

Beamforming Networks for antenna array, useful in WiFi applications *Redes Beamforming para agrupación de antenas, útiles en aplicaciones WiFi*

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Abstract: In this paper several types of beamforming networks have been presented, this proposal can be used for an array antenna, which are used in several types of WiFi applications, IEEE 802.11b/g/draft-n. The first design corresponds to a 4x4 Butler Matrix for a resonance frequency at 2.45 GHz, depending on the port through which the signal is excited, it will be possible to obtain several variations in phase at the output ports (45°, 135°, -45° and -135°), the proposed Butler matrix has been optimized from a generalized matrix scheme, reducing the size through a simple overlap of multiple transmission lines to $\lambda/4$ at the central frequency. The second design corresponds to a Rotman lens with a characteristic resonance frequency of 5.8 GHz, with a maximum focal angle of 30°, for this design has been used geometric optics concept, and the last design has been made for a frequency of 5.8 GHz using a slot array designed with Substrate Integrated Waveguide technology.

Keywords: Array Antena, Butler Matrix, Rotman Lens, Slots array with SIW guide, WiFi

Resumen: En este artículo se han presentado varios tipos de redes conformadoras de haz, estas propuestas pueden ser utilizadas para una agrupación de antenas útiles en diversos tipos de aplicaciones. El primer diseño corresponde a una Matriz de Butler de 4X4 para una frecuencia de resonancia de 2.45 GHz, dependiendo del puerto por la cual la señal sea excitada, se podrán obtener diversas variaciones en fase en los puertos de salida (45°, 135°, -45° y -135°), la matriz de Butler propuesta ha sido optimizada a partir de un esquema de matriz generalizada, reduciendo el tamaño a través de una simple superposición de múltiples líneas de transmisión a $\lambda/4$. El segundo diseño corresponde a una lente de Rotman con una frecuencia de resonancia característica de 5.8 GHz, con un máximo ángulo focal de 30°, para este diseño se ha utilizado el concepto de la óptica geométrica, y el último diseño ha sido realizado para una frecuencia de 5.8 GHz usando una agrupación de ranuras diseñadas con tecnología Substrate Integrated Waveguide.

Palabras clave: Agrupación de antenas, Matriz de Butler, Lentes de Rotman, Agrupación de ranuras con guías SIW, WiFi



1 Introduction

Multibeam and beam-scanning antennas are crucial to modern communication systems such as Direct-Broadcast Satellite (DBS), Multipurpose Radar, multiple beam antenna for mobile communications. Talking about these systems is talking about the smart antennas and indirectly of multibeam systems the require wide-angle coverage with very directive beams. Multibeam and beam-scanning antennas are implemented using multiple antennas to create several beam patterns in different directions, either as beam switch or continuous beam terminated in a sophisticated signal processor, which can adjust or adapt its own beam pattern in order to emphasize signals of interest and to minimize interfering signals (Abdelghani *et al.*, 2012a,b; Bialkowski *et al.*, 2008; Moscoso-Mártir *et al.*, 2014).

Beamforming networks are a great solution to generate several beams with great directivity and good bandwidth, they have been classified into several ways, it was reported in the applications cited previously, so to facilitate our learning it has been divided into 3 groups according to their applications: based on transmission lines (Network BFNS), based on quasi-optical lenses (Quasioptical BFNS) and based on digital data processing networks (digital BFN), (Lo and Lee, 1988; Hansen, 2009; Hall and Vetterlein, 1990; Josefsson and Persson, 2015).

All these solutions offer multiple-beam or beam-scanning capabilities by selecting one or several input ports, or mechanically displacing a moving feed, but the Butler matrix and Rotman lens are widely used since they can achieve a large number of switched beams using well-known design algorithms.

In the present research, three microwave circuits to generate multiple beams are proposed, each proposed beamforming network have been designed for a different resonance frequency. This paper is described in 3 sections, in the first section a 4X4 Butler Matrix design at 2.45 GHz is described in detail, in the next section a Rotman lens at 5.8 GHz is developed, and it is compared with a slots array designed with Substrate Integrated Waveguide (SIW) technology, which is described in section 3, finally the conclusions are presented in the last section.

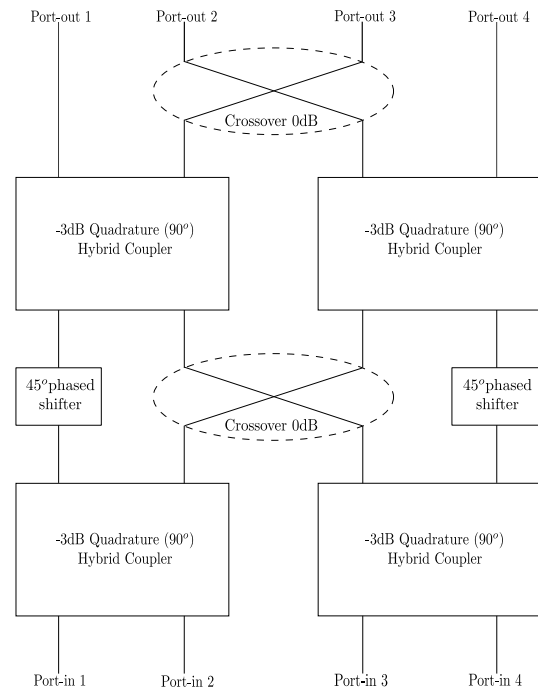


Figure 1: Scheme Butler Matrix 4X4.

2 Butler Matrix

A 4 x 4 Butler Matrix is designed using four -3 dB Quadrature (90 degree) Hybrid Coupler, two 0 dB Crossovers Coupler and two 45° phased shifter (Nachouane *et al.*, 2014), it is shown in figure 1. The prototype has been optimized at the center frequency of $f = 2.45$ GHz in WiFi applications (IEEE 802.11b/g/draft-n), with a characteristic impedance of $Z_0 = 50\Omega$. The material considered for the design has the following characteristics: Roger 4003C with $\epsilon_r = 3.38$, height $h = 0.813mm$, $\tan(\delta) = 0.0027$.

2.1 -3 dB Quadrature (90°) Hybrid Coupler

Quadrature hybrids are 3 dB directional couplers with a 90° phased difference in the outputs of the through and coupled arms. In the design of -3 dB Quadrature (90 degree) for Hybrid Coupler. The dimensions of the transmission lines are shown in table 1, these values have been obtained from the equations provided in (Pozar, 2011; Balanis, 2005). A generic hybrid coupler was designed based on the values specified in table 1, however the technological advancements require miniaturization of the systems to optimize space and compact

Table 1: Hybrid coupler dimensions.

Impedance	Length	Width
50 Ω	18.7438 mm	1.84139 mm
35.35 Ω	18.3137 mm	3.1044 mm

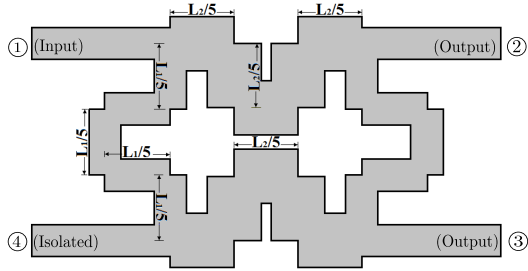


Figure 2: -3 dB quadrature (90 degree) hybrid coupler optimized.

structure, therefore each of the elements of the hybrid coupler have been divided into five equal segments, as a overlapping transmission lines resulting in a size reduction 30%, it is shown in figure 2.

2.2 Butler Matrix proposal

To build a Butler Matrix we have relied on the criterion of figure 1, where it requires hybrid couplers, crossover couplers, and phased shifters. Crossover couplers are known as couplers to 0 dB, these are an efficient way for crossing two transmission lines with minimal coupling between them, the simplest form of designing such devices is by means of a connection of two hybrid couplers 90°. Additionally, it is important to considerate the symmetry properties (Kholodniak *et al.*, 2000). In figure 3 is depicted the proposal Butler Matrix; to design the phased shifter we have decided to change the length value, this because a length at 45 degrees is too short to use, therefore, the new phased shifter length was calculated with an angle at 405 degrees. The resulting size was 7.8cm x 7cm, which corresponds to the proposal Butler Matrix.

The return loss and phase difference between the output ports of the Butler matrix (see figure 4), give us to identify that the proposed design is resonating at 2.45 GHz of frequency with a bandwidth about 28%; i.e. it has a working window of approximately 500 MHz.

In table 2 is shown the variation of the phase angle between the ports of entry ($P_{in1}, P_{in2}, P_{in3}, P_{in4}$) with respect to the output ports ($P_{out5}, P_{out6}, P_{out7}, P_{out8}$) of the designed Butler matrix. In figure 5(a), the phase diagram is obtained; for entering input port

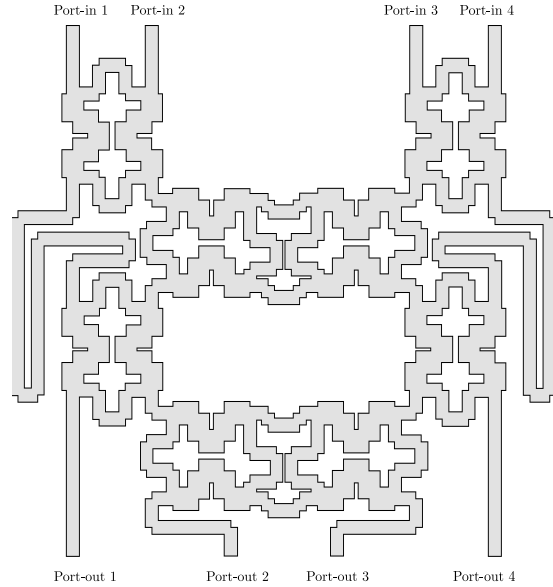


Figure 3: Optimized Butler Matrix.

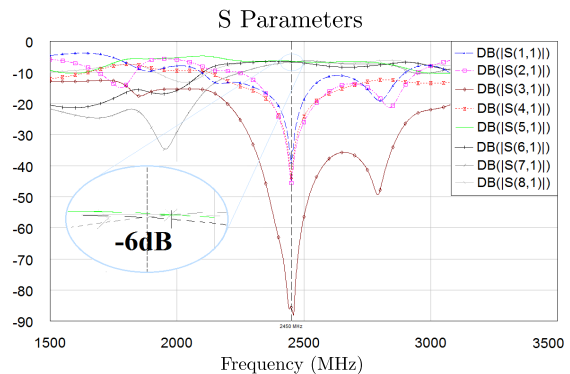
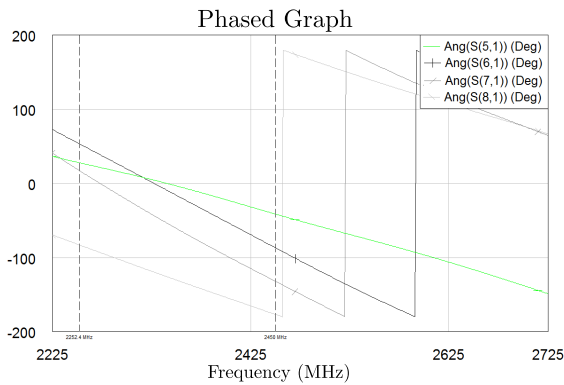


Figure 4: S parameters of the optimized Butler Matrix (1-4 are input ports and 5-8 are output ports).

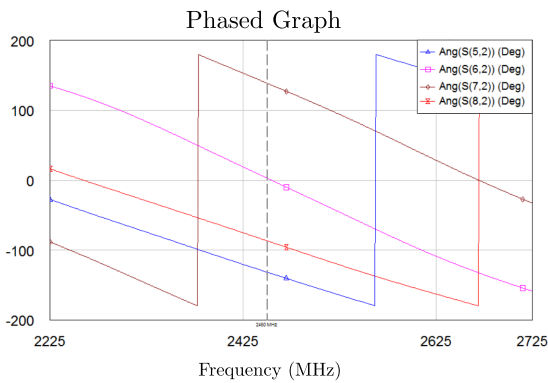
1 is shown, which presents an angular variation of -45 degrees. On the other hand, figure 5(b) depicted the second case, input port 2, describes the angular variation of 135 degrees. Based on both results, we could build a four elements array antenna to increase directivity.

Table 2: Variation of the phase angle between the ports of entry.

Ports	P_{out5}	P_{out6}	P_{out7}	P_{out8}	β
P_{in1}	-41.36°	-86.96°	-131.8°	-176.7°	-45°
P_{in2}	-131.6°	2.85°	138.6°	-86.69°	135°
P_{in3}	-86.69°	138.6°	2.85°	-131.6°	-135°
P_{in4}	-176.7°	-131.8°	-86.69°	-41.36°	45°



(a)



(b)

Figure 5: Phased output ports of the Butler matrix optimized. (a) Output ports with respect to the input port 1. (b) Output ports with respect to input port 2.

3 Rotman Lens

A Rotman lens is a device that uses the spread of an injected signal into the gap between two parallel metal plates to achieve the condition of a linear phase distribution in the output ports of the lens. The geometry of the metal plates and the length of the output cables are obtained using the geometrical optics model.

In practice, this condition is only true for the ports on the perfect focal points, whereas for the other ports located along focal arc, the phase variation will be approximately linear, resulting in phase errors (optical aberrations) that affect the performance of the lens.

The outputs of the lens will be used to feed a linear antenna array in order to change passively the phase distribution at the input ports of the array. By controlling the phase shift in the array ports, it is possible to direct the radiation pattern of the antenna toward a predefined direction (see figure 6).

A prototype of a Rotman lens using a NELTEC

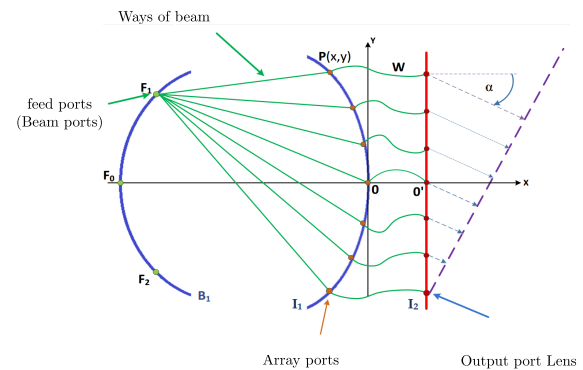


Figure 6: Rotman lens scheme used in the geometrical optics model.

NY9220 substrate was designed and simulated. The dielectric substrate has a permittivity of 2.2 and thickness of 0.127mm. The parameters used in the design of the lens are described in table 3.

Table 3: Rotman lens parameters.

Parameter	Value
Central frequency f_0	5.8 GHz
Bandwidth (BW)	4 MHz
Maximum scan angle (Ψ)	30°
Maximum focal angle (α)	30°
Output ports (antennas)	11
Distance between output ports	1.955cm
Input ports (beams)	7

3.1 Rotman Lens design using the geometrical optics model

In general, the design of a Rotman lens should follow a systematic procedure to obtain the expected results. A standard design procedure consists of definition of the lens specifications, this is proposed in two stages.

In the first stage are defined: maximum scan angle, maximum focal angle, number of beams, return losses, phase errors, amplitude errors, bandwidth, efficiency, among others. In order to determine the length of the normalized aperture of the lens (η_{max}), the path length errors for different pointing angles were evaluated (Rotman and Turner, 1963). Through figure 7 it is possible to verify that, to get an error less than 5×10^{-4} , η_{max} should be less than 0.5. That value will be taken as the maximum value for the normalized aperture.

In the second stage, the data contained in table 3 and the geometrical optics model were used to calculate the coordinates of the output ports of the cavity, and

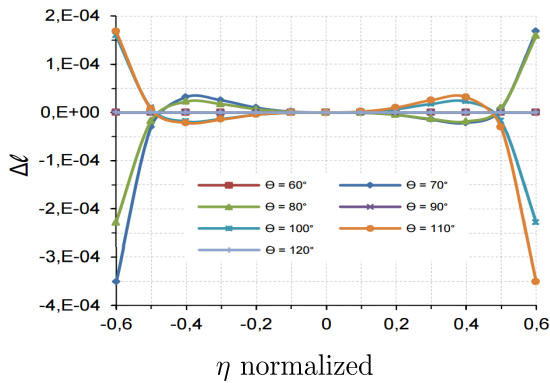


Figure 7: Path length errors for some pointing angles.

the length of the lines between these ports and the lens output ports (see figure 6).

The length of the central focal point (the width of the lens), can be calculated using the equation (1), where N_e = number of antenna elements, d = distance between elements, $\eta_{max} = 0.5$ and $\epsilon_r = 2.2$ is the permittivity of the substrate.

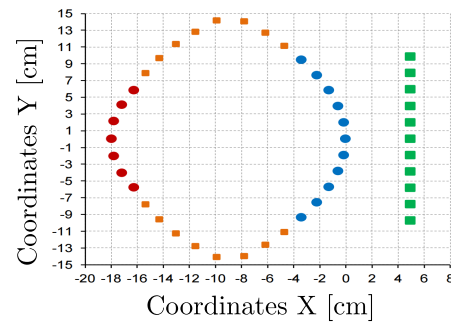
$$F_{min} = \frac{(N_e - 1)d}{2} \frac{1}{\sqrt{\epsilon_r \eta_{max}}} \quad (1)$$

The positions of the lens elements are depicted in figure 8(a): the red dots correspond to the beam ports (input ports), the blue dots are the array ports (inner ports), orange squares are the dummy ports and the green squares are the output ports (linear array). The lengths of the lines connecting the array ports with antenna ports is plotted in figure 8(b).

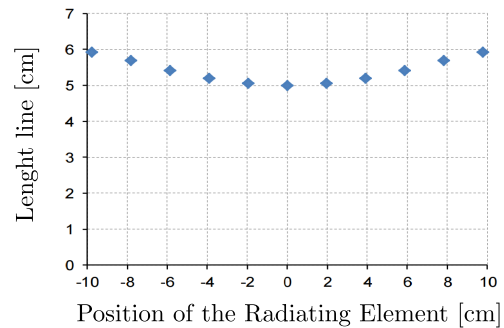
Once the geometrical parameters have been calculated, the two-dimensional model (Lo and Lee, 1988) was used to evaluate the performance of the lens. Radiation patterns for different pointing angles are presented in figure 9. The beams are pointing in the desired directions and the Side Lobe Level is better than 16 dB for all beams; furthermore, the nonexistence of grating lobes can be verified.

3.2 Ports and connection lines

An important aspect to consider is the proper design of the transitions between input/output ports and cavity. For the design of ports, it is necessary to calculate the value of the microstrip line considering that the characteristic impedance 50Ω , the next step is increase gradually the width (taper) for the purpose of to vary gently the impedance characteristics until are similar which presents the interface between line and parallel plate cavity (Musa and Smith, 1986, 1989). Another aspect



(a)



(b)

Figure 8: Rotman lens prototype in microstrip technology. (a) Coordinates ports input and output. (b) Length of the connecting lines.

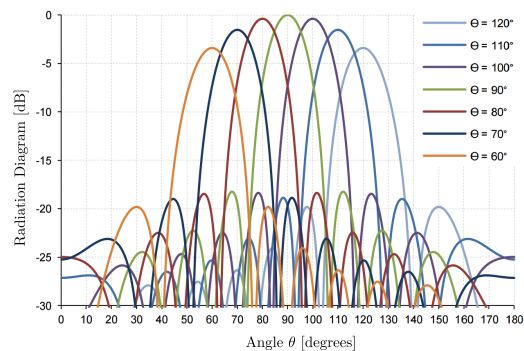


Figure 9: Length errors paths for some pointing angles.

to consider is the phase center of a microstrip port, ports of the lens should be located so that its phase center coincide with the points calculated in figure 8(a) and figure 8(b), otherwise, errors will occur in the phase of the output signals that can cause unfocused lens. On the other hand, Rotman equations do not define the geometry of the side walls, which connects the focal arc with the array

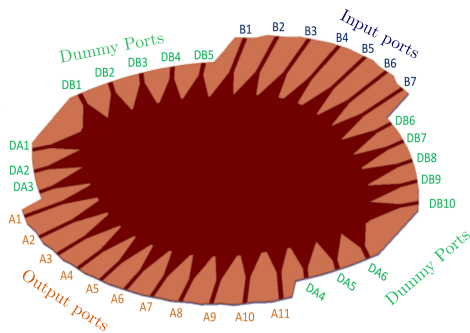
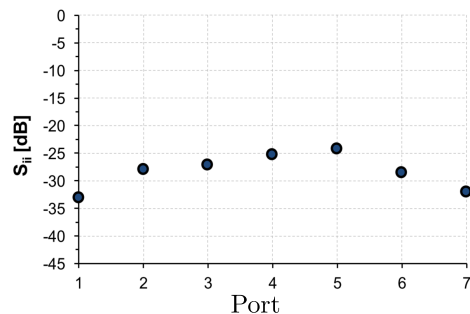
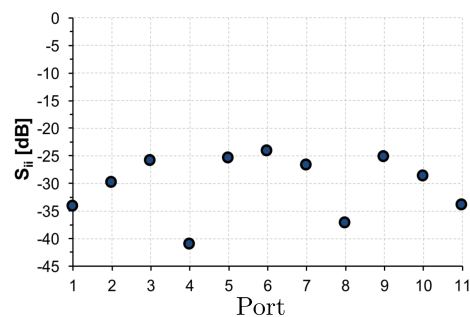


Figure 10: Rotman lens with microstrip technology.



(a)



(b)

Figure 11: S parameters Rotman lens. (a) S_{ii} parameters of the input ports. (b) S_{ii} parameters of the output ports.

lens arc. The side walls can be designed according to any geometrical shape. In this type of designs, the energy reflected on the walls, returns to the lens body, causing additional side lobes, and it can cause coupling between ports (Rausch and Peterson, 2005). In that reason, in implementations with microstrip or stripline technology, the absorption conditions usually are achieved by placing dummy lenses ports terminated in matched loads along the side walls (see figure 10).

To avoid direct connections between the loads matched resistances and the mass plane, a $\lambda/4$

stub length terminated in an open circuit is used. In figure 11(a) and figure 11(a), the reflection coefficients of the input ports and output ports of the lens are plotted. The coefficients are calculated at the center frequency of 5.8 GHz. It shows that for all ports the parameter is less than -20 dB.

4 Slot Arrays Antenna with Substrate Integrated Waveguides

A Slot Arrays Antenna with Substrate Integrated Waveguides (SIW), is designed by placing two rows of metalized holes in a dielectric substrate, where, d = holes diameters, b = space between them and the w = spacing between the rows are the physical parameters required for the design of the guide. A SIW guide can be modeled using a classic rectangular waveguide, so all design procedures and developed the theoretical basis for rectangular guides are directly applicable to SIW guides (Deslandes and Wu, 2006). The parameters are shown in table 4.

Table 4: SIW parameters used to slot antennas.

f_0 GHz	p mm	d mm	w mm	h mm
5.8	1.55	0.6	19.55	1.143

4.1 Slot antennas design

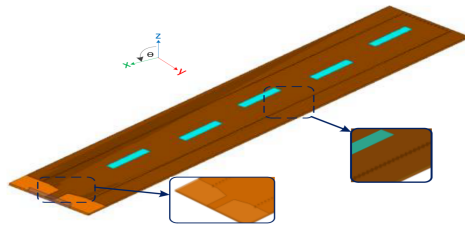
Given the geometry of SIW guides, the slots are placed in the wide face of the guide and parallel to the axis of symmetry. The slots have been shifted an u distance from the axis so that cut the current lines of the fundamental mode and to radiate too; this distance allows to control the power level radiated by the slot.

For the design, 5 resonant array with axial feed are used, so the end of the guide is shorted and the last slot will be at a $\lambda/4$ short distance. The other slots are separated $\lambda/2$ distance between them, and they are located alternately with respect to the longitudinal axis to compensate for the 180° phase produced by the standing wave generated inside the guide.

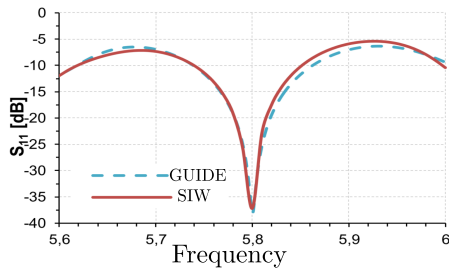
In table 5 are shown the initial values of the group of slots obtained through (Johnson and Jasik, 1984; Farrall and Young, 2004), in figure 12(a) the linear array are represented of slot with SIW guide used for simulations, in figure 12(b) are describe a comparison of S parameter of rectangular guide and SIW guide array.

Table 5: Slot with rectangular guide and SIW guide geometric parameters.

	λ_g mm	u mm	c mm	r mm
Equivalent guide	81.34	1.28	2.96	21.47
SIW guide	81.34	1.38	3.1	22.9



(a)



(b)

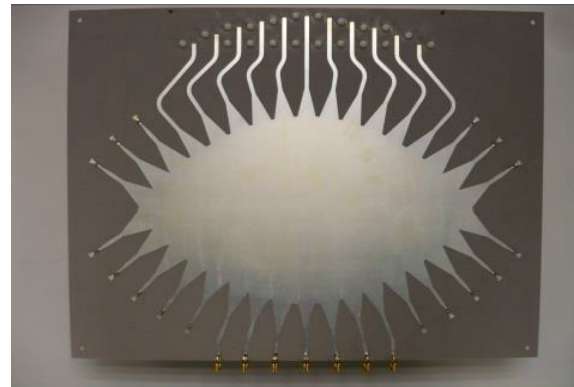
Figure 12: Slot Lineal array with SIW guide. (a) Simulated. (b) S_{11} parameters.

In order to implement the antenna, it is necessary to design a transition between microstrip lines (2 different layers) for obtaining a good bandwidth and also easy to build, in figure 13(a) is shown the proposed prototype with Rotman Lens, figure 13(b) shows a prototype with SIW guide, besides in figure 14 are shown the measured radiation patterns of multibeam antenna prototype.

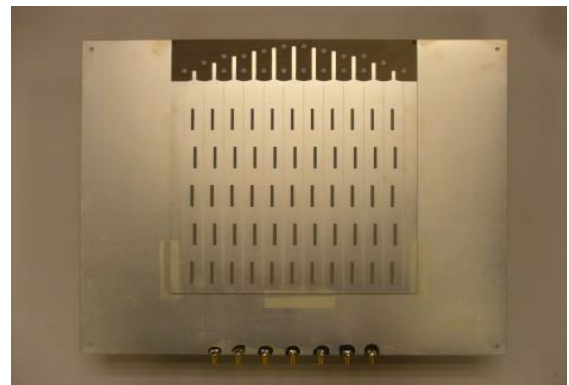
5 Conclusion

Thanks to the design and simulation of the elements of a Butler matrix as hybrid couplers, cross couplers and phase shifters, we achieved obtaining a new model to create a forming network beam, which can serve for antenna array used in applications WiFi. The developed model has the same properties and characteristics of a conventional Butler matrix, furthermore, it has succeeded reducing size up to 7.8cm x 7 cm; these dimensions represent only the 40% of a conventional design.

It was possible to design a beam forming network using a Rotman lens for a frequency of 5.8



(a)



(b)

Figure 13: Photographs of the prototype multibeam antenna. (a) Bottom view (Rotman lens). (b) Top view (SIW slots array).

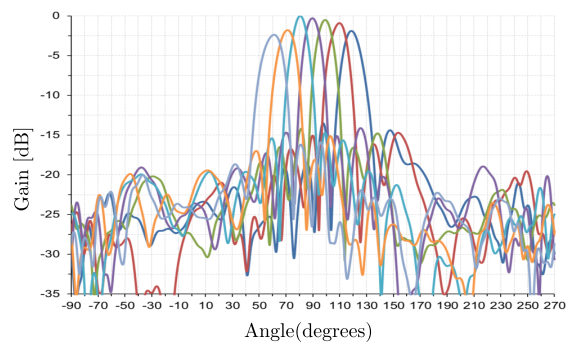


Figure 14: Measured radiation patterns in the prototype multibeam antenna.

GHz, this design could be performed through two types: based on conventional port and SIW guide ports, these results has been demonstrated through experimental procedures.

Interest Conflict

Authors declare that there is no conflict of interest in this research.

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