A Novel Multi-beam Lens Antenna for High Altitude Platform Communications

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Abstract— **Waveguide-form multi-beam lens antenna has several shortcomings, such like large size and weight of feed source. According to such situation, a lens antenna applied to high altitude platform is designed. The proposed antenna uses printed Yagi-Uda antenna as feed unit and applies CST MICROWAVE STUDIO® electromagnetic simulation software to analyze. The proposed antenna is manufactured and tested in microwave anechoic chamber. And the simulated and experimental results show that frequency range of the proposed antenna is from 1.77GHz to 2.44GHz with reflection coefficient less than -10dB, relative bandwidth is 31.8%. Antenna gain at 2.1GHz is 9.3dB, which basically accords with the simulated result. Finally, a multi-beam lens antenna fed independently with 6 printed Yagi-Uda antenna units is designed. The proposed antenna has characteristics of wide band, high gain, small volume and light weight. Thus it can be applied in the future high altitude platform communication system.**

Key words—high altitude platform, lens antenna, printed Yagi-Uda antenna, multi-beam

I. INTRODUCTION

Currently, wireless communication system is developing towards higher spectrum efficiency, larger system capacity and more flexible network coverage. High altitude platform communication [1-2] as a new mobile communication mean, its free-space attenuation is smaller and delay time is shorter compared to geostationary satellite. And when compared to ground cellular system [3], its coverage area is larger, and channel fading as well as transmit power could decrease significantly. At the same time, high altitude platform has high flexibility and does not need huge launch base. Besides, it can also transfer rapidly and could be applied to monitor and communicate in natural disaster area.

Antenna system is one of the most key techniques in high altitude platform communication system. Among those antennas, dielectric lens antenna is widely used in HAPS system [4] because of its superior performance. The most typical spherical lens is Luneburg lens [5], which could make incident waves on spherical surface converge to a point, and allow multiple power supplies to feed and generate multiple beams. While because of the difficulty of manufacturing such lens, in practice it is usually replaced by multi-layer coaxial spherical shells. A semi-spherical dielectric lens antenna with ground plane is designed in [6]. Such design can reduce antenna's volume and weight. At the same time, such antenna has relatively high aperture efficiency and multiple scanned beams over a very wide angle. Lens antenna fed by multiple circular waveguide is designed in [7] and the generated beam can cover seven cellular districts (each with radius 2.5km) at the same time. Currently, ITU-R has decided that 2.1GHz frequency band can be applied when HAPS is adopted as base station. Therefore, antennas working at such frequency band are urgent to be developed and designed. However, the lens antennas mentioned above have high working frequency band. If they are used at 2.1GHz frequency band, volume and weight of feed waveguide will increase greatly. Besides, it will be difficult to be installed on the high altitude platform.

Thus, as traditional lens antenna adopts waveguide to feed and unsuitable to work at low frequency, a multi-beam lens antenna working at L/S band is designed in this paper. Such antenna adopts multiple independent printed Yagi-Uda antenna units to feed. When applied in high altitude platform, antenna volume and weight will decrease greatly, and load of high altitude platform will decline. At the same time, the designed antenna has characteristics of small beam width, low side-lobe level, high gain and wide frequency band.

II. DESIGN AND ANALYSIS OF PRINTED YAGI-UDA ANTENNA UNIT

The design of a wideband HAPS antenna [8] has the following needs: (1) Lots of spot-beam designs are needed. Thus multi-beam antenna and phased-array antenna [9] are adopted as HAPS antenna; (2) Antenna should be high-gain directional antenna to overcome electric-wave transmission attenuation at high frequency band; (3) Antenna should have small size, relatively light weight and low mission payload power consumption. Printed Yagi-Uda antenna has characters of light weight, strong directional radiation and easy integration, thus it can be applied to high altitude platform.

Structure of printed Yagi-Uda antenna unit is shown in Fig.1. The whole antenna unit can be considered to consist of four parts, respectively balanced microstrip feeder line, a reflector, active dipole and a director. Feeder lines are respectively printed on the two sides of dielectric slab. On one side the feeder line is connected to the left arm of the dipole directly, on the other side the feeder line is connected to the right arm of the dipole through the via-hole. Thus equal amplitude and reverse phase of current on two arms are achieved. The metal strip on top of the antenna is a parasitic

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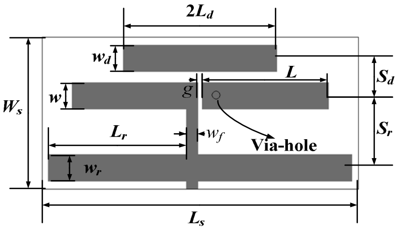
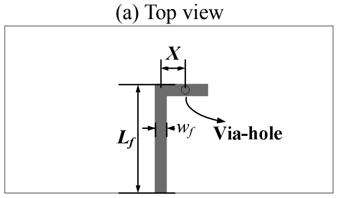
strip, which couples energy from the dipole to change the bandwidth and directivity of the antenna. The function of the parasitic strip is to work as a director. The metal strip on the bottom of the antenna is a reflector, and it also couples energy from dipole. The material of printed dielectric slab is FR4, relative dielectric constant is 4.4 and thickness h=1.5mm.



(a) Top view



(b) Bottom view

Fig.1. Structure of printed Yagi-Uda antenna unit
(w=7mm, w_d=7mm, w_r=7mm, r=0.5mm, w_f=3mm, L_f=26.25mm, L_s=78mm, W_s=40mm, g=0.3mm, x=8mm)

Antenna radiation process is as follows: first exciting current on active dipole generates induced current on director through space electromagnetic field distribution; then they generate free space radiation together. According to dipole lossy transmission line model, there will be a series of resonance phenomena on metal strap. And resonant frequency f is related with length of thin metal strap. Formula (1) can be used to describe:

$$f=\frac{c}{2l\sqrt{\varepsilon_e}} \tag{1}$$

In the formula, c is speed of light; l is length of the metal strap; ε_e is effective relative dielectric constant of the dielectric slab. Director, reflector and active dipole shown in Fig.1 are metal straps with different l. Multiple similar resonant frequencies will be achieved by selecting their lengths properly, and frequency band can be broadened by coupling. The simulated results shown in Fig.2 show that antenna's bandwidth is 1.67-2.50GHz and relative bandwidth reaches 39.8%. Compared with separate dipole antenna, its bandwidth has increased greatly.

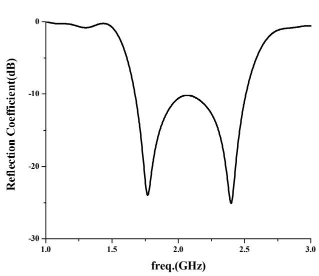


Fig.2. Simulated results of printed Yagi-Uda antenna unit reflection coefficient

Surface currents on the metals of antenna active dipole, director and reflector all present standing wave distribution. They can be equivalent to the current distribution of half-wave dipole. These half-wave dipoles are fed independently, and the feed amplitude and phase should be obtained through correspondingly simulated results of antenna metal surface current. The proposed antenna can be regarded as a array model composed of three half-wave dipoles (shown in Fig.3). Directivity function of such model can be described by formulas (2)-(6).

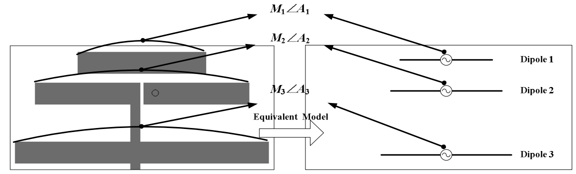


Fig.3. Equivalent dipole array model of the proposed antenna

$$f_E(\delta)=\frac{\cos(kl\cos\theta-\cos kl)}{\sin\theta}\times[(1+M_1\cos\psi_1+M_3\cos\psi_3)^2+(M_1\sin\psi_1-M_3\sin\psi_3)^2]^{\frac{1}{2}} \tag{2}$$

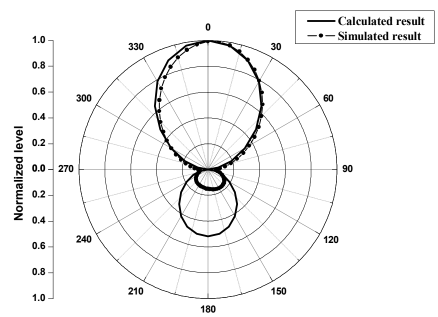
$$f_H(\delta)=[(1+M_1\cos\psi_1+M_3\cos\psi_3)^2+(M_1\sin\psi_1-M_3\sin\psi_3)^2]^{\frac{1}{2}} \tag{3}$$

$$\psi_1=ks_d\cos\delta+(A_1-A_2) \tag{4}$$

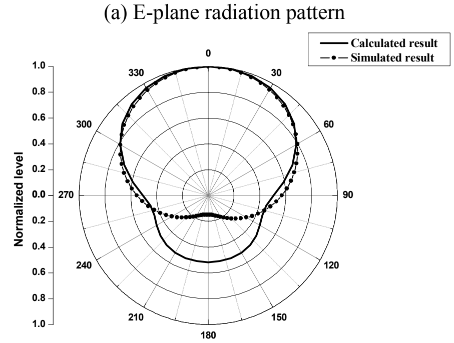
$$\psi_3=ks_r\cos\delta-(A_3-A_2) \tag{5}$$

$$k=\frac{2\pi f\sqrt{\varepsilon_e}}{c} \tag{6}$$

According to formulas(2)-(6), normalized pattern of the equivalent dipole array model can be got. When comparing with simulated pattern of the proposed directed antenna, it is found that their main lobes have good similarity (shown in Fig.4). Thus equivalent dipole array model can be applied to explain radiation characteristics of the proposed antenna.



(a) E-plane radiation pattern



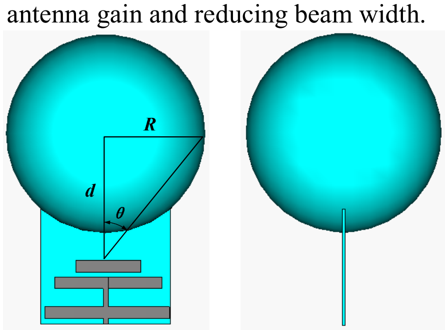
(b) H-plane radiation pattern

Fig.4. Comparison results of equivalent model's pattern and proposed antenna's simulated pattern (2.4GHz)

III. DESIGN AND ANALYSIS OF SPHERICAL DIELECTRIC LENS ANTENNA

A. Single-beam spherical dielectric lens antenna

Structure of lens antenna is shown in Fig.5. Relative dielectric constant of the dielectric lens ball is 2.2 and radius of the ball is R. The ball is connected with the dielectric slab of printed Yagi-Uda antenna and distance between ball center and printed Yagi-Uda antenna is d. Dielectric lens can have electromagnetic energy converged. Besides, it has effects of increasing antenna gain and reducing beam width.



a) Top view (b) Left view

Fig.5. Structure of spherical dielectric lens antenna

For lens which can have electromagnetic energy converged, feed source energy mainly focus on main lobe. So when designing lens' radius and feed-source phase center size, cone angle 2θ (formed when feed-source phase center casts on the lens) should be bigger than antenna's main beam width. Then formula (7) should be met to achieve optimal gain increase.

$$2\theta = 2\arctan\left(R/d\right) \geq \max\{\mathrm{HPBW_E}, \ \ \mathrm{HPBW_H}\} \tag{7}$$

When optimal gain value is achieved, antenna's gain will be of positive correlation with antenna's aperture. The relation can be described by formula (8).

$$\mathrm{G} = 4\pi S\nu/\lambda^2 = \left(2\pi R/\lambda\right)^2 \nu \tag{8}$$

Along with the change of θ, difference between lens antenna's gain and feed source's gain ΔG is shown in Table 1 (at 2.1GHz). It is found that when radius of the dielectric ball is fixed, as θ increases, ΔG also increases. This can be explained by formula (7). After energy in main beam of feed source has been converged by lens, increasing lens cone angle value will have little influence on antenna's gain. Thus there exists an optimal θ, and distance between lens and feed source can be designed by formula (7). Besides, parameter θ is not the only factor that determines antenna's gain. When θ is set with different values, antenna's gain will increase within certain range with the increase of dielectric ball radius. In this paper, the final θ=42°, and at this time R=45mm, d=5mm. These values are all selected according to the size of feed source and aims at achieving miniaturization of the whole lens antenna. As d is very small, for fear of causing reflection to influence feed source's reflection coefficient, lens relative dielectric constant should not be too big. Then the final ε_r is selected as 2.2.

TABLE 1 SIMULATED RESULTS OF ΔG WITH DIFFERENT Θ VALUES AT 2.1GHZ

	θ(deg.)	17.2	19.8	23.2	27.9	34.7	39.3	42.0
ΔG(dB)	R=45mm	3.1	3.5	3.9	4.2	4.4	4.5	4.5
	R=120mm	2.1	3.3	4.8	6.5	8.3	9.7	9.9

According to above size, an antenna unit prototype and a lens ball entity are manufactured. Lens antenna's reflection coefficient is tested with Agilent E8363B vector network analyzer. And the simulated and experimental results are listed in Fig.6. The simulated and tested results match well and the tested results show that from 1.77GHz to 2.44GHz, reflection coefficient is less than -10dB (relative bandwidth 31.8%). Besides, from 1.90~2.35GHz, reflection coefficient is less than -15dB (relative bandwidth 21.2%). This frequency range can cover working frequency band of high altitude platform communication system. Simulated results indicate that, because material's low relative dielectric constant, the proposed lens will not have much influence on feed source's reflection coefficient.

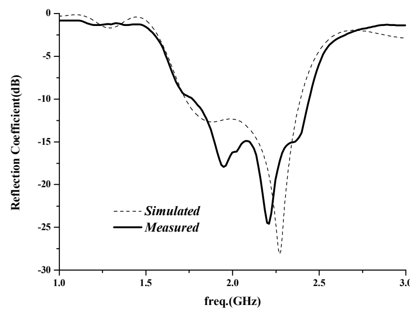


Fig.6. Simulated and tested results of lens antenna's reflection coefficient

Patterns of the proposed antenna are tested (shown in Fig.7) and the simulated and tested results are shown in Fig.8. The results indicate that lens antenna has relatively strong directional radiation characteristics. E-plane beam width is 58° and H-plane beam width is 64° at 2.1GHz. Through comparison method, antenna's tested gain value is 9.3dB, which increases by 4.0dB comparing to feed source. Simulated and tested results indicate that there is little difference between antenna's beam width on E-plane and H-plane. Thus beam with approximately rotational symmetry shape can be achieved. This will be beneficial for high altitude to cover cellular areas.

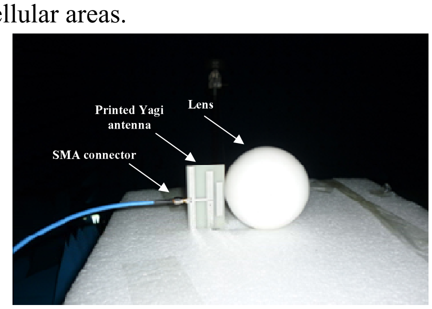
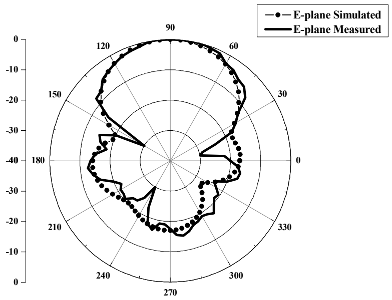
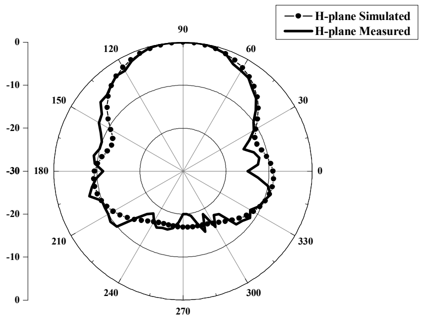


Fig.7. Tested environment of dielectric lens antenna



(a) E-plane radiation pattern



(b) H-plane radiation pattern

Fig.8. Simulated and measured radiation patterns of dielectric lens antenna at 2.1GHz

B Multi-beam dielectric lens antenna array

With the foundation of above discussion, multi-beam dielectric lens antenna array applied to high altitude platform communication system is designed. The antenna's structure is shown in Fig.9. Six independent feed units generate six beams. Included angle α between antenna units is 30°; radius of dielectric lens ball is 120mm; relative dielectric constant is 2.2; feed distance d is 5mm.

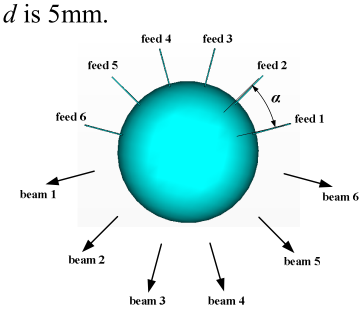


Fig.9. Structure of multi-beam dielectric lens antenna array

Simulated H-plane pattern of multi-beam dielectric lens antenna array is shown in Fig.10. The results indicate that H-plane beam width of the designed multi-beam dielectric lens antenna array at 2.1GHz is 27.5°. Side-lobe level is -14.4° and gain is 15.2dB. From Fig.10, antenna's 3dB beam achieves seamless coverage, which is to say that link gain of the cell boundary can also be up to 15dB. Because only a row of antennas are placed, so multi-beam antenna can cover angular domain of 177°×29.1°. Such antenna can achieve function of multi-beam switchover through electronic switch. Besides, it has wide-angle sweeping characteristics.

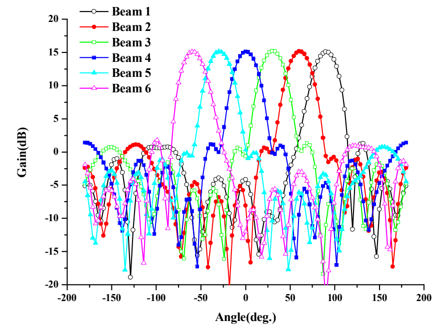


Fig.10. Simulated H-plane radiation pattern results of multi-beam lens antenna array

Note that the proposed antenna adopts low-profile and light-weight printed directed antenna, so six independent feed sources can realize to be set on spherical lens with radius merely 120mm. If traditional metal waveguide port is used as feed source, then the port size will be above 100mm. Besides, antenna's size and weight will increase greatly.

IV. Conclusion

According to the situation that traditional lens antenna array is usually fed by waveguide, in this paper a novel multi-beam dielectric lens antenna array fed by printed by Yagi-Uda antenna unit is proposed. The simulated and tested results show that frequency range of the proposed antenna is from 1.77GHz to 2.44GHz with reflection coefficient less than -10dB, relative bandwidth is 31.8%. Antenna's gain at 2.1GHz is 9.3dB. And multi-beam lens antenna array's gain at 2.1GHz is 15.2dB. H-plane beam width is 27.5° and can achieve 177° scanning characteristics. Besides, such antenna has advantages of small volume and light weight. It can be applied to high altitude platform communication system.

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Reference

[1] G.M. Djuknic, J. Freidenfelds, and Y. Okunev, "Establishing Wireless Communications Services via High-Altitude Aeronautical Platforms: A Concept Whose Time Has Come?", *IEEE Communications Magazine*, vol. 35, No. 9, pp. 128-135, 1997.

[2] S. Karapantazis, and F.-N. Pavlidou, "The Role of High Altitude Platforms in Beyond 3G Networks", *IEEE Communications Magazine*, vol. 12, No. 6, pp. 33-41, 2005.

[3] Wu Youshou, "High Altitude Platform Stations Information System--New Generation-Wireless Communications System", *China Radio Management*, vol. 6, pp. 3-8, 2003.

[4] John Thornton, "A Low Sidelobe Asymmetric Beam Antenna for High Altitude Platform Communications", *IEEE microwave and wireless components letters*, vol. 14, No. 2, pp. 59-61, 2004.

[5] Jinghui Qiu, Shu Lin, Ying Suo, and Qidi You, "The Simulation of the Focus Character of a Luneburg Lens Antenna", 1st International Symposium on Systems and Control in Aerospace and Astronautics(ISSCAA 2006), pp. 1429-1431, 2006.

[6] J. Thornton, "Wide-Scanning Multi-Layer Hemisphere Lens Antenna for Ka Band", *IEE Proc.-Microw. Antennas Propag*., vol. 153, No. 6, pp. 573-578,

2006.
[7] Marco Letizia, Jean-François Zürcher, Benjamin Fuchs, Juan Ramon Mosig, Anja Skrivervik, “Circularly Polarized Multi-Beam Lens Antenna System for High Altitude Platforms (HAPS)”, Proceedings of the 5th European Conference on Antennas and Propagation (EUCAP), pp. 1051-1055, 2011.
[8] Zain Elabdin Omer Elshaikh, Md Rafiqul Islam, Ahmad Faris Ismail and Othman O. Khalifa, “High Altitude Platform for Wireless Communications and Other Services”, International Conference on Electrical and Computer Engineering (ICECE'06), pp. 432-438, Dec. 2006.
[9] Yang-Su KIM, Dae-Sub OH, Jong-Min PARK, Bon-Jun KU, “Conceptual Design of Active Phased Array Antenna of Ka Band System for Stratospheric Platforms”, IEEE Global Telecommunications Conference (GLOBECOM'03), pp. 3302-3305, Dec. 2003