Printed Yagi-Uda Antenna Array on CubeSat

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***Abstract*—CubeSats are now becoming increasingly popular for space programs. This is because of their affordability. Moreover, CubeSats can be built using commercial Off-the Shelf (COTS) components. They are cost effective compared with traditional satellites. CubeSats can communicate with each other within a swarm, and with ground station. These capabilities require CubeSats to be equipped with small antennas to facilitate cross-link or downlink communications. Therefore, in this paper, we present a novel design of high gain printed Yagi-Uda antenna and a two element Yagi-Uda antenna array which can be perfectly attached on 3U CubeSat's aluminum bodies to avoid deployment. We have shown a numerical analysis of Yagi antenna array and simulated the antenna using the High Frequency Simulator Structure (HFSS). The simulation model is completed with the existing of CubeSat mental body. Our results show that the antenna array achieves good impedance matching with a return loss of -26.47 dB at the desired frequency of 2.47 GHz, a -10dB impedance bandwidth of 134 MHz (2.396-2.530 GHz) and has a total gain of 6.41dB.**

Keywords—CubeSat; Yagi-Uda antenna; Antenna array; 3D Yagi antenna

I. INTRODUCTION

CubeSats are the largest and most popular type of pico-satellites with a wet mass of about 1.3 kg [1-3]. They have a fixed face size of 10 cm×10 cm with the following depth configurations: 10 cm (1U), 20 cm (2U), and 30 cm (3U). CubeSats provide developers with standard specifications for designing their size, weight and basic construction. It allows one type of parts can suit all types of arrangements. CubeSats are also cost effective not only because they can be built from off the shelf parts but it can be launched as a second payload of larger missions such as the Poly-Picosatellite Orbital Deployer (P-POD) [4]. To date, several CubeSats have been designed, launched and operated successfully at low Earth orbit; examples include CanX-1, CUTE-1, and AUU; see [5]. However, CubeSats also have restrictions on mass and surface area. They are rarely to employ piggyback propulsion system on board, so they usually run on a fixed orbit such as low earth orbit (LEO). Their small size also brings challenges on antenna and solar panel designs. Currently, CubeSats are only limited to simple Earth observation of space exploration missions, sometime insufficient to answer a scientific mystery [6]. Current researching topics related to CubeSat are more related with improving their communication capabilities to support more demanding missions. Specifically, it is necessary to develop the ability of CubeSat communication to be capable with missions that require longer distance communications and higher data rate.

An obvious solution to achieve a more capable communication is to improve the antenna's gain. Antennas for small satellites are expected to support fundamental functions such as telemetry, tracking and command, high-speed downlink for payload data, GPS/GNSS signal reception and inter-satellite cross links. This requires different types of antennas with various frequency range, gain, coverage area and applications. Traditionally, CubeSats running on LEO aiming to operate on VHF, UHF or S-band. Theoretically, most linear antennas such as monopole, dipole and patch antennas that operate in the VHF or UHF bands have large sizes and they cannot fit on CubeSat surface. To this end, antenna designs for CubeSats are required to meet the size and weight restrictions of CubeSats while yielding high gain. To date, some CubeSats employ wire and patch antennas. As an example, the authors of [7] propose a wire antenna as long as five times of a CubeSat edge, so it also requires a deployment mechanisms once satellite launched into space. On the other hand, patch antennas do not require deployment and have low profile. However, they are not capable with steerability and have low gain. Engineers from Jet Propulsion Laboratory have developed several deployable antennas and folded panel reflect array for 6U CubeSat to deal with the oversize problems that can also achieve high gains [8-10]. Moreover, authors of [11] proposed directional inflatable antenna that provides high gain, but its main limitation is the complex structure of the design which needs to fill gas, that not easy for application. Our design is based on a new type of onboard antenna for CubeSat – Yagi-Uda antenna. We propose to employ small-size Yagi-Uda antenna, which is able to be printed on board and avoid deployment mechanism.

Yagi-Uda antenna is a series of dipole antennas, which are widely used in practice since they give directionality to single dipole antenna, but it is rarely seen in CubeSat applications. The typical structure of Yagi antenna includes one driven element, one reflector element and one or multiple directors. With different numbers of driven element, the radiation pattern and gain of the antenna are various. Therefore, it offers good directivity, simple structure, and flexibility to meet various requirements of gain and radiation direction.

The operating frequency plays a major role on the design of Yagi antenna parameters because of the equation: $\lambda = c/f$, where c is the velocity of the light. Thus, when CubeSat operates in the

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VHF (0.03-0.3 GHz) or UHF (0.3-3GHz) bands, it can be noted that the size of the Yagi will definitely exceed the edge of a CubeSat panel. This means that antenna needs to be folded and deployed once reach space. This deployment mechanism incurs extra cost and complexity. In our design, we addressed this limitation by using a small size printed antenna with a planar shape.

In this paper, we design a high gain printed Yagi-Uda antenna array that operates at 2.45 GHz (S-band) and in particular we will demonstrate its performance when mounted on a 3U CubeSat. Due to interference could be created by the CubeSat mental body, our idea is to use the CubeSat's body as an addition reflector to redirect the back radiation forward and hence improve the total antenna gain. A 3D antenna array is also simulated in the section 4.

2. NUMERICAL ANALYSIS

2.1 Model of original Yagi-Uda antenna

Considering a Yagi-Uda antenna is located along the x-axis; see Fig.1. according to [12], the total radiation field at location R is given by:

$$F_{\theta,\varphi} = \sum_{p=1}^{K} I_p e^{jkx_p \sin\theta \cos\varphi} \frac{\cos(kh_p \cos\theta) - \cos kh_p}{\sin kh_p \sin\theta} \quad (1)$$

where K is the number of elements consisting a Yagi antenna that includes a reflector, a driven and multiple directors, where $k = \frac{2\pi}{\lambda}$ the wave number, x_p the x-axis coordinates for $p = 1, 2, \ldots,$ K, h_p the half-length of the pth element.

In this case, we only consider electric field in x-z plane where $\varphi = \varphi_0 = 0^\circ$ in Fig.2, thus the radiation field in equation (1) become to:

$$E_\theta = \sum_{p=1}^{K} I_p e^{jkx_p \sin\theta} \frac{\cos(kh_p \cos\theta) - \cos kh_p}{\sin kh_p \sin\theta} \quad (2)$$

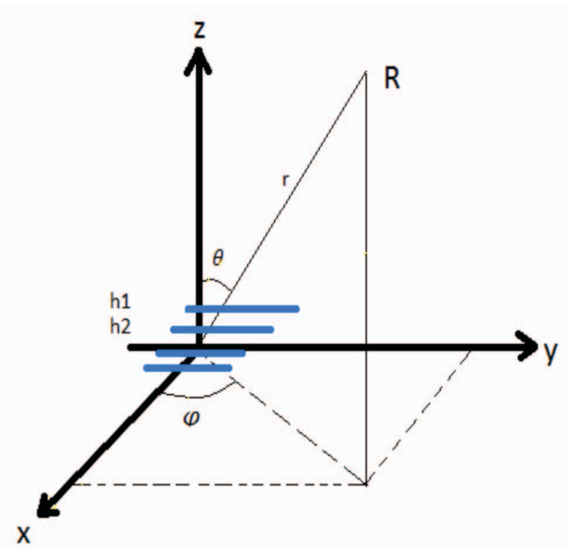

Fig.1. Model of Yagi-Uda antenna in x-y-z axis

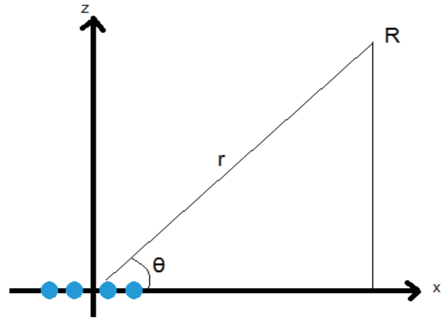

Fig.2 A Yagi-Uda antenna in x-z axis plane

2.2 Multiple parallel Yagi-Uda antenna arrays

A two parallel Yagi-Uda antenna array is illustrated in Fig.3.

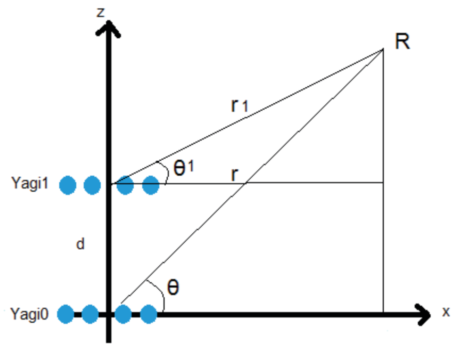

Fig.3 Two parallel Yagi-Uda antenna in x-z axis plane

According to the aforementioned equations, the electric field at location R created by Yagi0 is E_θ, while the electric field produced by Yagi-1 at the point is given by:

$$E_{\theta 1} = \sum_{p=1}^{K} I_p e^{jkx_p \sin\theta 1} \frac{\cos(kh_p \cos\theta 1) - \cos kh_p}{\sin kh_p \sin\theta 1} \quad (3)$$

where $\sin\theta 1 = \frac{r\sin\theta - d}{r1} = \frac{r\sin\theta - d}{\sqrt{(r\sin\theta-d)^2+(r\cos\theta)^2}}$, $\cos\theta 1 = \frac{r\cos\theta}{r1} = \frac{r\cos\theta}{\sqrt{(r\sin\theta-d)^2+(r\cos\theta)^2}}$

Thus, the electric field of each Yagi-Uda antenna element can be expressed by a function of distance between location R and first Yagi antenna (Yagi-0). If there are N identical Yagi-Uda antennas distributing along z axes by equal spacing d, and they are parallel with each other, the electric field of the n-th Yagi antenna is:

$$E_{(\theta n,r)} = \sum_{p=1}^{K} I_p e^{jkx_p \frac{r\sin\theta - d}{\sqrt{(r\sin\theta-d)^2+(r\cos\theta)^2}}} \times \frac{\cos\left(\frac{kh_p r\cos\theta}{\sqrt{(r\sin\theta-d)^2+(r\cos\theta)^2}}\right) - \cos kh_p}{\sin kh_p\left(\frac{r\sin\theta-d}{\sqrt{(r\sin\theta-d)^2+(r\cos\theta)^2}}\right)} \quad (4)$$

The total electric field at location R created by N identical Yagi antenna will be:

$$E_{T\theta} = E_{\theta 0} + E_{\theta 1} + E_{\theta 3} + \cdots + E_{\theta N-1} = \sum_{n=0}^{N-1} E_{\theta n} \quad (5)$$

Based on the analysis in equation (4), equation (5), the total electrical field is:

$$E_{T(\theta,r)} = \sum_{n=0}^{N-1}\sum_{p=1}^{K} I_p e^{jkx_p \frac{r\sin\theta - nd}{\sqrt{(r\sin\theta - nd)^2 + (r\cos\theta)^2}}} \times \frac{\cos\left(\frac{kh_p r\cos\theta}{\sqrt{(r\sin\theta - nd)^2+(r\cos\theta)^2}}\right) - \cos kh_p}{\sin kh_p\left(\frac{r\sin\theta - d}{\sqrt{(r\sin\theta - nd)^2+(r\cos\theta)^2}}\right)} \quad (6)$$

3.ANTENNA CONFIGURATION

A Yagi Uda antenna is printed on a FR4_epoxy substrate with a thickness of 4mm, and attached on one of the 3U CubeSat's surfaces; see Fig.4. The reflector elements of the Yagi are designed as two rectangular sheets on the left, followed by two driver slots and three director slots. The reflector, driver1 and three directors are printed on the top surface of substrate while the driver2 is printed on the other surface of the substrate to create 180° phase difference between arms, so providing the correct feed to the antenna. All of the elements are fed from the same feeding slots and details of the design specifications can be found in Table.1. The size of substrate is 98mm×150mm. A plastic sheet is placed between substrate and 3U CubeSat body to reduce the interference with electronics inside CubeSat. We designed the length of Yagi element as shown in table 1, and then located the Yagi on a largest surface of a 3U CubeSat as shown in Fig.4.

Table 1. Yagi-Uda Antenna Designed Specifications

Length Parameters	Value (mm)
Reflector	49.0
Driven element	42.2
Director 1	40.3
Director 2	38.9
Director 3	37.5
Space between each element	28.1
Elements width	2.0

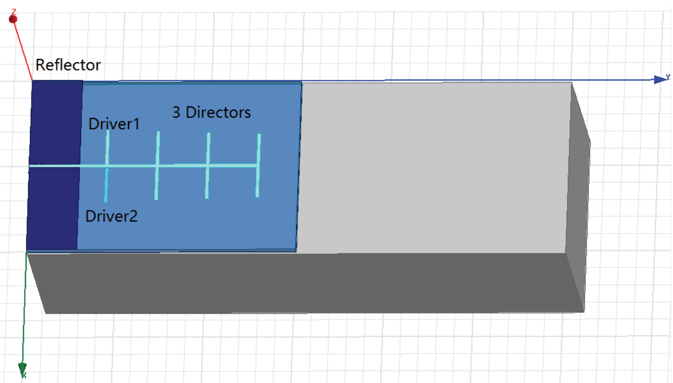

Fig.4 A printed Yagi-Uda antenna on a 3U CubeSat

4.SIMULATION RESULTS

This section outlines the simulation results of a single and two parallel Yagi antennas when they are mounted on CubeSat's body; i.e., return loss, impedance bandwidth, gain and radiation pattern. As known, the aluminium CubeSat body can create interference to the radiation of antenna, the design we proposed had taken this factor into consideration and regarding the CubeSat body as a reflector to achieve the shown antenna performance. Thus, the achieved radiation results are redirected and not symmetric but still provide good performance.

4.1 Printed Yagi Antenna on 3U CubeSat

Fig. 5 and 6 show the 3D and 2D simulated radiation pattern of one printed Yagi on a 3U CubeSat at the resonant frequency of 2.45 GHz. The back lobe is reduced because of the large (3U CubeSat's surface and hence a unidirectional pattern is achieved. The highest gain achieved is 6.19dB with the main radiation direction along z-axis. Fig.7 shows a good return loss of -29.8dB at 2.47GHz. The obtained bandwidth is about 139MHz. The maximum directivity is along z-axis (broadside) instead of endfire due to the influence of CubeSat body.

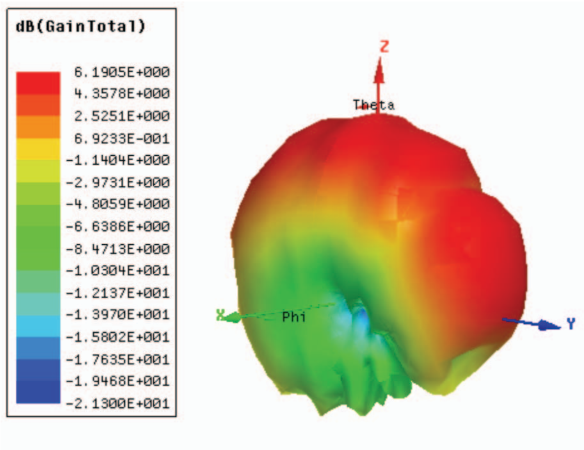

Fig.5 3D polar plot of a printed Yagi on a 3U CubeSat

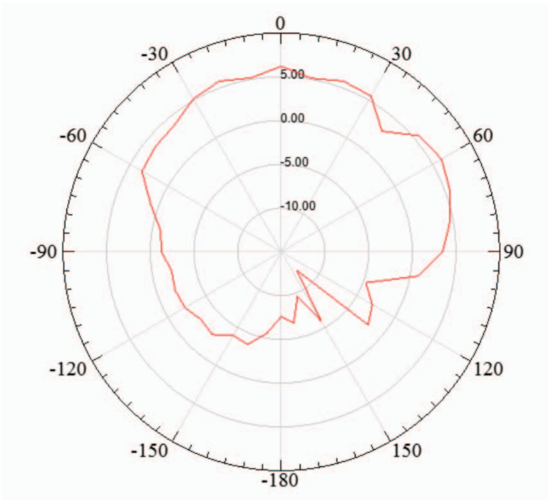

Fig.6 Radiation pattern of a printed Yagi on a 3U CubeSat

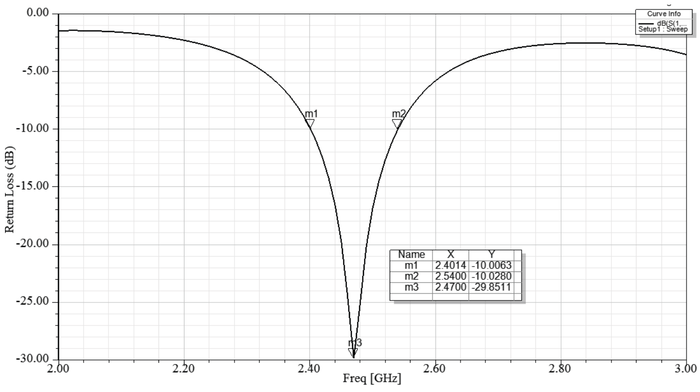

Fig.7 Return Loss of a printed Yagi on a 3U CubeSat

4.2 Two Parallel Printed Yagi Antenna on 3U CubeSat

Based on the pre-mentioned design, we use the same specifications of printed Yagi antenna in last section and placed two same Yagi antennas on two opposite surfaces of a 3U CubeSat as shown in Fig.8. The two Yagi are parallel with each other and fed from the same direction (along positive direction of y axis). The excitation phases of the two Yagi are 0^0 degree and 180^0 representatively.

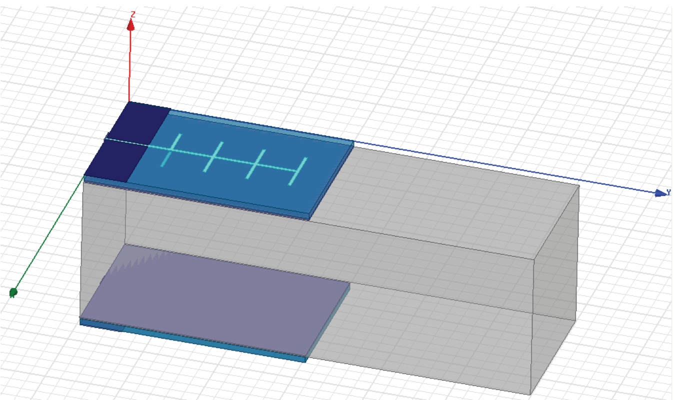

Fig.8 Two parallel printed Yagi on a 3U CubeSat

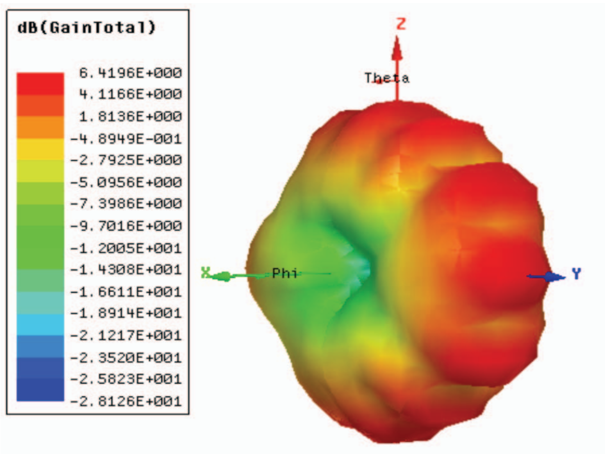

Fig.9 3D Polar Plot of two parallel Yagi on a 3U CubeSat

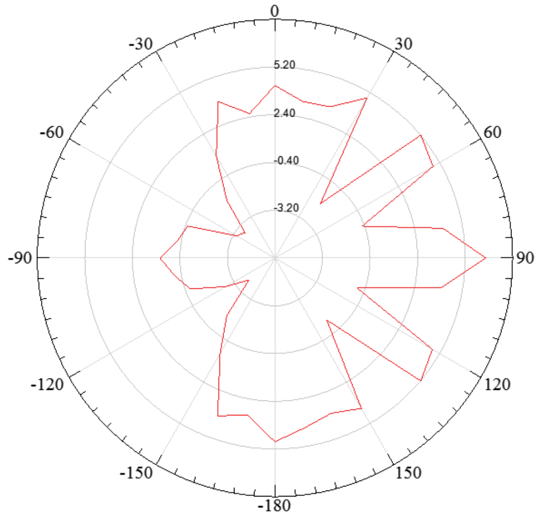

Fig.10 Radiation pattern of two parallel Yagi on a 3U CubeSat

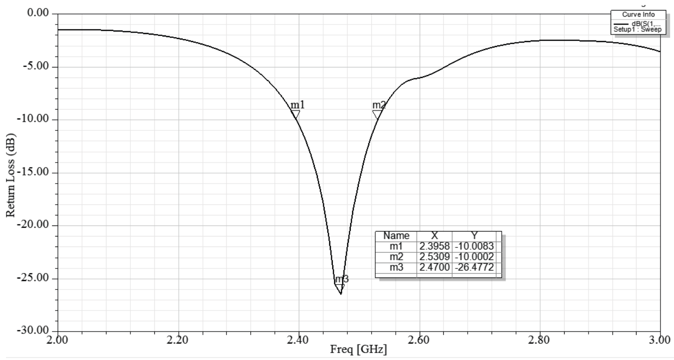

Fig.11 Return loss of two parallel Yagi on 3U CubeSat

As shown in Fig.9 and 10, the highest gain achieved is around 6.4dB. As shown in Fig.11 the return loss is -26.5dB at 2.47GHZ and the bandwidth is up to 135MHz. The direction of main radiation beam is along y axis but not totally uniformed. In this case, it is possible for the application that installing a camera on the 100mm×100mm surface pointing to the earth. Further improvements can be made on gathering the radiation power to create a narrower beam. It is also likely to attach two more Yagi antennas on the remaining two 300mm×100mm CubeSat's surfaces to create a directional beam by adjusting phases. Compared with single Yagi in previous section, the maximum simulation is directed back to endfire.

5.CONCLUSION

The designs of CubeSat antenna have strict restrictions on their size if refuse deployment mechanisms. We proposed a design of 2.5 GHz printed Yagi antenna that can be produced on a 98mm×150mm substrate and attached on a 3U CubeSat to create a high gain of 6.19dB. The CubeSat's aluminum surface is used as a reflector to redirect the back lobe forward and hence significantly increased the total gain. Moreover, two Yagi antennas are used as a two-element array and attached on two opposite surfaces of a CubeSat. The total gain has been slightly improved to 6.41dB. This array can be further improved to achieve higher gain with a uniform pattern. It also has potential to add additional elements.

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