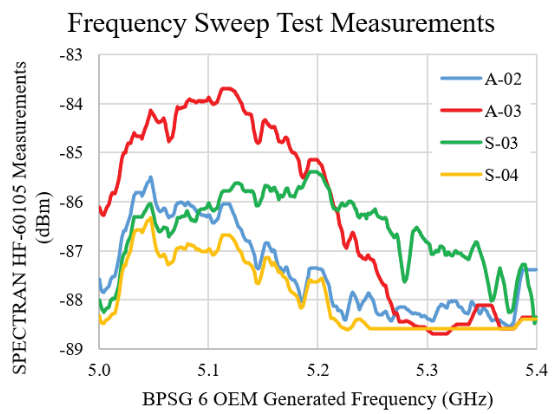

Figure 7. Frequency sweep measurements for each patch antenna.

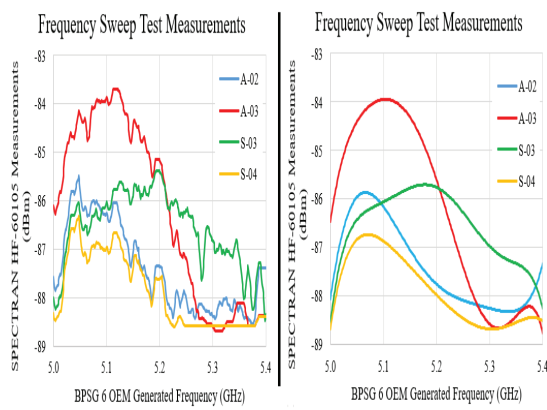

Figure 8. Frequency sweep 6th order polynomial regression for each antenna.

For the radiation patterns test, the reference axes in Figure 9 are used. Each radiation pattern measured is plotted in Figure 10, Figure 11, Figure 12 and Figure 13, as the result of overlaying the different radiation patterns obtained by each of the more than 50 frequencies per patch antenna. Each circle in the grid of radiation patterns represents a step of 10 dBm, with the center being -90 dBm and the outermost circle -40 dBm.

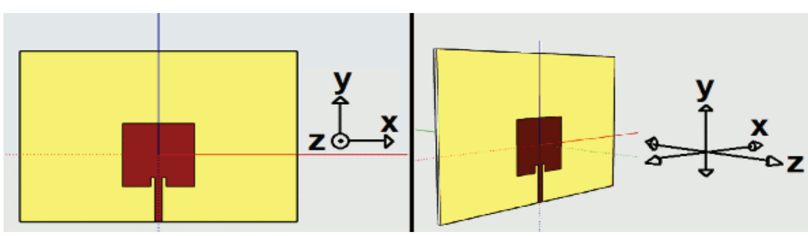

Figure 9. Reference of the x, y, z axes assigned to the patch antennas.

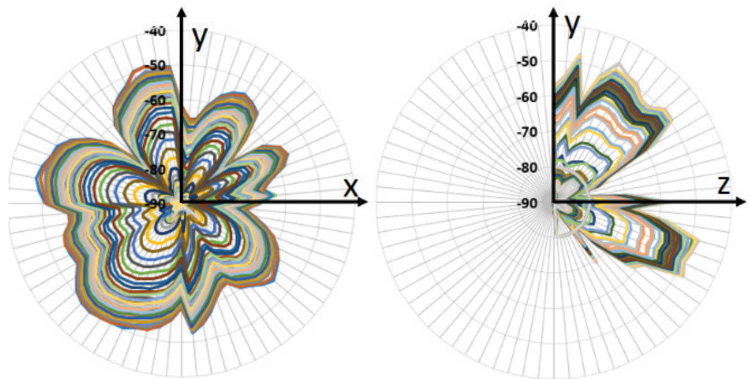

Figure 10. Measured and plotted radiation pattern of the S-04 antenna: from 5.137 GHz to 5.143 GHz. Higher gains at 5.14 GHz.

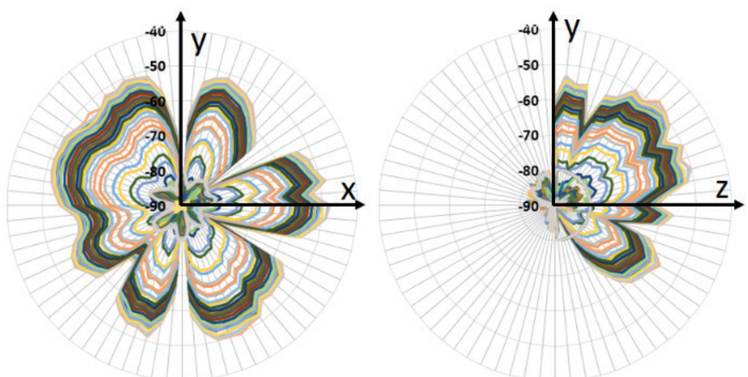

Figure 11. Measured and plotted radiation pattern of the S-03 antenna: from 5.197 GHz to 5.203 GHz. Higher gains at 5.2 GHz.

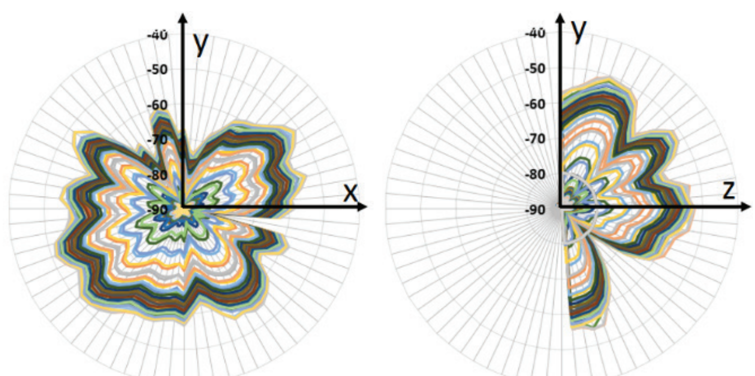

Figure 12. Measured and plotted radiation pattern of the A-02 antenna: from 5.052 GHz to 5.058 GHz. Higher gains at 5.055 GHz.

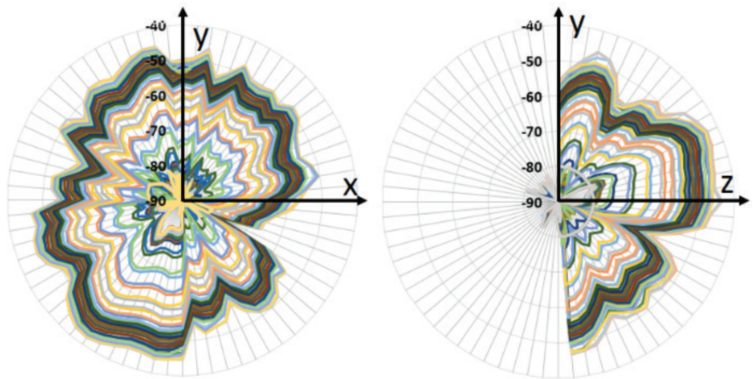

Figure 13. Measured and plotted radiation pattern of the A-03 antenna: from 5.112 GHz to 5.118 GHz. Higher gains at 5.115 GHz.

Experimental commercial compatibility

Additional antennas are used for these tests: An Ubiquiti sector antenna model LAP-120 (LiteBeam 5 AC AP, 16 dBi, 120 deg) named as LAP-01 and an Ubiquiti parabolic antenna model LBE-5AC-GEN2 (5GHz airMAX AC LiteBeam Gen2, Radio up 450+Mbps) named as LBM-01. For the experimental set-up the distance between LAP-01 and LBM-01 is 2.8 m. The tested patch antenna is set to be 3.1 m from the LAP-01 and 1.7 m from the LBM-01.

The results of using the tested patch antennas as receivers or Rx mode appears in Table 2 and shown in Figure 14, where the tested patch antenna is connected to the spectrum analyzer and it is set to a central frequency of 5.2 GHz and span of 30 MHz.

The detection of the signal by LAP-01 has even been verified when the patch antennas operate in transmission or Tx mode, that is, connected to the frequency generator as shown in Figure 15.

Table 2. Gains measured by the spectrum analyzer.

Tested Antenna Rx mode	Measurements made by the spectrum analyzer	
	LAP-01 and LBM-01 Linked	LAP-01 and LBM-01 both switched off
S-04	-60.4 ± 1.2 dBm	-86.0 ± 4.8 dBm
S-03	-65.1 ± 1.4 dBm	-88.2 ± 3.6 dBm
A-02	-67.5 ± 1.4 dBm	-87.8 ± 6.0 dBm
A-03	-74.1 ± 3.8 dBm	-89.3 ± 2.2 dBm

Figure 14. Screen capture of the measured spectrum with S-04 in Rx mode with the LAP-01 and LBM-01 linked (up) and then both switched off (down).

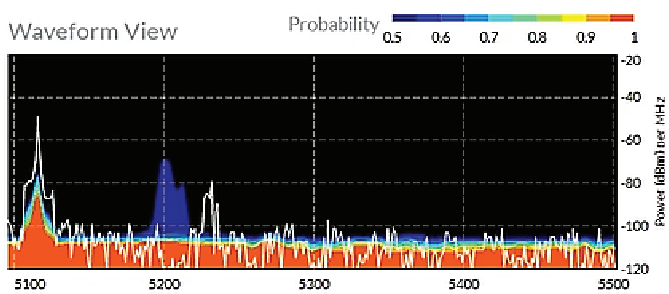

Figure 15. Screen capture of the measured spectrum by the Airview tool of the LAP-01 with S-04 in Tx mode. 5115 MHz and 5 dBm by the signal generator.

Conclusions

During design and calculations, it is noted how doubling the width of the microstrip has the effect of varying a few micrometers over the calculated slots, this helps to explain how patch antennas work well despite the handcrafted process. According to the radiation patterns, the A-03 prototype (the array of six patch antennas connected in series) as a transmitter has the highest gain in dBm between 5.0 GHz and 5.4 GHz.

The design and manufacture of patch antennas for applications in about 5.2 GHz, whether simple or in array, can be done in a practical way with satisfactory experimental results. A clear and simple methodology can be used even in training programs and encourage the local electronics industry to aim at the manufacture of faster, more competitive radio frequency devices compatible with the current market. Tests with digital modulation that include bit error rates can be a later work since the range and behavior of the prototype patch antennas are known.

Acknowledgments

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Instrumental test of patch antennas manufactured for C-Band applications

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Introduction

Nowadays, digital communications require higher bandwidths and operating bands in the order of GHz. Fortunately, this allows the use of compact antennas, even the ones that take advantage of designs that improves the gain and width of the basic antenna by applying stacked patch topology with printed circuit boards or PCBs. Mass production ensures profitability in this type of product, but there are also prototyping process that can be less complex and less expensive : alternatives that may be attractive to researchers and engineers from Central American countries. So the research questions arise, what models and design rules must be respected as a minimum for the basic functional designs of patch antennas?, what kind of experimental results can be obtained with this type of products?

Equipment and Materials

- Spectrum Analyzer SPECTRAN HF-60105, Aaronia.
- Antenna HyperLOG 6080, Aaronia.
- Signal generator BPSG 6 OEM, Aaronia.
- Antenna LiteBeam, 16 dBi, Ubiquiti.
- Antenna LBE-5AC-GEN2, 5GHz airMAX AC LiteBeam Gen2, Ubiquiti.
- Double layer PCBs 70x100 mm.
- Double layer PCBs 300x200 mm.
- Hydrochloric acid.
- Hydrogen peroxide.
- Acetone, varnish.
- SMA Connectors, 50 ohm.

Methods and Setup

The basic design of a patch antenna like the one in Fig. 1 consists of calculating its width W and length L, slots methods with x_0 and y_0 dimensions are used for impedance matching.

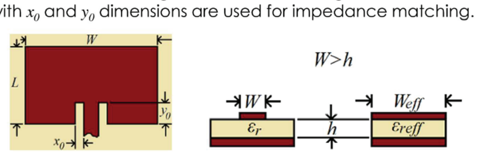

Fig. 1. Patch antenna with an inset feed and its planar waveguide model.

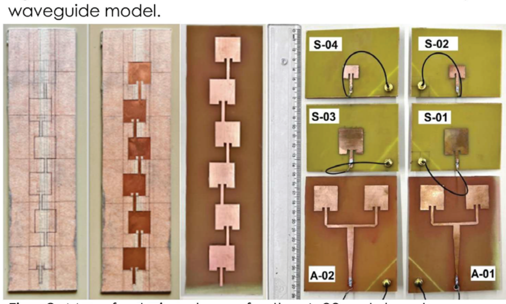

Fig. 2. Manufacturing shown for the A-03 patch antenna array prototype (left) and the others prototypes (right).

Manufacturing these antennas consists of drawing, cutting of the adhesive tape for the mold, varnish on the mold and remove the rest of the tape, use of the acid, removing the varnish (Fig. 2). This is how we proceed to do the tests of frequency sweep and the radiation pattern (Fig. 3).

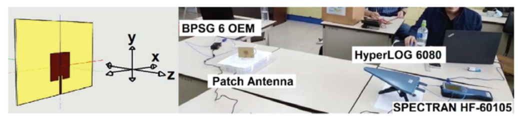

Fig. 3. Experimental set up of measurements for the frequency sweep and the radiation pattern.

Results and Discussion

The results of the tests in this work should be considered mostly from a qualitative approach as they are not carried out in an anechoic chamber.

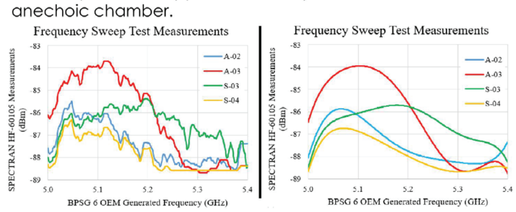

Fig. 4. Frequency sweep measurements for each patch antenna.

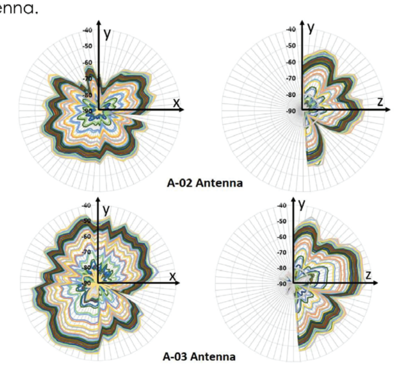

Fig. 5. Measured (dBm) and plotted radiation pattern of the A-02 antenna and the A-03 antenna, both around 5,1 GHz.

Conclusions / Next Steps

The design and manufacture of patch antennas for applications in about 5 GHz, whether simple or in array, can be done in a practical way with satisfactory experimental results. A clear and simple methodology can be used even in training programs and encourage the local electronics industry to aim at the manufacture of faster, more competitive radio frequency devices compatible with the current market. Tests with digital modulation that include bit error rates can be a later work since the range and behavior of the prototype patch antennas are known.

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