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A Dual-Band Quasi-Yagi Reconfigurable Binomial Weighted Phased Antenna Array Design

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***Abstract*—In this study, a dual-band Quasi-Yagi reconfigurable binomial weighed phased array design is proposed for the unlicensed Wi-Fi and planned 5G band for European Zone. The analytical calculations, numerical simulations, and experimental analysis are done. The antenna array operates at 2.45 and 3.6 GHz. By analog beamforming and the binominal weighting, the antenna has three distinct main lobes for each corresponding phased configuration with reduced sidelobes. The simulations are done on the High-Frequency Structure Simulator (HFSS), and experimental measurements are carried out on the fabricated prototype. The numerical and experimental results are presented.**

***Keywords*—analog beamforming, antenna design, an electronic switching circuit, reconfigurable binomial weighted phased array.**

I. Introduction

The number of subscribers participating in wireless communication is increasing day by day. Furthermore, it is an expected development for the future, which will be the machines that will be the participants. Despite the increase in wireless communication, the frequency spectrum usage is specified and limited. Therefore, it is sufficient to operate in the narrow band for the remote controlling centered at (2.45 GHz) of indoor vehicles while communicating with the operator via the planned 5G band of European Zone (3.6 GHz central frequency) [1, 2]. The Yagi - Uda antenna type was first published in [3] and since then has kept its importance due to its broadband characteristics and directivity [4, 5]. This design was also inspired by it. The smaller loop stands for, the higher frequency band (3.6 GHz), and the larger rectangular loop corresponds to the lower frequency (2.45 GHz). The scattering parameter at both two bands is less than -15 dB [6, 7]. The design allows steering the beam through the requested or densely used part of the houses or offices. For this reason, the switch mechanism with PIN diode, low loss power divider, and transmission line phase shifters are utilized. Previously, in a similar way, there were studies related to phased arrays for beam steering [8-9].

In Section II, the main design parameters and the design steps for the antenna array are investigated. In the following section, the components responsible for the amplitude weighting, phase shifting, and switch mechanism are explained in detail. In Section IV, the numerical and experimental results are presented. Then, the conclusion and references are drawn as final words.

II. The Antenna Element & Array Desingn

In this section, the antenna design of the system is presented. For the antenna part, a dual-band Quasi-Yagi antenna is preferred. Quasi-Yagi antenna is a special microstrip antenna that composes of two half-loops. The top view of the antenna element can be seen in Fig.1 with the dimensions of each section.

The antenna contains two loop-like structures. Half of the loops are placed on top of the substrate, where the other halves are located at the ground plane. Although there are two similar loop structures, the radiation characteristics due to loops are different. As the antenna is designed to operate in a dual-band fashion, it supports frequencies 2.45GHz and 3.6 GHz. The high frequency of the band resonates at a smaller loop whose side length is denoted as Wm2. This radiator operates as a folded dipole and creates radiation characteristics resembling the dipole. However, as there exists a larger metallic loop closer to the fed point, the symmetric radiation characteristic of the dipole is distorted towards the y-direction. Due to the reflector effect of the ground rectangle and larger loop, the main beam of the 3.6 GHz resonance is directed towards the y-direction.

Even though loop structures seem to resonate and create radiation, this phenomenon is not always applicable. The lower frequency band of the application (2.45GHz) uses a linear section of the antenna denoted as legth1 as the main radiator. For this operation larger loop behaves like a load that achieves matching in the input terminal. As the antenna structure uses a straight line as a radiator, the radiation characteristic of this frequency is identical to a regular dipole. As the resonating loop of 3.6 GHz is located in the null direction of the dipole, the radiation characteristic of the 2.45 GHz is not distorted. The radiated fields plot of both 2.45 GHz and 3.6 GHz can be seen in Fig. 2, respectively.

In Table, I, the corresponding parameters for the unit-cell as given in Fig. 1 are provided.

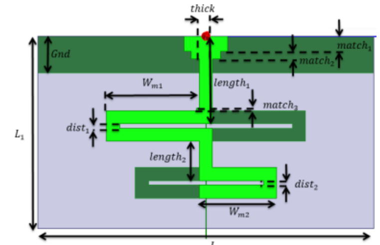
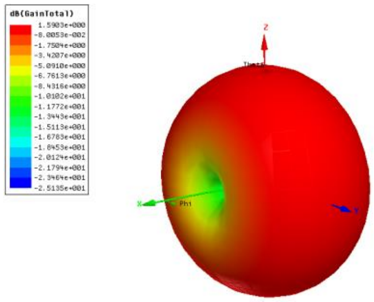
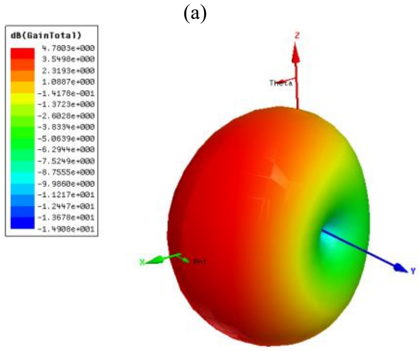


Fig. 1. The geometry of the single unit.



(a)



(b)

Fig 2. The 3D radiation pattern is at 2.45 GHz (a) and 3.6 GHz (b).

TABLE I. PARAMETERS AND DIMENSIONS

Parameters	Dimension (in mm)	Parameters	Dimension (in mm)
$length_1$	10	L_2	38
$length_2$	4.5	Wm_1	10.5
$match_1$	1.7	Wm_2	8.75
$match_2$	0.9	$dist_1$	0.5
$match_3$	0.3	$dist_2$	0.5
L_1	22	thick	1.5

After introducing the antenna element, this paper will continue to explain the array structure and the topology. The reader should not forget to pay attention to the maximum radiation directions of the resonance frequencies. As the operation principle of 2.45GHz and 3.6GHz differs in the antenna element, the radiation patterns after arraying satisfy different properties.

To reduce the sidelobe level, Binomial weighting is preferred. The inter-element distance of the array is determined concerning the half free-space wavelength ($\lambda_0/2$) of the higher frequency (3.6 GHz), and then small optimization is done by the simulation tools. FR4 is employed for the prototype.

III. RF SYSTEM DESIGN

In this section, the RF system design is presented. RF system includes phase shifters, switching mechanism with DC voltage controlled by PIN diode and its circuit, power divider, and the voltage source. To have the required binomial weighting, two power dividers are employed. They are connected as a cascade block in such a way that, the amplitude weightings are 1, 2, and 1, respectively. For the phase compensation of the antenna with the higher amplitude, a special transmission line is also designed to have an equal phase for each transmission line before the phase shifter mechanism [7, 9]. As a first step for the phase shifter part, the different lengths of the transmission lines are required. The corresponding lengths for the different values of the phase difference between each antenna element can be found analytically as (1). Then, the numerical simulations are done for the exact design [10].

$$\phi_0 \approx \frac{\omega}{cl}\sqrt{\epsilon_{eff}} \qquad (1)$$

Here, ω is the angular frequency (rad/sec), c is the speed of light in the vacuum, ϵ_{eff} is the effective permittivity of the substrate and l (meter) is the length of the transmission line. This is the first approximate solution for non-magnetic material. To steer the beam, the different phase change to each antenna element is required. For this purpose, different transmission line lengths are necessary. After that, the switching mechanism is needed to choose the path that corresponds to the desired radiation direction.

In the design, it is planned that there are three options which are 0^0, $\pm30^0$ degree in the elevation axis (θ axis in the spherical coordinate system). To steer the beam $\pm30^0$ degree, it is needed to apply a progressive phase shift of 120^0. For 30^0 steering, the phases $+120^0, 0^0$ and -120^0 are applied while, for -30^0 steering, the phases $-120^0, 0^0$ and $+120^0$ are applied. Those phase changes can be made easily by selecting different signal paths. Another fundamental requirement for beamforming is to have a switching mechanism. To guide the RF signal with minimum loss and to block the DC signal from the antenna element, lumped inductors and capacitors are placed accordingly.

When the DC voltage is turned on, the PIN diodes become active. Then, together with the RF signal and DC pass through the PIN diode. Then, the DC is blocked by the capacitor nearby the antenna elements, as given in Fig. 3. For DC, another path is provided. The prototype of the design is illustrated in Fig. 4. In the figure, the overall picture of the RF design and the antenna is given. The components are designed to be modular to have flexibility, simplicity, and low cost [7, 9].

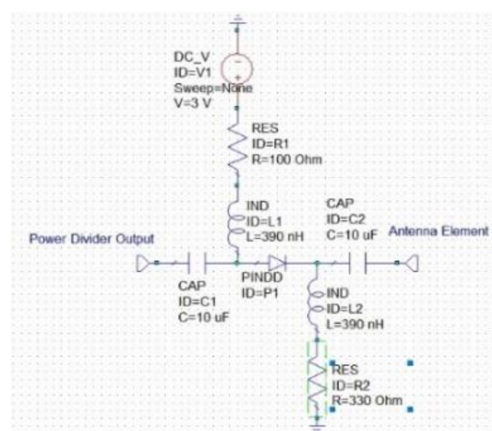


Fig. 3. The circuit schema of the switching mechanism.

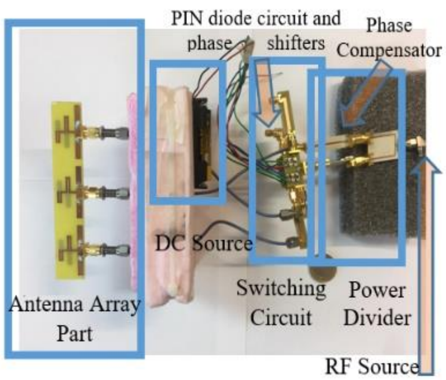


Fig. 4. Designed Groups and manifactured prototype.

IV. NUMERICAL AND EXPERIMENTAL RESULTS

The simulation results of the design are made on the ANSYS HFSS simulation tool. According to this tool, the proposed design achieves both $|S_{11}|$ and far-field radiation patterns. Therefore, to verify performance, a prototype antenna and RF section are manufactured by using LPKF H Promat Machine.

In the corresponding section, the scattering parameter ($|S_{11}|$) of the overall system and the radiation pattern for different beamforming scenarios are presented. Both simulation and experimental results are provided. First, in Fig. 4, the scattering parameters ($|S_{11}|$) is given. As can be seen in the figure, there exist two resonances in the region of interest. These resonances cover both the Wi-Fi and planned 5G bands. From the corresponding figure, the simulation and the experimental outcomes are in harmony. The deviation in frequency is due to soldering and fabrication errors.

Apart from the scattering parameters, to verify the performance of the proposed antenna, the radiation characteristic should be considered. Therefore, the radiation patterns for different resonance frequencies are analyzed considering various spatial planes. To observe the steering of the beam, the pattern measurements are conducted in an anechoic chamber. In Figs. 6, 7, 8, and 9, the far-field radiation patterns are presented. As it is seen, the radiation characteristics are quite similar to the numerical simulation in the main lobes and the beam steering ($\pm 30^0$) is achieved by supplying the predefined phases to each corresponding antenna element. As shown in Fig. 5, the proposed antenna operates in a dual-band fashion in 2.45 and 3.6 GHz.

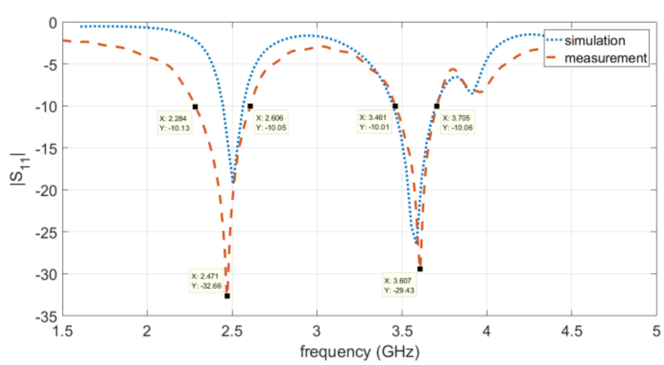


Fig. 5. The amplitude of the scattering parameter $|S_{11}|$.

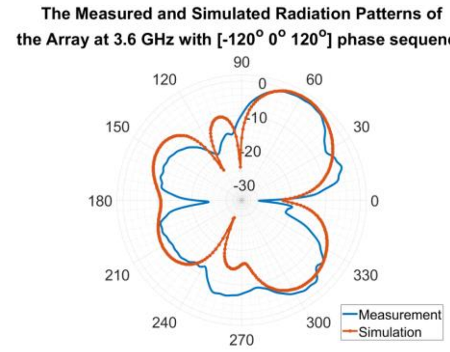


Fig. 6. The radiation pattern for $+30^0$ steered beam in elevation at 3.6 GHz.

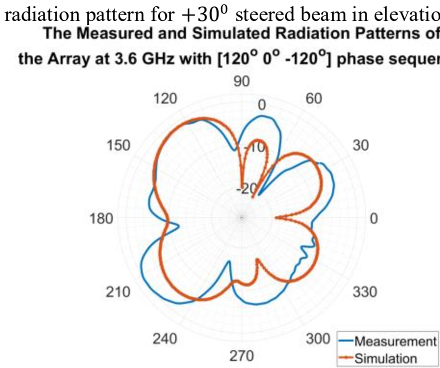


Fig. 7. The radiation pattern for -30^0 steered beam in elevation at 3.6 GHz.

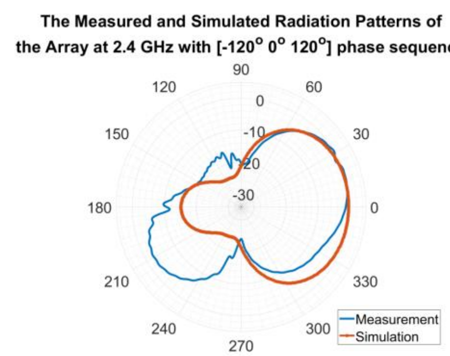


Fig. 8. The radiation pattern for $+30^0$ steered beam in elevation at 2.45 GHz

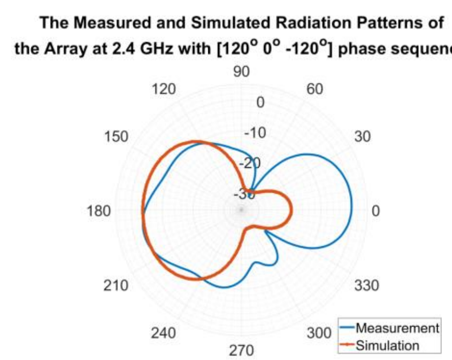


Fig. 9. The radiation pattern for -30^0 steered beam in elevation at 2.45 GH.

The radiation pattern results illustrate a great match with the simulation results. The elevation pattern measurements are taken by sweeping $x - z$ plane. As the plane of interest has a different meaning for both elements, different radiation characteristics are observed from the array structure.

V. Conclusion

In this paper, a reconfigurable binomial weighted phased array antenna is studied. The main lobe beam of the antenna scans 60^0 ($\pm 30^0$) in degree by employing the phase shifters and switching circuit. To verify the performance of the antenna, the scattering parameters and the radiation patterns are simulated and measured. The results are coinciding and the reasons for the deviations between the simulated and the measured outcomes are explained. The antenna array can be utilized for the communication of the devices in houses. The phased arraying and binomial weighting are exploited to steer the beam and reduce the sidelobe levels. The switching mechanism is done by the PIN diode and its circuit. The circuit is designed uniquely by using the fundamentals of circuit theory and the working principle of the PIN diodes.

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