

Handmade Microstrip Leaky-Wave Antenna in UHF band for Educational Purposes

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Abstract—The design, manufacture and testing of a microstrip leaky-wave antenna in the UHF band is reported. The antenna is fabricated using low-cost materials and handmade techniques. This activity is intended for educational purposes and hands-on training of antenna engineering and related applications. Particularly, the proposed antenna can be used for localization of passive RFID tags and DVB-T base stations.

Index Terms— leaky-wave antennas, microstrip antennas, education, direction finding, UHF, passive RFID.

I. INTRODUCTION

Innovation in teaching of antenna engineering at undergraduate/postgraduate levels has been a challenging topic in the last decades [1] – [5]. To increase the interest of the students and reach deep learning levels in such discipline, the combination of theoretical classes with practical initiatives has shown to be a good option [3] – [5]. More particularly, the use of handmade antennas and modular antenna building kits [6], [7], and project-based learning courses [8], gives the student the opportunity to manually fabricate and tune their own antenna designs. Also, if the homemade antennas are used by the same students in real scenarios [9] – [12], the future antenna engineers can gain a priceless and broad vision from electromagnetic theory to antenna signal processing and end-user applications.

In this paper we present the design, homemade manufacturing, and hands-on tuning of a microstrip leaky-wave antenna (MLWA) [13] – [16] for direction finding in the 900 MHz band. It is demonstrated how the MLWA is fabricated by the own students with low-cost materials, and how the radiation patterns are tuned to synthesize amplitude-monopulse patterns [17] – [20]. This way, the students acquire practical knowledge about antenna engineering. The authors have demonstrated in recent works, the application of monopulse-scanned MLWAs for localization in real scenarios [21], such as Zigbee Wireless Sensor Networks (WSN) [22], Bluetooth Wireless Personal Area Networks (WPAN) [23], and Wi-Fi Wireless Local Area Networks (WLAN) [24] operating in the 2.4 GHz ISM band. More recently, this MLWAs have also been proposed for passive-tags RFID localization in the 900 MHz ISM band [25]. All previous MLWAs were fabricated by professional PCB prototyping companies. In this paper we show how UHF MLWAs can be manufactured and tested by university students, using low-cost materials and hand-made techniques.

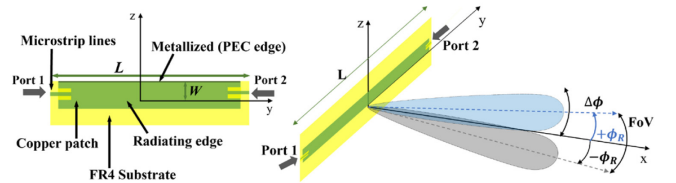


Fig. 1. Bi-directional MLWA a) Main dimensions b) Scanned beams.

II. HANDMADE MICROSTRIP LWA WITH MONOPULSE

A. Monopulse Leaky-Wave Antenna Theory

The half-width microstrip (HWM) LWA is basically formed by a long metal patch of width W and length L (see Fig. 1a) radiating with its fundamental EH_1 leaky mode [14]. Amplitude-monopulse patterns can be synthesized if this HWM LWA is bi-directionally fed [17], creating two mirror-symmetric beams scanning at $+\phi_R$ and $-\phi_R$ which overlap at their half-power beam width (HPBW, $\Delta\phi$) points in the perpendicular direction ($\phi=0^\circ$) (see Fig. 1b). This condition can be written as [19]:

$$\phi_R = \frac{\Delta\phi}{2} = \frac{\text{FoV}}{2} \quad (1)$$

Where the Field-of-View (FoV) is the angular region where the Direction-of-Arrival (DoA) of a radio signal can be estimated without ambiguity, by just processing the RF power received at each antenna port. In our case, we specify the design frequency of 902 MHz, with a $\text{FoV} = \Delta\phi = 40^\circ$ and thus $\phi_R = 20^\circ$ (1). As explained in [25], these specs are well suited for passive-tag RFID localization using the UHF ISM band.

The main two dimensions of the HWM LWA to be designed are the radiating microstrip width W and length L . By varying the width W , the specified scanning angle ϕ_R can be tuned for a given frequency f_0 and substrate relative dielectric permittivity constant of ϵ_r , according to [19]:

$$W \approx \frac{\lambda_0}{4} \frac{1}{\sqrt{\epsilon_r - \sin^2 \phi_R}} \quad (2)$$

where $\lambda_0 = c_0/f_0$ is the free-space wavelength and c_0 is the speed of light. In our case, we will use low-cost FR4 substrate with $\epsilon_r = 4.5$, and setting with $f_0 = 902$ MHz and $\phi_R = 20^\circ$, we obtain $W = 39.7$ mm. Then, the strip length L determines the HPBW $\Delta\phi$ by the following well-known equation [13], [19]:

$$L \approx \lambda_0 \frac{57^\circ}{\Delta\phi \cos \phi_R} \quad (3)$$

TABLE I. COMPARISON BETWEEN THEORETICAL, NUMERICAL AND EXPERIMENTAL DESIGN VALUES

	Theoretical	Numerical (Matlab)	Numerical (HFSS)	Experimental
W (mm)	39.7 (2)	38	38	38
ϕ_R (°)	20 (1)	15	22	21
L (cm)	50.4 (3)	58	58	58
$\Delta\phi$ (°)	40 (1)	36.5	39.5	43

In our case, with $\Delta\phi = 40^\circ$ and $\phi_R = 20^\circ$ at 902 MHz we obtain $L = 50.4$ cm. These initial theoretical and approximate dimensions are summarized in Table I, and they will be subsequently optimized for a more accurate antenna design.

B. Antenna Numerical Design and Optimization

Once the main dimensions of the radiating strip (namely W and L) have been calculated for a given substrate (ϵ_r) using the approximate expressions (1)-(3), the HWM LWA can be optimized before fabrication. For that, a first design will be obtained with an in-house tool programmed in Matlab and based on a Transverse Resonance Method [16], and then simulations will be performed with the commercial software Ansys HFSS. For that, the substrate material must be selected. In our case, a low-cost FR4 laminate has been chosen [26], with $\epsilon_r = 4.5$, $\tan\delta = 0.018$ and a thickness $H = 1.6$ mm.

The Matlab graphical-user interface of the tool is depicted in Fig. 2. As previously commented, W and L must be simultaneously optimized to adjust the radiation pattern (scanning direction ϕ_R and HPBW $\Delta\phi$) as desired. It must be highlighted that this ad-hoc tool provides an efficient analysis of the structure, allowing to optimize W and L with a minimum simulation time of 2 second per frequency point. As a hint for the students to adjust the pattern, a wider strip (higher W) will tune the beam direction towards higher angles ϕ_R -see (2)-, and longer antennas (higher L) will provide narrower radiation patterns -lower $\Delta\phi$, see (3)-. Since the antenna will be manufactured by hand, the width W and the length L will be varied in steps of 1 mm due to the low fabrication tolerances that can be manually achieved. As an example of this tuning process, Fig. 3 shows in dashed lines the radiation patterns obtained when W is varied from $W = 37$ mm to $W = 40$ mm in the aforementioned steps of 1 mm. The optimization might need a total of 20 iterations, taking the student a total time of 5 min, as summarized in Table II. After optimization, the design with Matlab provides the dimensions $W = 38$ mm and $L = 58$ cm, as summarized in the second column of Table I.

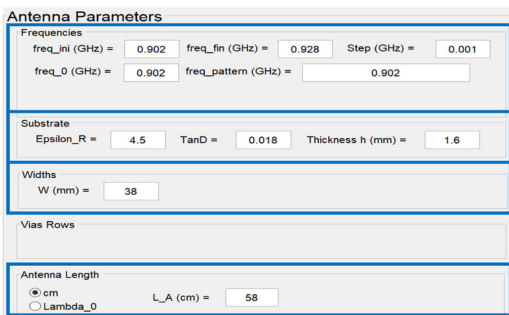


Fig. 2. Matlab graphical interface for efficient numerical design.

TABLE II. ESTIMATED TIME FOR ANALYSIS AND OPTIMIZATION OF THE ANTENNA

Time	Matlab	HFSS	Experimental (set-up and measurements)
Single point analysis	2 s.	10 min.	2 h. 30 min.
Design / Optimization	5 min.	6 h.	7 h.

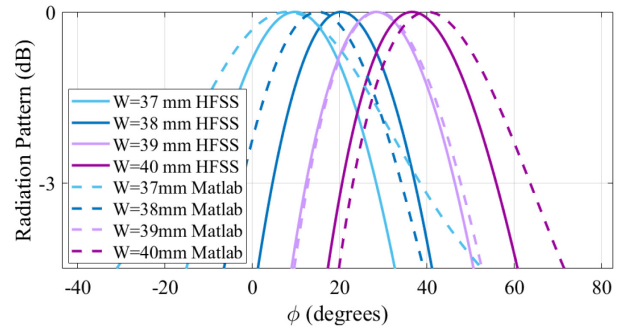


Fig. 3. Optimization of the strip width W with $L = 58$ cm.

As observed in Fig. 3 with dashed lines, the Matlab tool predicts an approximate increase of 10° in the scanning direction of the main beam as W is increased in 1 mm steps, from $\phi_R = 8^\circ$ with $W = 37$ mm to $\phi_R = 39^\circ$ with $W = 40$ mm. Therefore, the optimal design with Matlab code is for $W = 38$ mm, which provides a scanning angle of $\phi_R = 15^\circ$, whose radiation pattern is shown in Fig. 4. The obtained HPBW is $\Delta\phi = 36.5^\circ$, which is very close to the requirement.

After the design, the structure must be simulated with a commercial full-wave software such as Ansys HFSS or CST. In order to obtain a final design that will be manufactured, the antenna feeding network must be also added. In this occasion, a simple feeding network consisting of a microstrip line with an inset in the printed strip is created in the model, as shown in Fig. 5. The task now consists of optimizing the dimensions of the feeding network. At this stage, the optimization tool of the commercial software will be used to obtain the proper values to reduce the reflections from the ports. It took a total optimization time of 6 hours to obtain the final dimensions of the optimized antenna and the feeding network in HFSS, which are summarized in Table III. With those dimensions, the optimized structure is simulated to evaluate the proper performance with a good matching and the correct radiation pattern. The S parameters are depicted in Fig. 6, showing good matching with S_{11} below -10 dB at the design frequency.

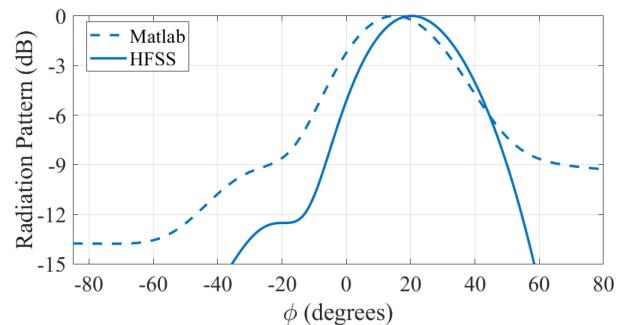


Fig. 4. Numerical radiation pattern obtained with Matlab and HFSS for optimal designs in Table I.

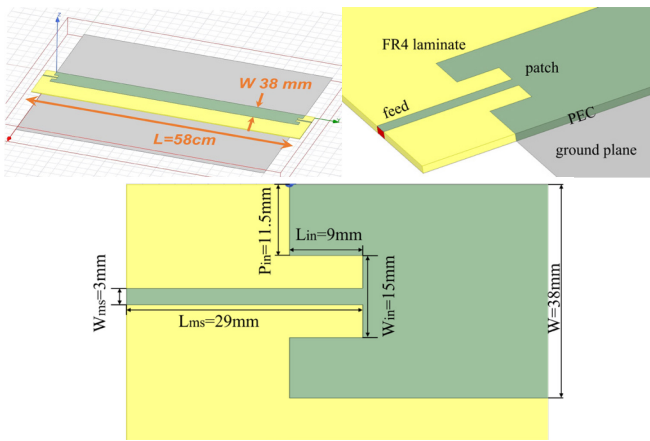


Fig. 5. Dimensions of the optimized antenna in HFSS.

TABLE III. ANTENNA DIMENSIONS AND FEEDING NETWORK

	Parameter	Value (mm)	Parameter	Value (mm)
Radiating strip	W	38	L	580
	W_{ms}	3	L_{ms}	29
Feeding network	W_{in}	15	L_{in}	9
	P_{in}	11.5		

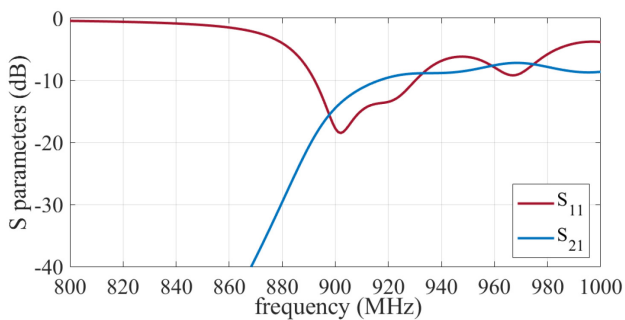






Fig. 6. Antenna S parameters simulated in HFSS.

The parameter S_{21} below -10 dB indicates a good radiation efficiency, since the amount of power reaching the end port is very low. HFSS simulated radiation patterns are plotted in blue color in Fig. 10b. The optimized strip width $W = 38$ mm provides a pointing angle of $\phi_R = 22^\circ$ and a beamwidth of $\Delta\phi = 39.5^\circ$. As commented, full-wave HFSS simulations are needed for an accurate analysis and optimization of the antenna including in the input the matching circuits before fabrication. However, the initial design values provided by the Matlab code make the student face the optimization in a more efficient way in terms of time, as summarized in Table II. The optimization with ad-hoc Matlab tool took only 5 minutes, while in HFSS this process can take several hours.

Also, it is important to note that (as previously demonstrated with both Matlab and HFSS simulations in Fig. 3), fabrication tolerances of the metallic strip width of only 1 mm imply a change in the pointing angle of the antenna of around 10° . Therefore, it is important to be precise when fabricating the homemade antenna to obtain the desired scanning angle. The manufacturing process is described in the next Section.

TABLE IV. MATERIALS TO FABRICATE THE ANTENNA

	Materials	Units	Unit price (euros)
	Copper Clad Boards, 1.6mm thickness, single sided 91 x 60 cm. 1/16in., [26]	1	86,17 €
	Conductive Adhesive copper tape, 50.8 mm x 16 m [27]	1	151,46 €
	Coaxial connector. [28]	2	2,58 €
	Cutter, ruler, pencils	1	18,0 €
TOTAL PRICE			260,79 €

C. Hand-made fabrication

The materials requested and associated cost for the hand-made manufacturing of the designed HWM LWA, are summarized in Table IV. The purchased low-cost FR4 board [26] is grounded with a copper layer at one side, so the radiating strip will be added at the other side of the board. To create the radiating strip and the feeding network, copper tape [27] is used. As shown in Table IV, the copper tape length is 16 m and the width is 50 mm, sufficient to construct the radiating strip with $W = 38$ mm and $L = 58$ cm. Similarly, the FR4 board substrate size is 91 cm x 60 cm, which is sufficient for manufacturing many antennas. It is important to note that the width W must remain constant throughout the 58 cm length of the LWA. Therefore, a long ruler is requested to avoid width variations while cutting the copper tape with a cutter.

With all these materials, the next fabrication steps can be followed as illustrated in Fig. 7. The first step is to fix the copper tape, from the edge of the board to the design width $W = 38$ mm, as seen in Fig. 7a. To create the Perfect Electrical Contact (PEC) wall of the microstrip LWA, the copper tape is wrapped around the edge of the FR4 board and fixed to the ground side, as shown in Fig. 7b. Then, the feeding network is drawn, and the excess tape is removed with the help of a cutter, Fig. 7c. Since the width of the FR4 board is very similar to the one of the antenna length L , the length of the microstrip input line is chosen so the radiating aperture is centered. After that, the SMA connectors are welded to the microstrip lines and the ground plane, as shown in Fig. 7d. The final step is to cut the FR4 board to separate the fabricated antenna from the rest of the board, getting the final prototype in Fig. 7e. The cutting of the FR4 board can be done before the manufacturing process, so the students only need to perform the first four steps. Finally, the manufactured antenna is presented in Fig. 7f.

Once the antenna has been manually manufactured, the central frequency can be tuned by adjusting the strip width W . This can be done by adding or removing (cutting) copper tape in real time, while the antenna response is being measured as described in the next Section. In our case, we have removed 1 mm (initial manufacture was 39mm) from the strip width to tune it to the desired scanning angle, as illustrated in Fig. 8. The estimated time to measure the manufactured antenna is 2h 30 min, while the experimental tuning process can take several hours as summarized in Table II.

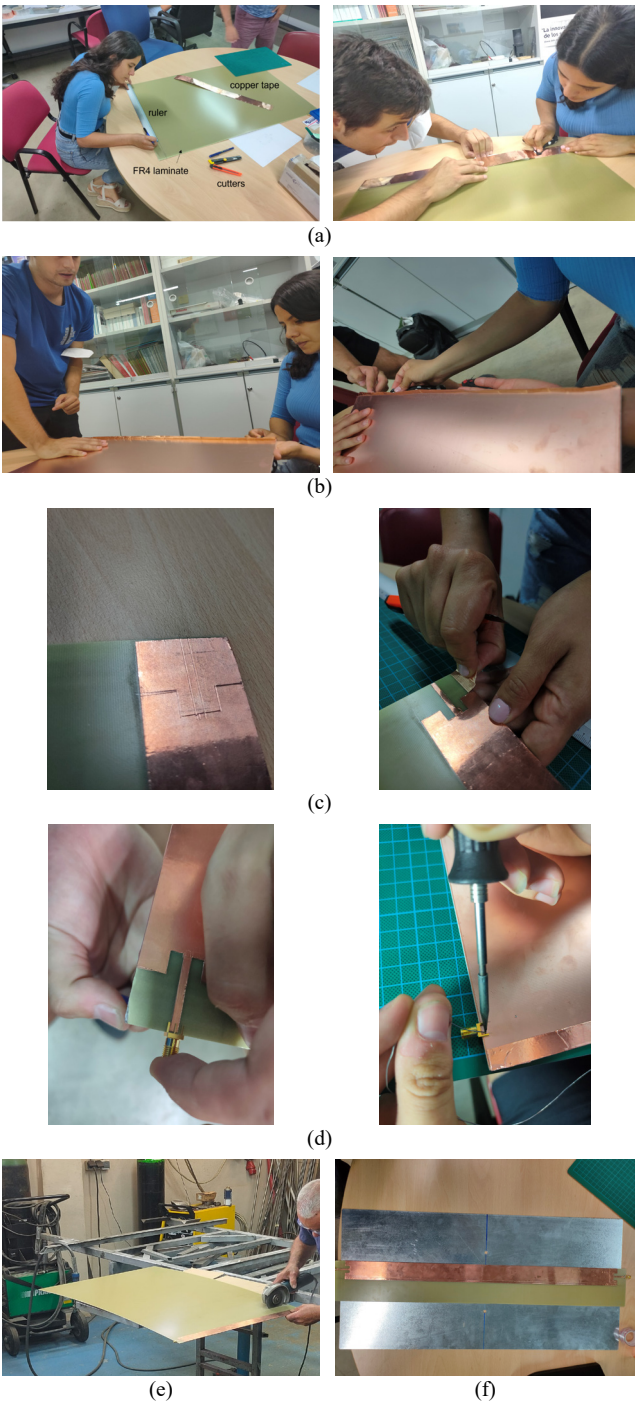


Fig. 7. Steps of the manufacturing process LWA.

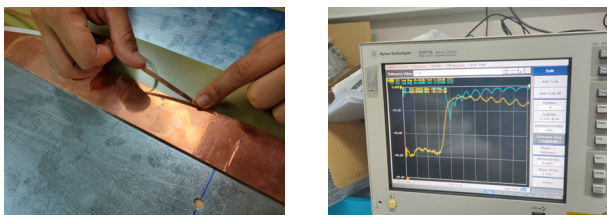


Fig. 8. LWA hands-on manual tuning.

III. MEASUREMENTS

The last step is to measure the performance of the manufactured antenna. First, the matching and coupling between ports (S_{11} and S_{21} , respectively) are measured with a Vector Network Analyzer (VNA). In Fig. 9, the measured S parameters are shown. It can be seen how the matching (S_{11} and S_{22}) is not similar in both ports due to the different inaccuracies when cutting the copper tape and welding the connectors. In any case, input matching below -20 dB is obtained at both ports at the design frequency of 902 MHz.

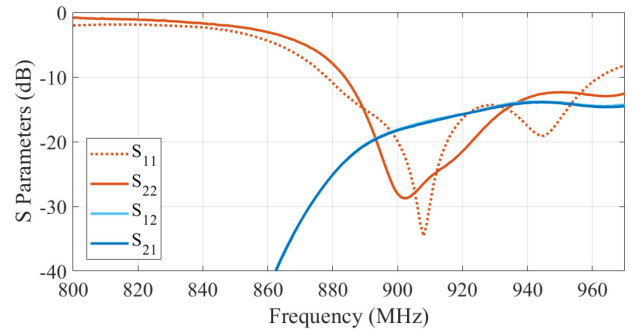


Fig. 9. Measured S-parameters of fabricated and tuned HWM LWA.

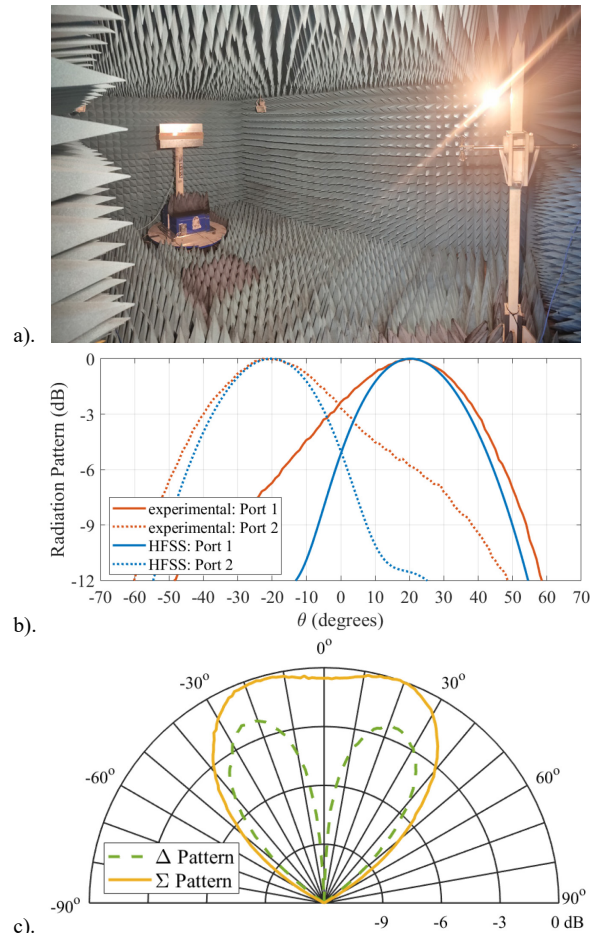


Fig. 10. Measured radiation patterns. a). Anechoic chamber b). Individual scanned beams c). Sum and difference monopulse patterns.

The characterization of the radiation patterns of the antenna is carried out in the anechoic chamber of the university. The antenna is located on a robotic turntable that rotates from -90° to 90° at a distance of 2.5 m from a reference biconical antenna, as shown in Fig. 10a. The measured radiation patterns are presented in Fig. 10b, showing the good agreement with HFSS simulations, and thus confirming the successful synthesis of two beams with a HPBW $\Delta\phi = 43^\circ$ scanning at the pointing angles $\phi_R = 21^\circ$ for Port 1 and $\phi_R = -23^\circ$ for Port 2. As a result, we obtain the sum and difference monopulse radiation patterns shown in Fig. 10c, which can be applied for direction finding in UHF RFID networks as proposed in [24].

IV. CONCLUSION

It has been demonstrated the capacity to design and manually fabricate a microstrip leaky-wave antenna for monopulse direction-finding applications in the UHF band. For that, low-cost materials, and hands-on manufacturing techniques (basically cutting and pasting copper tape to a low-cost FR4 substrate) are used. The complete design, optimization, fabrication, and tuning process has been described. More detailed information on the practical application of the designed antenna for localization of passive UHF RFID tags in the 900 MHz band, will be given in the oral presentation. We believe that this educational initiative can make university students gain practical skills and deeper knowledge on this interesting antenna engineering topic.

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