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MODIFIED TWO-ELEMENT YAGI-UDA ANTENNA WITH TUNABLE BEAMS

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Abstract—A modified two-element Yagi-Uda antenna with tunable beams in the H-plane (including four significant beams: forward, backward, omni-directional, and bi-directional beams) is presented. These tunable beams are achieved by simply adjusting the short-circuit position of the transmission line connected to the parasitic element. The principle of operation is investigated by examining the current relations between the driven and parasitic elements. Measured results of a fabricated prototype are presented and discussed.

1. INTRODUCTION

The Yagi-Uda antenna is one of the most popular and widely used antennas because of its simplicity, low cost, directional radiation and relatively high gain. From the early stage of its existence, The Yagi-Uda antenna and its variations have been used not only for home TV applications but also for modern wireless communications [1–7]. A conventional Yagi-Uda antenna, composed of a driven element and several parasitic elements (reflectors and directors), radiates end-fire beams [8]. For home TV application, the feature of directional radiation (end-fire beams) of the Yagi-Uda antenna is desirable because the positions of the TV stations and TV sets are all fixed. However, for wireless communication, the situation is different: the base station is fixed but the terminals carried by users are mobile regularly. Sometimes the Yagi-Uda antenna, similar to other antennas with fixed directional radiations, may not illuminate the terminals efficiently,

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causing a limitation for its application in many new generation mobile communication systems.

Several interesting approaches to modify the Yagi-Uda antenna for this purpose have been studied and reported in the recent literatures: To realize omni-directional coverage, a two-element array was formed by using two back-to-back quasi-Yagi antennas fed in-phase [9]. To realize controlled directional radiations, one method used two or more Yagi-Uda antennas placed at different directions [10], and the other used two or more directors placed at different sides of the driven element [11–15]. Then, the directional radiations were realized and controlled for these antennas by means of electronic switches. In general, the latter method, compared with the former one, can achieve a size reduction because of the sharing of the driven or parasitic element. However, for application in modern wireless communication systems, the relatively high power ratings, severe constraints on PIM (Passive Intermodulation) generation and relatively low production costs usually limit the use of electronic switches, so mechanical techniques must be used [16].

In this paper, a modified two-element Yagi-Uda antenna is presented. Compared with the above-mentioned designs, the proposed antenna features a simple structure (comprising a driven element and a parasitic element) and mechanically tunable beams (including four beams of critical importance: omni-directional beam, forward beam, backward beam and bi-directional beam). One example of utilizing this antenna is that Users are statistically mobile regularly in every single day. They collect at uptown in the night and disperse (or gather) in working area in the daytime. By tuning the beams according to the moving rules of the users, the proposed antenna can illuminate the terminals efficiently, making it very flexible for application in such a system as a base-station antenna. The outline of this paper is as follows. In Section 2, the configuration of the proposed antenna is described, and then the principle of operation is investigated by examining the distributions of current on the two elements. In Section 3, a prototype is fabricated and measured. The simulated and measured results are presented and discussed.

2. DESIGN AND PRINCIPLE

2.1. Configuration of the Proposed Antenna

Figure 1 shows the geometry of the proposed modified two-element Yagi-Uda antenna along with its coordinate and parameters. As a Yagi-Uda type antenna, it consists of two radiating elements. The longer one excited at its center is a driven element, and the shorter

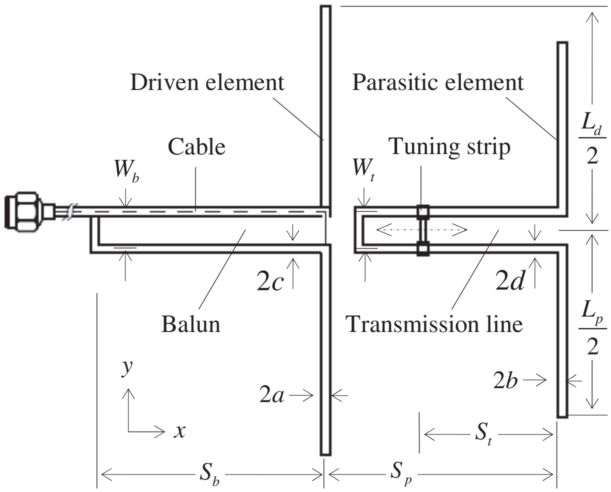


Figure 1. Geometry of the modified two-element Yagi-Uda antenna along with its coordinate and parameters.

one without any excitation is a parasitic element. It should be noted that there is an obvious difference between the conventional Yagi-Uda antenna and the proposed modified Yagi-Uda antenna, which is summarized as: the parasitic elements (directors or reflectors) of the conventional Yagi-Uda antenna are usually straight and continuous metal wires, whereas the parasitic element of the modified Yagi-Uda antenna is formed with two straight metal wires and connected with a short-circuit transmission line at its center. Moreover, the parasitic element of the modified Yagi-Uda antenna, as shown in the following section, acts as not only a director but also a reflector (tunable and controllable), hence it is called a parasitic element herein instead of a director or a reflector directly. The driven element is a dipole antenna with a $\lambda/4$ balun [17].

The short-circuit transmission line connected with the parasitic element is an important tuning device for the modified Yagi-Uda antenna, which has a movable short-circuit strip (i.e., the tuning strip shown in Fig. 1) and a tunable length S. The radiation patterns of the modified Yagi-Uda antenna change when the tuning strip moves along the transmission line, leading to some tunable beams in the horizontal plane (H-plane). Among these tunable beams, four beams are of critical importance and should be highlighted, which are omni-directional, forward, backward and bi-directional beams. The operation principle of the proposed antenna will be investigated further in the next section, which is fulfilled by examining the current relations between the driven and parasitic elements.

2.2. Principle Explanation by Examining Current Relations

As with the conventional Yagi-Uda antenna, the analysis of the modified Yagi-Uda antenna needs to evaluate the currents on both the driven and parasitic elements. Fig. 2 gives a simplified two-element array model with one driven element and one parasitic element. A voltage source is connected to the driven element, and an ideal short-circuit transmission line is connected to the parasitic element. This model is effective and simple for the analysis of current relations versus the variations of length of the short-circuit transmission line.

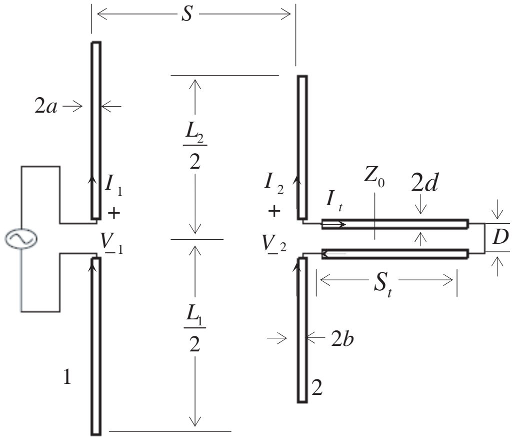


Figure 2. Two-element array model with one driven element and one parasitic element connected with a short-circuit transmission line for current analysis.

Based on the model in Fig. 2, the two-element array can be represented by a two-port network, and the voltage-current relations are [18]

$$V_1 = I_1 Z_{11} + I_2 Z_{12} \tag{1}$$

$$V_2 = I_1 Z_{21} + I_2 Z_{22} \tag{2}$$

On the other hand, the port of the parasitic element is also connected with the short-circuit transmission line, so the voltage V_2 can also be represented by the voltage-current relations of transmission line as follows [19]

$$V_2 = I_t Z_0 \tan\theta \tag{3}$$

where Z_0 and θ are the characteristic impedance and the electrical length of the transmission line, respectively [20]

$$Z_0 \approx 120 \ln \left[\frac{D}{2d} + \sqrt{\left(\frac{D}{2d} \right)^2 - 1} \right] \tag{4}$$

and

$$\theta = 2\pi \frac{L_t}{\lambda} \tag{5}$$

Note that the current on the transmission line (I_t) has an opposite direction to the current on the parasitic element (I_2), so we have

$$I_t = -I_2 \tag{6}$$

Using (3) and (6), we rewrite (2) as

$$-I_2 Z_0 \tan\theta = I_1 Z_{21} + I_2 Z_{22} \tag{7}$$

Solving for I_2/I_1 gives

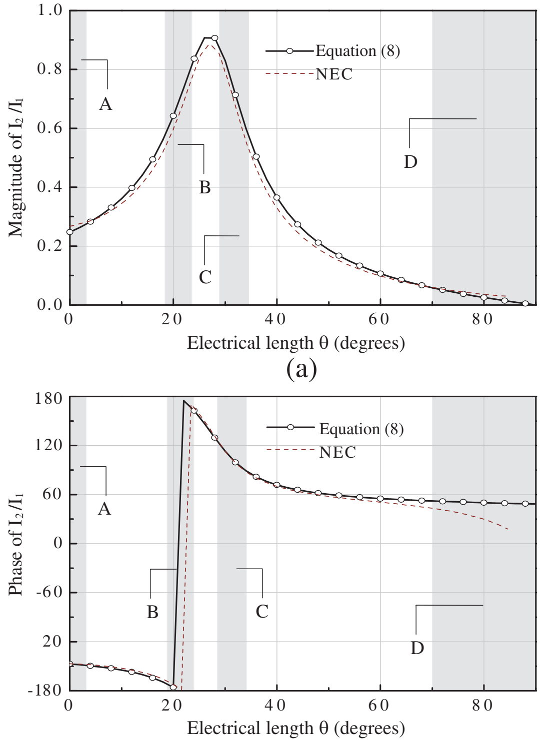
$$\frac{I_2}{I_1} = -\frac{Z_{21}}{Z_{22} + jZ_0 \tan\theta} = -\frac{Z_{21}}{R_{22} + j\left(Z_0 \tan\theta + X_{22}\right)} \tag{8}$$

where R_{22} and X_{22} represent the real and imaginary parts of Z_{22}, respectively.

By using (8), we can further evaluate the radiation pattern for the two-element array. In practice, the proposed antenna can be easily simulated by the use of any MOM (method of moments) software. However, it is worth noting that the evaluation of the current relations between I_1 and I_2 using Equation (8) here is important, not only for understanding the principle of operation but also for predicting useful beams during the tuning process, as demonstrated in the following.

A two-element array with $L_1 = 0.46\lambda$, $L_2 = 0.38\lambda$, $S = 0.25\lambda$, $D = 0.028\lambda$, and $a = b = d = 0.0029\lambda$ is analyzed. The calculated results by using (8), along with the simulated results by using the method of moments-based numerical electromagnetic code (NEC) [21], are shown in Fig. 3. Note that the mutual impedance parameters Z_{21} and Z_{22}, necessary for the calculation of (8), are obtained by the use of an NEC simulation under the condition that the short-circuit transmission line is removed from the model in Fig. 2 (i.e., the model becomes a classic two-element array for mutual analysis as in [18]).

As shown in Fig. 3, the calculated data by (8) are in good agreement with the results directly simulated by NEC software, verifying the validity of (8). Both the magnitude and the phase of I_2/I_1 change when the electrical length of the short-circuit transmission line



(b)

Figure 3. Variations of I_2/I_1 versus the length of the short-circuit transmission line. (a) Magnitude, and (b) phase.

changes. The magnitude reaches its maximum value when $Z_0 \tan\theta = -X_{22}$ and is

$$\left|\frac{I_2}{I_1}\right|_{\max} = \frac{|Z_{21}|}{R_{22}} \tag{9}$$

which means that the capacitance of Z_{22} is just canceled out by the equivalent inductance of the short-circuit transmission line. The phase delay of I_2/I_1 increases monotonically when the electrical length of the short-circuit transmission line increases.

From the variations of I_2/I_1 versus the length of the short-circuit transmission line as discussed above, we can infer that tunable current on the parasitic element can be obtained simply by adjusting the position of the tuning strip (see Fig. 1), resulting in tunable beams for the proposed modified two-element Yagi-Uda antenna. Though the beams can change continuously during such a tuning process, we notice that four beams are of critical importance in our study. These beams are related to the four regions marked as A, B, C, and D in Fig. 3, which is discussed as follows:

Region A: In this region, $\theta \approx 0^\circ$ typically, which means that the tuning strip is moved very close to the port of the parasitic element. In other words, the parasitic element is shorted at its center, forming a parasitic element similar to that of a convectional Yagi-Uda antenna. The current induced on the parasitic element has a lagging phase about -140° and a moderate magnitude relative to the current excited on the driven element. The parasitic element acts as a director, and then the two-element array radiates an end-fire beam in the direction of the parasitic element (towards the positive x-axis in Fig. 1), referred to as forward beam herein.

Region B: In this region, $\theta \approx 20^\circ$ typically. The current induced on the parasitic element has an opposite phase and a relatively larger magnitude relative to the current excited on the driven element. So the parasitic element does not act as a director or a reflector but act as an anti-phase radiating element, making the two-element array radiate a bi-directional beam in the directions of the driven and parasitic elements (towards the positive and negative x-axis).

Region C: In this region, $\theta \approx 33^\circ$ typically. The current induced on the parasitic element, opposite to that for region A, has a leading phase about 90° and a relatively large magnitude relative to the current excited on the driven element. The parasitic element acts as a reflector, and the two-element array radiates a directional beam in the directions of the driven element (towards the negative x-axis), referred to as backward beam herein.

Region D: In this region, $\theta \approx 90^\circ$ typically, which means that the tuning strip is moved very close to the end of the transmission line of length $\lambda/4$. Note that the magnitude of the current induced on the parasitic element is very small. Therefore, the parasitic element has negligible effects on the radiation of the two-element array, i.e., that the two-element array radiates an omni-directional beam in the H-plane. This can also be explained directly by the fact that the impedance of a $\lambda/4$ short-circuit transmission line is equivalent to open circuit.

All of these beams will be demonstrated in the following section with a fabricated and measured prototype operating in the 850 MHz-band.

3. MEASUREMENTS AND RESULTS

3.1. Fabricated Prototype

A prototype of the modified Yagi-Uda antenna operating in the 850 MHz-band was designed and fabricated. The operating frequency was chosen for the prototype because it allows the performance of the proposed antenna to be validated while making the fabrication and measurements convenient. A photograph for the prototype is shown in Fig. 4, and its dimensions are listed in Table 1. The driven element, parasitic element and transmission line were constructed of brass wires. A semi-rigid coaxial cable with a SMA connector was connected to the driven element, which also acts as one of the wires of the balun. The tuning strip was constructed by a copper strip and assembled on the transmission line, which is movable along the line with good electrical contact. An epoxy resin plate was attached to the driven and parasitic elements to provide mechanical supporting and fixing.

Table 1. Geometrical parameters of the fabricated prototype (unit: mm).

Parameter	Definition	Dimension
L_1	Length of the driven element	162.3
L_2	Length of the parasitic element	148.2
S_p	Separation between the two elements	77.7
S_b	Length of the balun	87
a	Radius of the driven element	1.05
b	Radius of the parasitic element	1.05
c	Radius of the balun	1.05
d	Radius of the transmission line	1.05
W_b	Separation of the balun	10
W_d	Separation of the transmission line	10
S_t	Position of the tuning strip	$0 \leftrightarrow 74$

3.2. Simulated and Measured Results

To examine the novel features of tunable beams (especially four significant beams), a large number of radiation patterns for the fabricated prototype were measured in the H-plane which corresponds to the xz-plane in Fig. 1. It was first observed that the radiation patterns changed its formations during the tuning strip moved along the transmission line.

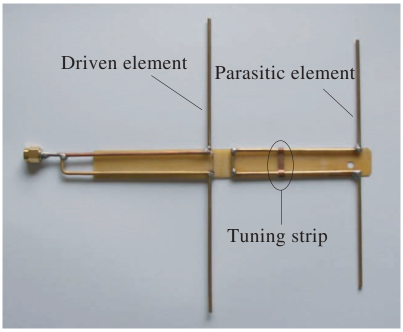


Figure 4. Fabricated prototype of the modified two-element Yagi-Uda antenna.

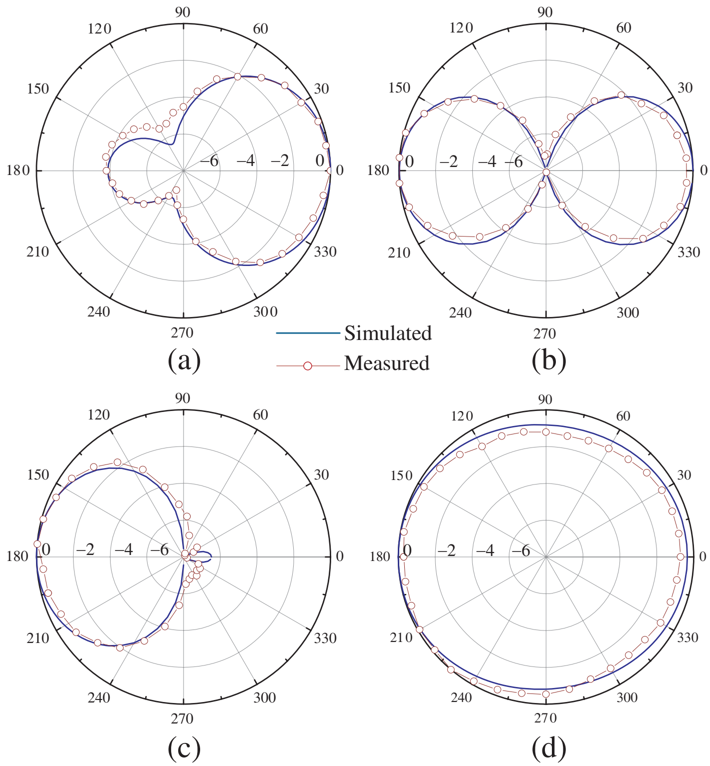


Figure 5. Simulated and measured radiation patterns for the prototype. (a) Forward beam, (b) bi-directional beam, (c) backward beam, and (d) omni-directional beam.

Then, exact measurements of radiation patterns were carried out at 850 MHz under conditions that $\theta = 0°$, $17.3°$, $24.5°$, and $75.6°$ in turn. These values of θ were chosen by examining the current relations between the driven and parasitic elements as discussed in Section 2 and expected to result in a forward beam, a bidirectional beam, a backward beam, and an omni-directional beam for the prototype. The measured radiation patterns for the prototype with each selected θ, along with the simulated results by NEC, are shown in Fig. 5. There is good agreement between the measured results and the simulated data. It is clearly seen that the four desired beams, i.e., a forward beam, a bi-directional beam, a backward beam, and an omni-directional beam are all realized. The data in Fig. 5 are normalized for easy comparison. The maximum gains for the four patterns shown in Figs. 5(a) to (d) are 4.7 dBi, 4.5 dBi, 5.3 dBi, and 2.06 dBi, respectively.

It is also important to examine the impedance matching characteristics for the modified two-element Yagi-Uda antenna at different beam states, which was carried out by using a HP8753D network analyzer to measure the VSWRs versus frequency. A selection of the measured results, corresponding to the four beams in Fig. 5, is shown in Fig. 6.

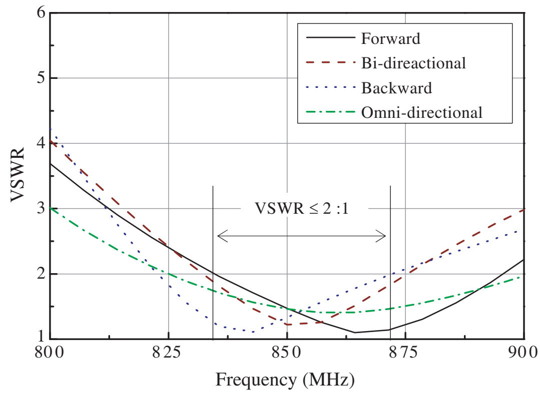


Figure 6. Measured VSWR versus frequency for the prototype.

Two things should be noted: the first thing is that the measured VSWRs change as the tuning strip moves along the transmission line, which is due to the fact that the adjustment of the short-circuit position causea the change of the antenna input impedance as follows

$$Z_{\text{in}} = Z_{11} - \frac{Z_{12}^2}{Z_{22} + jZ_0 \tan\theta} \tag{10}$$

which is derived from (1) by using (8) and $Z_{21} = Z_{12}$ from reciprocity.

Z_{in} represents the antenna input impedance. The second thing is that a more rigorous definition of impedance bandwidth is used, which is defined in terms of the range of frequencies within which VSWR $\leq 2:1$, and this condition must be satisfied for all beam states. As shown in Fig. 6, the measured impedance bandwidth for the prototype of modified Yagi-Uda antenna is 36 MHz (835–871 MHz).

4. CONCLUSION

A modified two-element Yagi-Uda antenna has been proposed. A transmission line with tunable short-circuit position was connected to the parasitic element at its center, forming a tunable device for the modified two-element Yagi-Uda antenna. By adjusting the short-circuit position, i.e., moving the tuning strip along the transmission line, tunable beams for the proposed antenna in the H-plane were achieved. Among these beams, four special beams, i.e., a forward beam, a backward beam, an omni-directional beam, and a bi-directional beam are of critical importance and highlighted.

To evaluate the performance of the proposed design, especially to predict the four significant beams, a simplified two-element array model is introduced to examine the current relations between the driven and parasitic elements. By examining the magnitude and phase of I_2/I_1, four special regions of electrical length of the short-circuit transmission line are pointed out to relate to the four beams, and details of the principle of operation are discussed in each region.

The novel features of tunable beams were demonstrated with a fabricated prototype operating in the 850 MHz-band. Simulated and measured results indicate that all of the four significant beams are obtained by properly tuning the short-circuit positions. A more rigorous definition of impedance bandwidth is used, which takes account of the variations of VSWRs at different beam states.

Though the modified Yagi-Uda antenna features a simple structure and hence a low cost, the antenna has agile beams, making it suitable for application in many modern wireless communication systems. It is reasonable to assume that the configuration proposed in the paper can also be used to develop antennas for other applications.

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