

# Compact Design of Two-elements Cubic Yagi-Uda Array Antenna with High Gain

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**Abstract:** A cubic Yagi-Uda array antenna with high gain for 500 MHz rectenna is proposed. The proposed antenna is composed of two elements of Yagi-Uda antenna. The proposed antenna is compact and its volume is  $\lambda/3 \times \lambda/3 \times \lambda/3$  because the Yagi-Uda antennas share a reflector and director. Performance of the proposed antenna is demonstrated and resultant gain is as high as 8.5 dBi. Finally, the proposed antenna is applied to a 500 MHz rectenna system with voltage doubler rectifiers and its performance is demonstrated experimentally.

**Keywords:** Yagi-Uda antenna, Rectenna, Wireless Power Transfer

**Classification:** Antennas and propagation

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## 1 Introduction

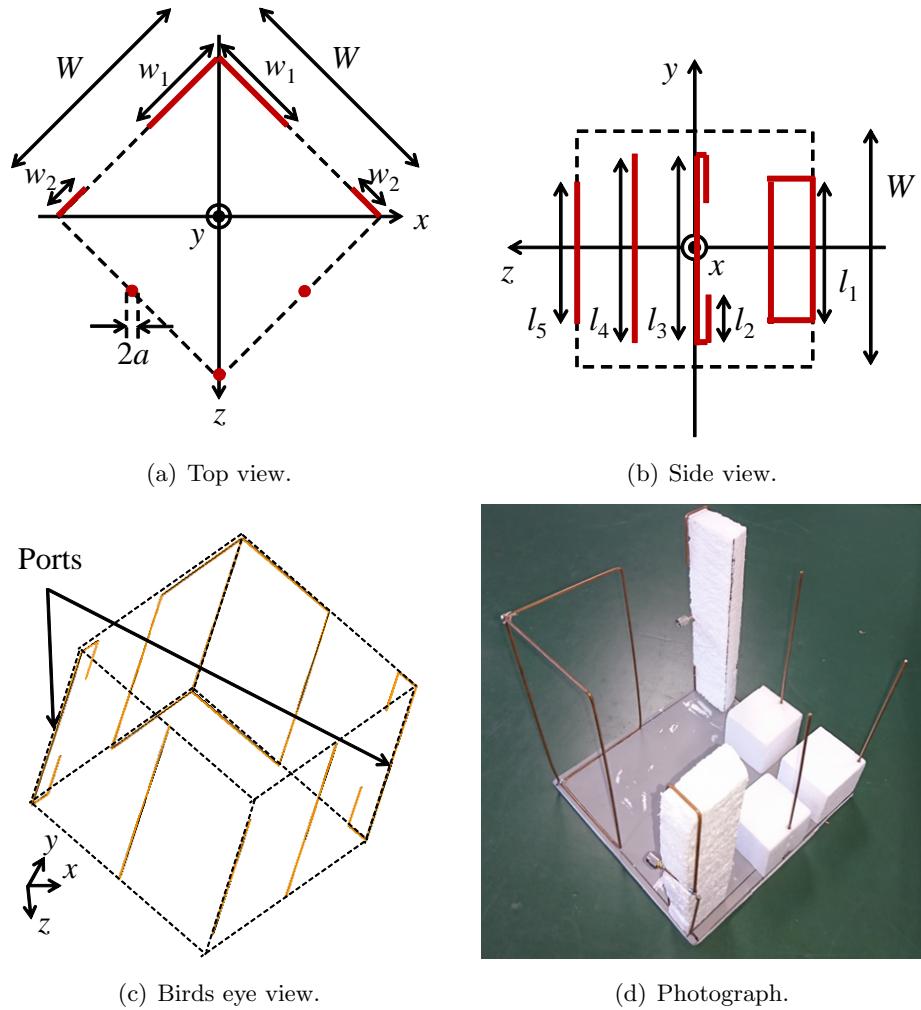
Wireless power transfer (WPT) system has received much attention over 100 years. Extensive efforts have been dedicated to the WPT system since so-called evanescent resonant coupling method, which is able to achieve high power transfer efficiency, was experimentally demonstrated [1]. Although the evanescent resonant coupling method only works for short range, theoretically achievable 100% power transmission efficiency is attractive.

On the other hand, so-called RF energy harvesting is expected to be the next breakthrough for the WPT system. All wireless signals for TV broadcasting, Wi-Fi, and mobile communication system can be “harvested” as an energy source for an electronic device. Especially, the energy harvesting is a potential energy source for low-power, battery-less devices such as IoT (internet-of-things) system.

Previously, studies on rectennas for RF energy harvesting from TV broadcasting signal have been performed. A log periodic dipole array antenna (LPDAA) with a four stage power harvesting circuit has been developed [2]. The TV broadcasting signal was harvested at 4.1 km away from a TV tower and 60  $\mu\text{W}$  was available. A prototype of RF energy harvesting system for TV broadcasting system has been demonstrated [3]. A LPDAA on a A-4 sized sheet was designed and optimized for harvesting the TV broadcasting signal. Shigeta et al. has developed an ink-jet printed dipole antenna for RF energy harvesting from TV broadcasting signal [4].

One of the challenging problems for RF energy harvesting from the TV broadcasting signal is how to increase both antenna gain and rectification efficiency  $\eta_r$  simultaneously. According to antenna theory, it is well-known that antenna gain increases as the size of the antennas increases. Therefore, high receiving power is available for large antennas and rectification efficiency  $\eta_r$ , which strongly depends on input power to a rectifier becomes high when the rectifier is combined with such large antennas. On the other hand, a compact antenna is preferable for RF energy harvesting from the TV broadcasting signal in order to reduce its installation space. Although a couple of antennas have been developed for RF energy harvesting, design of high gain but compact antenna for RF energy harvesting is still remaining as a challenging problem.

In this letter, a high gain cubic Yagi-Uda array antenna is proposed. The proposed antenna is composed of two elements of Yagi-Uda antenna working at 500 MHz band. The Yagi-Uda antennas share a director and reflector in order to achieve high gain without losing its compactness. As a result, volume of the proposed antenna is only  $\lambda/3 \times \lambda/3 \times \lambda/3$ . High gain of the proposed antenna is demonstrated numerically and experimentally. Finally, a fabricated prototype of the proposed antenna is applied to a 500 MHz rectenna and high rectification efficiency is shown. This letter is an enhancement of a reference [5].



**Fig. 1.** Compact two-elements Yagi-Uda array antenna.

## 2 Proposed Two-elements Yagi-Uda Array Antenna

Proposed high gain cubic Yagi-Uda array antenna is shown in Fig. 1. The proposed antenna has two radiators, three directors, and one bended wire reflector. All of these elements are on side of a cube whose volume is  $W \times W \times W$  and  $W = \frac{\lambda}{3}$ . Since the two radiators share the directors and reflector, the proposed antenna is compact. Two radiators are folded in order to match its impedance to rectifier while keeping their compactness. Broadside direction of the proposed antenna is directed to  $z$  direction and is normal to the diagonal plane whose area is larger than any other planes of the cube. The proposed antenna efficiently utilize cubic volume in this manner and high gain is expected to be achievable.

Dimensions of the proposed antenna were optimized via numerical simulation in order to maximize its gain. Numerical simulation was performed using a commercial simulator software FEKO. Operating frequency of the proposed antenna is 500 MHz. Resultant optimum dimensions of the proposed antenna are  $w_1 = 0.1$  m,  $w_2 = 0.02$  m,  $a = 0.001$  m,  $l_1 = 0.2$  m,  $l_2 = 0.05$  m,  $l_2 = 0.035$  m,  $l_3 = 0.2$  m,  $l_4 = 0.2$  m,  $l_5 = 0.15$  m.

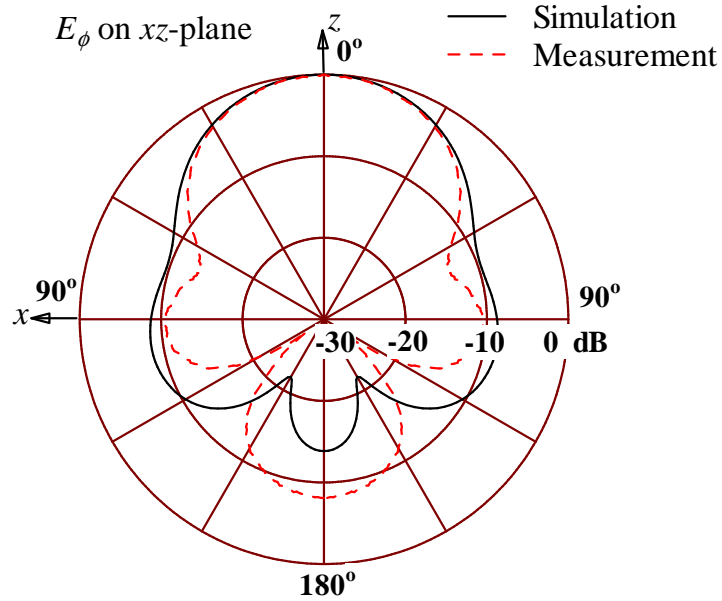


Fig. 2. Radiation patterns(500 MHz).

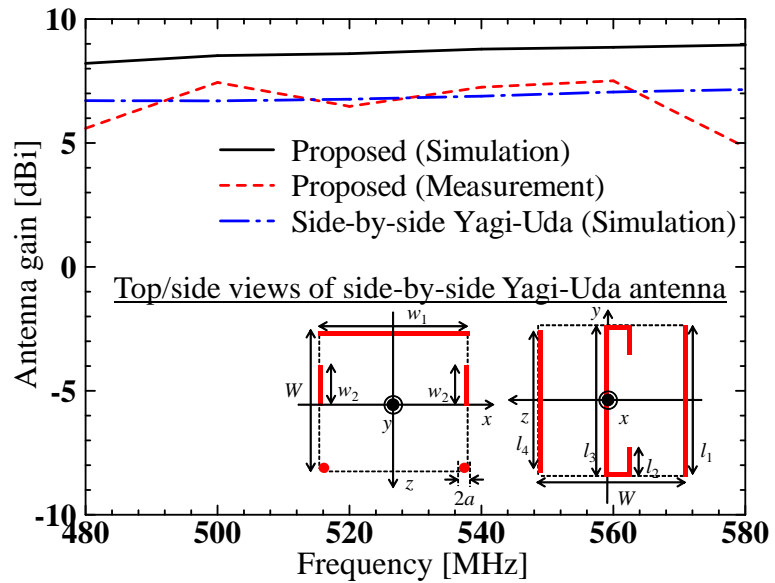


Fig. 3. Antenna gain (Geometry of side-by-side Yagi-Uda antenna:  $l_1 = 200$  mm,  $l_2 = 35$  mm,  $l_3 = 200$  mm,  $l_4 = 180$  mm,  $w_1 = 200$  mm,  $w_2 = 20$  mm,  $a = 1$  mm,  $W = 200$  mm).

### 3 Performance of the Proposed Antenna

Performance of the designed high gain antenna is demonstrated numerically and experimentally. Radiation pattern of the proposed antenna is shown in Fig. 2. Here, two ports are excited by voltage sources with  $50 \Omega$  load during simulation. One port is excited by voltage source with  $50 \Omega$  load and remaining port is terminated by  $50 \Omega$  load during measurement of array element pattern. Measured radiation pattern is obtained from the measured

array element pattern. The simulated radiation pattern is in good agreement with that of the measured one. Back lobe of the measured radiation pattern is larger than that of simulated one because of feeding cables and fabrication error.

Simulated and measured antenna gain of the proposed antenna is shown in Fig. 3. As a reference, simulated antenna gain of a side-by-side two elements Yagi-Uda array antenna, whose volume is  $\lambda/3 \times \lambda/3 \times \lambda/3$  is shown.

Simulated gain of the proposed antenna is 8.5 dBi at 500 MHz while measured one is 7.6 dBi. 0.9 dB discrepancy between the simulated gain and measured gain comes from polarization mismatching, conducting loss, and fabrication error. Owing to our proposed design methodology, the proposed antenna can be designed smaller than conventional Yagi-Uda array of loops whose size is  $1\lambda$  while its gain is comparable to conventional one [6]. On the other hand, simulated antenna gain of the side-by-side two elements Yagi-Uda array antenna is 6 dBi at 500 MHz. Although the geometry of each element in the side-by-side Yagi-Uda array antenna is quite similar to the proposed antenna, the side-by-side Yagi-Uda array antenna is unable to efficiently utilize the given volume while the proposed antenna is able to efficiently utilize its volume. It can be concluded that the design methodology of the proposed antenna is useful to design high gain antenna in a given volume.

Finally, the fabricated antenna is applied to a rectenna for 500 MHz band. This rectenna is composed of the fabricated antenna and two voltage doubler rectifiers. The rectifiers were connected in series and terminated with 1 k $\Omega$  load. Wireless power transmission was performed in a radio anechoic chamber and the performance of the rectenna is demonstrated. A transmitting antenna was a log periodic dipole array antenna (USLP model9143) and its gain is 6.29 dBi @ 500 MHz. Spacing between the transmitting antenna and the rectenna was 3 m. Incident power to the transmitting antenna was 8 W and resultant output DC voltage was 4.37 V. According to the Friis transmission formula, receiving RF power is estimated to be 17.6 dBm. Since the rectifiers were designed so that the maximum power was delivered from the antenna to them, input RF power to rectifiers is estimated to be 14.3 dBm including 0.3 dB mismatching loss between the antenna and rectifiers. Resultant rectification efficiency is  $\eta_r = 71.3\%$ .

It is well known that rectification efficiency strongly depends on input power to rectifiers. Therefore, high rectification efficiency cannot be achieved when the gain of the antenna used for the rectenna is poor and receiving RF power is small. High rectification efficiency of the proposed rectenna demonstrates not only high performance of the designed rectifier but also high gain of the proposed antenna.

#### 4 Conclusion

In this letter, a high gain cubic Yagi-Uda array antenna for 500 MHz rectenna has been proposed. Since the proposed array antenna share a director and reflector, the proposed antenna is compact ( $= \lambda/3 \times \lambda/3 \times \lambda/3$ ). The proposed

antenna efficiently utilize its volume and resultant gain is as high as 8.5 dBi. The proposed antenna has been applied to a rectenna for 500 MHz band and rectification efficiency 71.3 % is realized.

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