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Planar Yagi-Uda Antenna Array based on Split Ring Resonators (SRRs)

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***Abstract*—A novel planar Yagi-Uda antenna is presented in this letter. The proposed antenna uses electrically small resonators as radiating elements that behave as short electric dipoles. Its radiation pattern, gain, front-to-back ratio (FBR) and efficiency are maintained close to that of a Yagi-Uda antenna of stacked half-wavelength dipoles. However, its physical dimensions are considerably reduced. The choice of the resonant particle and its radiation properties, along with the antenna structure, are discussed. Simulated results show a good impedance matching (–29 dB) at the working frequency of 5.5 GHz for a 15-elements antenna, as well as a high gain (11.5 dBi). These characteristics are experimentally validated and compared with that of others Yagi-Uda designs from the literature.**

***Index Terms*—Electrically small resonators, end-fire array, front-to-back ratio, gain, planar Yagi-Uda antenna.**

I. Introduction

THE Yagi-Uda antenna [1], [2] has been widely used as an end-fire antenna in the last years for TV and amateur radio applications. The classical Yagi-Uda antenna consists of an array of parallel electric dipoles, where only one element needs to be fed and the remaining parasitic elements contribute to build a directional radiation pattern. To optimize the gain and front-to-back ratio (FBR), the lengths and spacing between elements must be properly adjusted [3], [4]. In order to reduce the bulkiness, Yagi-Uda antennas have been implemented in planar substrates, which provide low profile, light weight and mechanical support, as well as compatibility with printed circuitry. On the other hand, feeding the active element can be troublesome due to the presence of the parasitic radiators, although a truncated microstrip ground plane as reflecting element can avoid the use of a reflector dipole [5]. Planar Yagi-Uda antennas can be also configured into arrays to improve the directive gain [6] or the fractional bandwidth [7].

Microstrip Yagi-Uda array antennas based on rectangular patches, first studied by Huang in 1989 [8], avoid the feeding issue and also have the advantages of low profile, simple topology and high gain. However, this solution provided low FBR and was not able to radiate completely end-fire, due to the radiation properties of the patch elements. Successive works focused on improving such limitations achieved high FBR [9], [10] and end-fire radiation [11], where vertical polarization was also obtained due to the excitation of magnetic moments orthogonally to the antenna surface.

Although the length of Yagi-Uda arrays can be tailored by modifying the number of directors, which controls the directivity, their width is typically set by the length of the radiating elements, which is usually close to a half-wavelength. A classic approach to reduce the width consists of using one-wavelength loop elements [12], [13], whose diameter is roughly $\lambda_0/3$ (being λ_0 the free-space wavelength at the working frequency). However, this solution involves a significant increase in the antenna cross-section, and it can not be applied in planar topology.

In this letter, a new planar Yagi-Uda antenna design with significantly reduced width in comparison with conventional designs is presented. The main idea consists in replacing the array elements with electrically small resonators, such as the split-ring resonator (SRR), typically employed in metamaterial devices [14], [15]. Such resonators, along with several derived structures, have also been employed to enhance the functionality of antennas [16], [17], including Yagi-Uda arrays as follows. In [18], meander SRRs etched in the active element reduced the width to $\lambda_0/3.3$, though the gain was significantly reduced. In [19], multiband functionality was obtained by means of square spiral resonator (SSR) loading, and recently, a dual-band design with opposite beam directions was achieved by adding SRRs to the passive element [20]. Nevertheless, the use of such resonators as radiators in Yagi-Uda antennas has not been reported to date. The radiation properties of the SRR antenna at the first (fundamental) and second resonance have been recently analyzed in [21] and [22], respectively. The analysis highlighted that the SRR operated at its second resonance behaves similarly to a half-wave dipole antenna, in terms of input impedance and radiation resistance, yet its lateral dimensions are reduced by almost a factor two. This fact allows a significant reduction of the antenna width, while maintaining similar radiation properties (mainly the gain and the FBR) of the original configuration. As a proof of concept,

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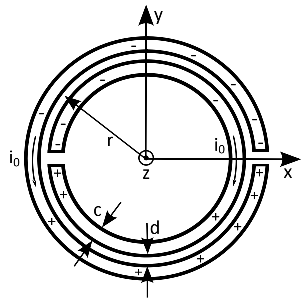

Fig. 1. Layout and charge distributions of the Split Ring Resonator at the second resonance.

a 15-elements planar Yagi-Uda array based on SRRs working at $f_0 = 5.5$ GHz for wireless local area network (WLAN) applications is implemented in this letter.

The work is organized as follows. Section II is focused on the analysis and design of the antenna. To validate the simulated results, a prototype is fabricated and its characteristics are measured and compared with the state-of-the-art in Section III. Finally, the main conclusions are highlighted in Section IV.

II. Proposed Structure

A. *Principle of Operation*

The proposed antenna is an arrangement of electrically small resonators, in this work the SRR, whose topology is illustrated in Fig. 1. As already mentioned, the SRR operating at the second resonance shows high radiation efficiency and an input resistance close to that of a half-wavelength dipole, while reducing the lateral dimensions by roughly a factor of two [22]. At the second resonance, the SRR mainly exhibits an electric dipole moment in the *y*-direction, since the currents in the internal and external rings flow in opposite directions. Such a current configuration also leads to a significant cancellation of the axial magnetic dipole moment generated by the individual rings. Although the far-field contribution of the residual magnetic dipole moment generates a cross-polar component in most directions, that contribution becomes entirely co-polar along the *xz*-plane, where the fields radiated by both moments are parallel. As a result, the polarization along the main beam of the proposed antenna (*x*-direction) is expected to be linear.

To take advantage of the abovementioned behavior, a Yagi-Uda antenna has been designed, where the canonical half-wavelength dipoles implementing the active and parasitic elements (directors and reflector) have been replaced by SRRs. In order to achieve a very directional radiation pattern with high gain in the end-fire direction, a great number of directors has been used. As suggested by conventional Yagi-Uda antenna theory [23], the directors were set to be slightly smaller than the active element, whereas the reflector was set to be slightly larger. Also, the separation between the reflector and the active element was set to be somewhat smaller than the spacing between directors.

B. *Design Process*

The layout of the proposed SRR-based Yagi-Uda antenna consists of 15 elements, as shown in Fig. 2(a). An *ArlonCU 233LX* substrate slab is used, with relative permittivity $\varepsilon_r = 2.43$, dielectric loss $\tan\delta = 0.0022$ and thickness $h = 0.49$ mm.

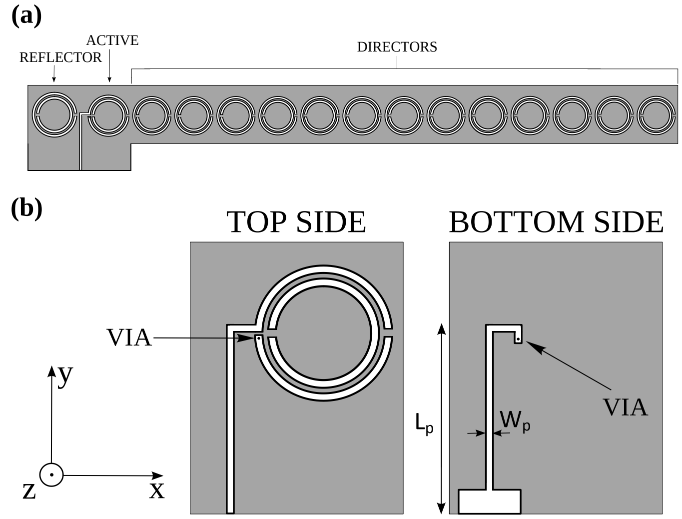

Fig. 2. (a) Illustration of the planar SRR Yagi-Uda array, (b) Feeding network of the active element

TABLE I
Geometrical Parameters of the SRRs

	Reflector	Driven	Directors
c (mm)	0.72	0.70	0.67
d (mm)	0.36	0.35	0.34
r (mm)	5.11	4.96	4.76

Let us now proceed to design the active element. As stated in [22], the SRR mean radius *r* is determined to be $r = \lambda_0/11$ in order to adjust its radiation resistance (which is close to the input impedance due to the low dielectric and ohmic losses) to 50 Ω at resonance. Thus, the mean radius was fixed to $r = 4.96$ mm at $f_0 = 5.5$ GHz. The second step consists of obtaining the strip width *c*. The radiation efficiency of the SRR can be expressed as a function of the metal conductivity *σ*, the mean radius *r* and the strip width *c*. Therefore, to ensure an efficiency above 90% by using copper, the strip was set to $c = 0.7$ mm. The last step consisted of adjusting the second resonance of the SRR at the operating frequency f_0 by tailoring the distance *d*, which controls the coupling between rings. As a result, a distance of $d = 0.35$ mm was chosen. The ring cut width, which does not significantly affect the SRR behavior, was set to 1.3 mm.

The parasitic radiators are designed to optimize the antenna end-fire gain and FBR while keeping the input impedance close to 50 Ω. By means of a parametric analysis, their size and separation were swept around their initial values. As a result, the director was chosen to be 4% smaller than the exciter (while preserving its aspect ratio) and the reflector was found to be 3% larger. The spacing between all directors was set to 17.5 mm center-to-center ($0.32\lambda_0$). Finally, the distance between the active element and the reflector, which has a strong influence on the antenna input impedance [23], was swept to maintain good impedance matching to 50 Ω,

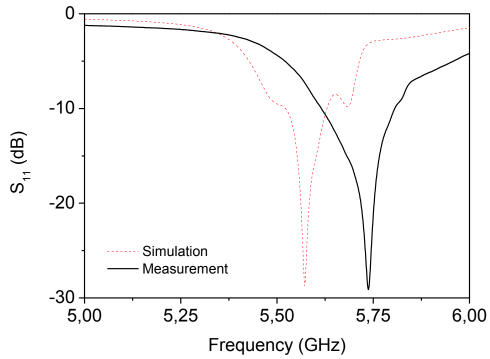

Fig. 3. Simulated and measured power reflection coefficient of the proposed antenna.

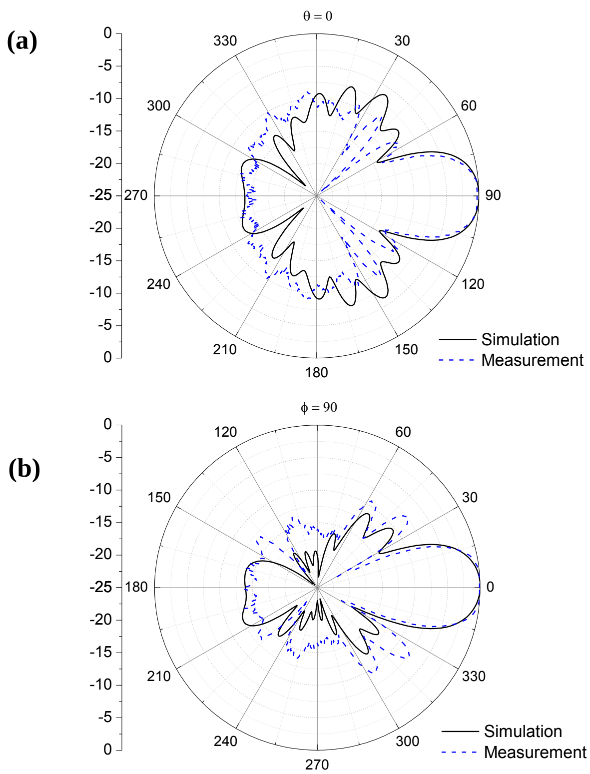

Fig. 4. Normalized simulated and measured radiation pattern evaluated at 5.72 GHz in the (a) *H*-plane (*xz*) and (b) *E*-plane (*xy*).

resulting in a value of 15 mm center-to-center ($0.28\lambda_0$). Table I summarizes all the geometrical parameters for the different elements.

An antipodal excitation based on a paired strip transmission line was used to feed the exciter at the center of the external ring [Fig. 2(b)]. By this means, the use of a balun to feed the antenna is avoided [24], [25]. The strip located in the back side is connected to the lower half of the SRR trough a metallic via. The electrical length of the line was fixed to $\lambda_0/2$ in order to maintain the input impedance equal to that of the antenna, which, as mentioned above provides good impedance matching. Its dimensions were found to be L_p = 18.2 mm and W_p = 0.7 mm, respectively.

III. Simulated and Experimental Results

The layout of the antenna described in Section II has been simulated by means of CST-Microwave Studio. Its power reflection coefficient is depicted in Fig. 3, showing a good impedance matching level (almost –30 dB) around f_0, with a −10 dB bandwidth of 179 MHz. The simulated radiation pattern is shown in Fig. 4. The antenna exhibits a maximum gain of 11.5 dBi or, equivalently, 9.35 dBd in the end-fire direction ($\theta = 90º$, $\phi = 0º$) with a radiation efficiency of 84%. The FBR and the 3-dB beam-width are about 14 dB and 32.5º, respectively, for both planes, but the SLL (Sidelobe Level) is equal to −6.1 dB in the *H*-plane and −10.4 dB in the *E*-plane.

Fig. 5. Illustration of the fabricated SRR Yagi-Uda antenna prototype.

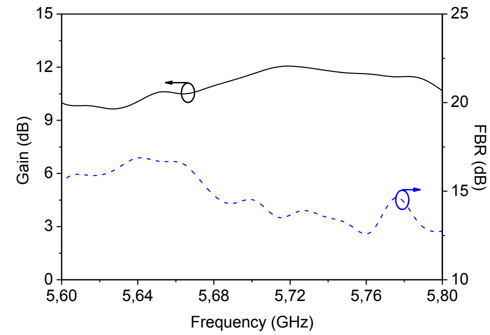

Fig. 6. Measured maximum gain and FBR within the −10 dB bandwidth.

To validate the simulated results, the proposed antenna has been manufactured (Fig. 5) by means of a printed circuit board (PCB) milling machine *LPKF-H100*. A 50-Ω SMA connector soldered on the input port is used to feed the array. The power reflection coefficient of the proposed antenna has been measured by means of an *Agilent N5221A* network analyzer. The results (Fig. 3) show an excellent impedance matching and a −10 dB bandwidth of 191 MHz, which are in concordance with simulations. However, a frequency shift of 165 MHz is produced, as a result of fabrication tolerances.

The experimental radiation pattern of the antenna was obtained with an *Agilent N5221A* network analyzer using the gain transfer method [26]. The Antenna Under Test (AUT) and a reference antenna (*DE0518* broadband horn antenna) were connected to the two ports of the network analyzer and the S_{21} was measured (taking the reference plane at the input of each antenna). The separation between both antennas was set to 8 m, which is higher than the inner boundary of the far field (Fraunhofer) region [23] of the reference antenna (7.4 m) and the AUT (2.3 m). The power gain of our antenna was calculated then from the measured S_{21} using the Friis transmission formula.

The measured radiation pattern is plotted in Fig. 4, showing minor variations with the simulated results due to the scattering effects from the measurement setup. The maximum gain, FBR and 3-dB beam-width are close to the simulated values. However, the measured SLL is 3 dB below its expected value in the *H*-plane and 3 dB higher in the *E*-plane. As shown in Fig. 6, the FBR is more sensitive as a function of frequency than the gain, but both parameters show smooth

TABLE II
COMPARISON OF THE STATE OF THE ART OF PLANAR YAGI-UDA ANTENNAS

	This	[11]	[9]	[27]	[6]	[7]
Nº of elements	15	12	7	7	4	3
Gain (dBi)	11.3	10.4	10.7	9.8	9.3[(b)]	4
Efficiency (%)	84[(a)]	-	85[(a)]	90[(a)]	-	-
FBR (dB)	14	10	15	20[(a)]	11[(a)]	16
FBW (%)	3.3	11.7	10	16.6	2.5	48
Length	$4.6\lambda_0$	$3.47\lambda_0$	$1.95\lambda_0$	λ_0	$1.3\lambda_0$	$\lambda_0/2$
Width	$\boldsymbol{\lambda_0/4}$	$\boldsymbol{1.73\lambda_0}$	$\boldsymbol{1.95\lambda_0}$	$\boldsymbol{\lambda_0/2.1}$	$\boldsymbol{\lambda_0/2.3}$	$\boldsymbol{\lambda_0/2}$

[(a)]Simulated value; [(b)]Directivity

variations within the operational bandwidth. Regarding the normalized cross-polarization in the end-fire direction, the measured value (−25 dB) allows considering the radiation as purely linear, as expected from theory (see Section II).

The main features of the proposed antenna, including the electrical dimensions at the corresponding f_0 and the fractional bandwidth (FBW), are compared with other Yagi-Uda designs in Table II. As expected, the SRR-based antenna shows relatively narrow bandwidth, as its elements are electrically small resonators, so that their quality factor tends to be higher as compared to half-wave dipoles or patches [28]. It can also be seen that the designed antenna follows the general trend in terms of gain, i.e., it exhibits good performance related to its number of elements. Furthermore, the width is reduced by almost a factor two as compared to the state of the art. Since the proposed design does not involve a significant increase in length for a given number of elements, the area occupied by the antenna is halved, while maintaining similar behavior.

IV. CONCLUSION

A novel planar Yagi-Uda antenna, which employs electrically small resonators as the active element, reflector and directors, has been presented in this letter. As a proof of concept, a 15-elements array based on SRRs and working in the WLAN band (5.5 GHz) has been designed and fabricated. The experimental measurements, in good agreement with simulations, confirm that the proposed design allows for a significant reduction of the antenna area while maintaining similar performance as compared to conventional Yagi-Uda antennas, which are usually based on half-wave dipoles or patches.

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