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W-band high aperture efficiency monopulse Cassegrain antenna based on aperture field approach

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Abstract: A high aperture efficiency W-band Cassegrain dual-reflector monopulse antenna is proposed for helicopter collision avoidance radar applications. Aperture field approach method has been investigated to increase the whole performance of the proposed antenna with unequal phase aperture distribution in W-band. The proposed monopulse antenna integrated with the aperture size of 135 mm and focal length of 40.5 mm was fabricated. A sum-difference network based on the E-plane branch line bridge was designed to test the antenna. Measured results show that the gain of the antenna is 38.6 dBi at 93 GHz, corresponding to the aperture efficiency of 54.7%. In addition, it owns the null-depth better than −24 dB and the side-lobe below −18 dB. Measured results are in good agreement with predicted ones. It is demonstrated that the proposed structure is an attentive candidate of high aperture efficiency W-band monopulse antenna.

Key words: aperture field approach, Cassegrain antenna, monopulse, sum-difference network, W-band
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基于口面场方法的W波段高口面效率单脉冲卡塞格伦天线

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摘要:提出来一种应用于直升机防撞雷达的高口面效率W波段单脉冲双反射面卡塞格伦天线.口面分析方法的提出解决了W波段反射面天线口面相位分布不均匀的缺陷,从而有效地提高了口面的利用效率.利用该方法,本文研究并制作了口径为135 mm、焦距为40.5 mm的W波段卡赛格伦天线,并且设计了由四个E面多缝隙电桥和四个四分之一波导波长延迟线级联构成的和差网络.经测试,该单脉冲天线在93 GHz具有38.6 dBi的和波束增益,相应的口面效率为54.7%;差波束的零深优于−22 dB,副瓣电平小于−18 dB.测试结果与基于口面分析方法的仿真结果吻合,从而证明了本文所研究天线可以应用于高口面效率的W波段单脉冲系统中.

关　键　词:口面分析方法;卡塞格伦天线;单脉冲;和差网络;W波段

中图分类号:TN823+.27;TN823+.28　　**文献标识码**:A

Introduction

Recently, the challenging of obstacle avoidance has witnessed explosive growth driven by the low-altitude aircrafts development. For example, helicopters are commonly used for the agricultural insecticide spraying operation and the aerial photography, and they will fly at very low altitudes closing to the ground[1]. Encountering natural and man-made obstacles is the biggest risk for low-altitude aircrafts, like helicopters. With the development of computational capacity, sensor capability and signal processing technique, a variety of avionic auxiliary equipments has been adopted in the low altitude flight regimes. Though optical sensors like laser radar[2] or optical imaging radar[3] have higher location accuracy of obstacles, they cannot work under all-weather conditions and need complex image-processing stage. Microwave ra-

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dar is larger and has lower detection accuracy[4]. With increasing of the demand for more comfortable and safer aircrafts, millimeter wave radar can help drivers to deal with complex traffic scenarios and improve the user-driving experience. Within it, the micrometerave antenna is the core component. For the radar to monitor the surrounding accurately, the antenna is required with high efficiency to obtain high gain, better positioning accuracy under the condition of limited aperture, low side-lobe level to avoid false-alarm, and low profile to save space.

Reflector antennas or lens antennas are preferred comparing with the others by using of dielectric substrate material, because the loss of substrate at W-band is large. The encouraging progresses in dielectric lens design are studied in Ref. 5-7, but the cost is very high. Though reflectarray antennas have been employed in many areas[8], some drawbacks exist when working at W-band. A W-band planar Fresnel printed reflector antenna with the aperture size of 130 mm is introduced in[9]. However, the aperture efficiency of the antenna is only 35.3%. A 94 GHz offset dual-reflector antenna with reflectarray sub-reflector was proposed[10] for beam steering application, with the aperture size of 120 mm and aperture efficiency of 53%. However, this antenna is bulky and the reflectarray sub-reflector is complicated. A 300 mm W-band offset-feed reflector antenna is presented in Ref. 11 for radiometer application. In this antenna, the multi-mode feed was designed to reduce the amplitude of cross-polarization, but the measurement gain is 41.18 dBi with the aperture efficiency of only 15.2%.

A high aperture efficiency W-band Cassegrain monopulse antenna is proposed in this paper. The antenna consisting of metal parabolic main-reflector and hyperbolic sub-reflector is a good candidate in W-band for helicopter collision avoidance applications. It has been said that the blockage and near-field effects on smaller size and lower profile aperture based on the traditional Cassegrain antenna are serious[12-13]. Hence, aperture field approach was adopted and investigated to design the proposed high aperture efficiency antenna, which is with lower profile and better performance than the traditional approaches of Cassegrain antenna.

The designed antenna is integrated with a sum-difference network. The reflection coefficient and radiation characteristics of the designed W-band Cassegrain monopulse antenna were measured. Results show that the antenna exhibits a high gain of 38.6 dBi with the aperture of 135 mm. The aperture efficiency is calculated to be 54.7%. It is found that the proposed structure is an attractive and promising candidate to design high aperture efficiency Cassegrain monopulse antenna in W-band, although it is a challenge to design passive components with rigorous specifications to avoid high fabrication tolerance.

1 Proposed antenna geometry and analysis

In order to integrate the antenna system with the aircrafts configuration, Cassegrain dual-reflector system consisting of a parabolic main-reflector and a hyperbolic sub-reflector is considered here. Figure 1 shows the ge-

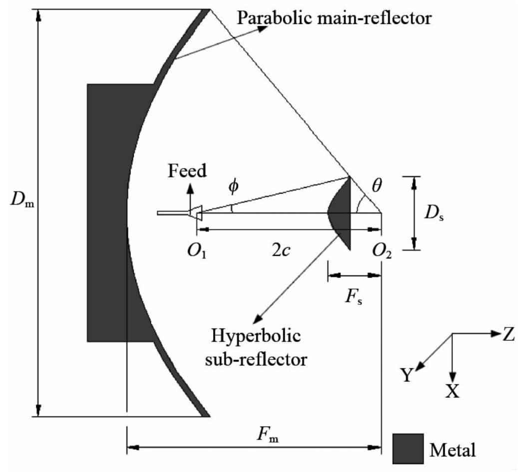

Fig. 1 Geometry of the high aperture efficiency W-band Cassegrain dual-reflector monopulse antenna
图 1 W 波段高口面效率卡塞格伦单脉冲双反射面天线几何模型

ometry of the studied Cassegrain antenna with a sum-difference network integrated on the back of parabolic main-reflector. The parabolic main-reflector is described by the diameter D_m of its XY plane projected circular aperture, focal length F_m, and half of the main-reflector edge angle observed of θ. The hyperbolic sub-reflector has a projected aperture in the XY plane with a diameter of D_s, focal length of $2c$, and the half of the sub-reflector edge angle of φ.

It is known that the antenna gain can be calculated as

$$G = 10\log\kappa \cdot \varepsilon_{ap}\left(\frac{\pi D_m}{\lambda}\right)^2 \text{ (dBi)} \quad , \quad (1)$$

where κ is efficiency factor, ε_{ap} is the aperture efficiency, and λ is the wavelength of free space in mm. The helicopter collision avoidance radar has a limited requirement on the antenna of aperture D_m with 135 mm and focal length F_m of 40.5 mm, due to the space constraint and the scanning angle of servo platform. The contour of the main-reflector should satisfy $y^2 = 162x$. Aperture efficiency improvement of the proposed antenna is a critical problem for designing W-band Cassegrain antennas.

Two design methods based on the theory of equal path equal phase[13] and Gaussion mode analysis[14], respectively, have been proposed before. Because of the short focal length in the Cassegrain antenna, the main-reflector is placed in the near-field range of the sub-reflector and the sub-reflector is also placed in the near-field range of the feed. So, the wave-front of the W-band signal radiating from the sub-reflector is not equiphase when they reach the main-reflector, and unequal phase aperture distribution and aperture efficiency declining are realized. Hence, the two design methods mentioned above are not suitable again for the short focal length Cassegrain antenna working in W-band.

Aperture field approach is adopted in this paper to solve this problem. For the axisymmetric antenna with a finite aperture D_m, one-dimensional aperture field distribution $E(x_\lambda)$ and its far-field distribution $E(\theta)$ are reciprocal Fourier transforms, given by [15]

$$\begin{cases} E(\theta) = \int_{-D_\lambda/2}^{D_\lambda/2} E(x_\lambda) e^{j2\pi x_\lambda \sin\theta} dx_\lambda \\ E(x_\lambda) = \int_{-\pi}^{\pi} E(\sin\theta) e^{-j2\pi x_\lambda \sin\theta} d(\sin\theta) \end{cases} , \quad (2)$$

where, $x_\lambda = x/\lambda$, $D_\lambda = D/\lambda$. Far-field distribution is determined according to the system requirement that is 3dB sum-beam width 1.55°, first side-lobe level of sum-beam less than −18dB. And then, aperture field distribution is obtained by Fourier transform. Based on classic theory of near-field aperture field distribution and the boundary conditions in full-wave analysis software, the contour of the sub-reflector is determined by

$$\begin{cases} \frac{x^2}{7.13^2} - \frac{y^2}{6.36^2} = 1 \\ D_s = 16.29 \text{ mm} \end{cases} . \quad (3)$$

It should be pointed out that the contour of the sub-reflector based on the equal path equal phase theory is $\frac{x^2}{12.22^2} - \frac{y^2}{11.96^2} = 1$.

Cassegrain dual-reflector systems designed based on the above-mentioned two methods are excited by an incident electromagnetic plane wave and simulated by hybrid algorithm of physical optics method and multilevel fast multipole approach built-in FEKO. The normalized results at 93 GHz are shown in Fig. 2. The gain of the antenna designed by using of the aperture field approach is 39.9 dBi, and the corresponding aperture efficiency is 56%. It is much better than the performance of the antenna based on traditional method, whose gain is only 36.1 dBi while the corresponding aperture efficiency is 23.2%. In addition, the antenna designed by the aperture field approach obtains lower first side-lobe level than the one designed by traditional method.

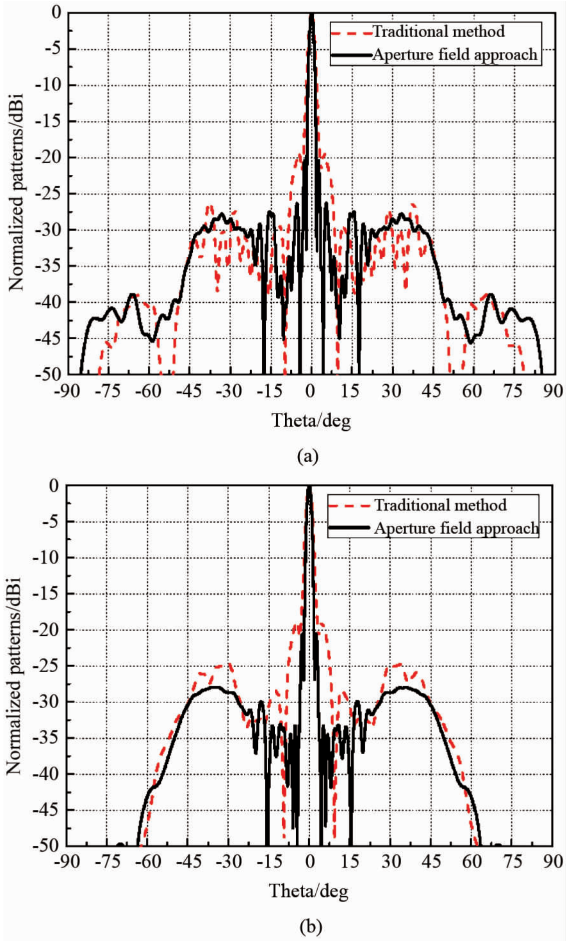

Fig. 2 Simulated results of sum beam between two methods (a) H-plane, (b) E-plane

图 2 传统方法与口面分析方法设计卡赛格伦天线仿真结果比较(a)H 面,(b)E 面

2 Experiments and measurement results

A sum-difference network consists of four E-plane branch line couplers[16] and four 90° delay lines was designed to test the proposed W-band monopulse cassegrain antenna. 90° delay transmission lines are added after the 90° couplers to mimic the function of in- and out-of-phase feeding mechanism. The sum-difference network can be constructed in a compact layout as shown in Fig. 3(a). The photograph of the fabricated sum-difference network is shown in Fig. 3(b). All ports are standard WR-10 W-band waveguides, with cross-section dimension of 2.54 mm × 1.27 mm. The measured reflection coefficient is less than −15 dB and the isolation greater than 21 dB from 90 to 98 GHz. The variation of magnitude and phase are within ±1.25 dB and ±18°, respectively.

The proposed antenna integrated with the sum-difference network was fabricated and measured operating from 92 to 94 GHz. Figure 4 shows the prototype of the fabricated monopulse antenna. The radiation patterns are simulated and measured to demonstrate the radiation characteristics of the proposed monopulse cassegrain antenna. Figure 5 is the measurement diagram of the proposed antenna.

Figure 6 shows the normalized sum radiation patterns at 93 GHz in H-plane and E-plane. The measured gain of the antenna is 38.6 dBi. The first side-lobe levels are -20 dB in H-plane and -18.6 dB in E-plane. The 3 dB beam-widths are 1.55° in H-plane and 1.56° in E-plane. The corresponding aperture efficiency is calculated to be 54.7% from the experiment results by eliminating the loss and phase errors of the sum-difference network. Table 1 is the aperture efficiency comparison. The proposed antenna shows the best aperture efficiency.

Table 1 Aperture efficiency comparison

表 1 设计的天线与同频段国内外同类天线口径效率对比

	Aperture size/mm	Aperture efficiency
W-band lens antenna[7]	100	32.8%
W-band planar Fresnel printed reflector antenna[9]	130	35.3%
A 94 GHz offset dual-reflector antenna with reflect array sub-reflector[10]	120	53%
A 300 mm W-band offset-feed reflector antenna[11]	300	15.2%
The proposed antenna in this paper	135	54.7%

The normalized difference radiation patterns are shown in

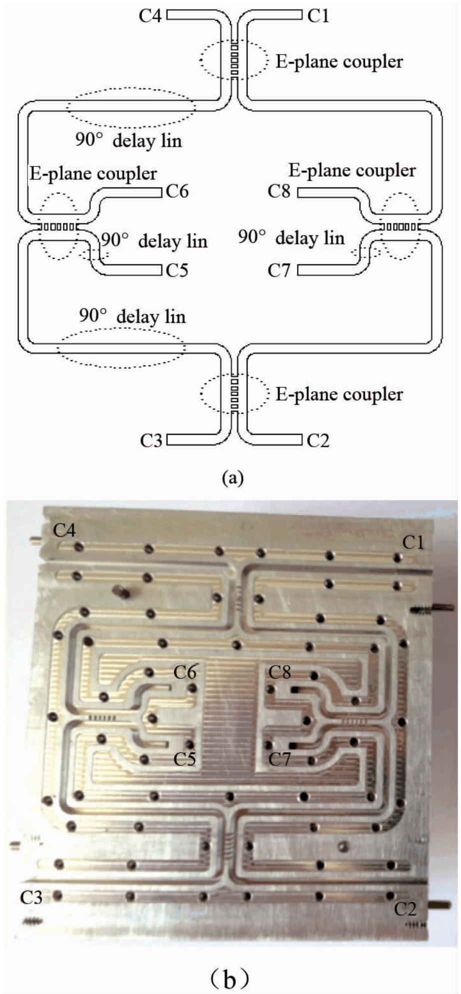

Fig. 3　The waveguide sum-difference network. (a) Layout, and (b) fabricated photograph
图 3　W 波段波导和差网络结构版图以及实体图

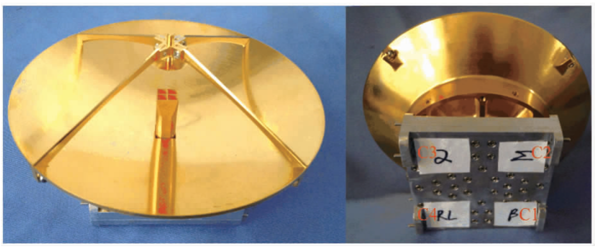

Fig. 4　Prototype of the fabricated monopulse antenna system
图 4　研究的单脉冲天线系统的实物图

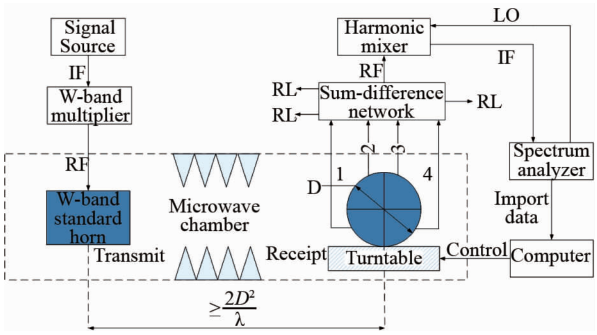

Fig. 5　Measurement diagram of the proposed antenna
图 5　天线测试原理框图

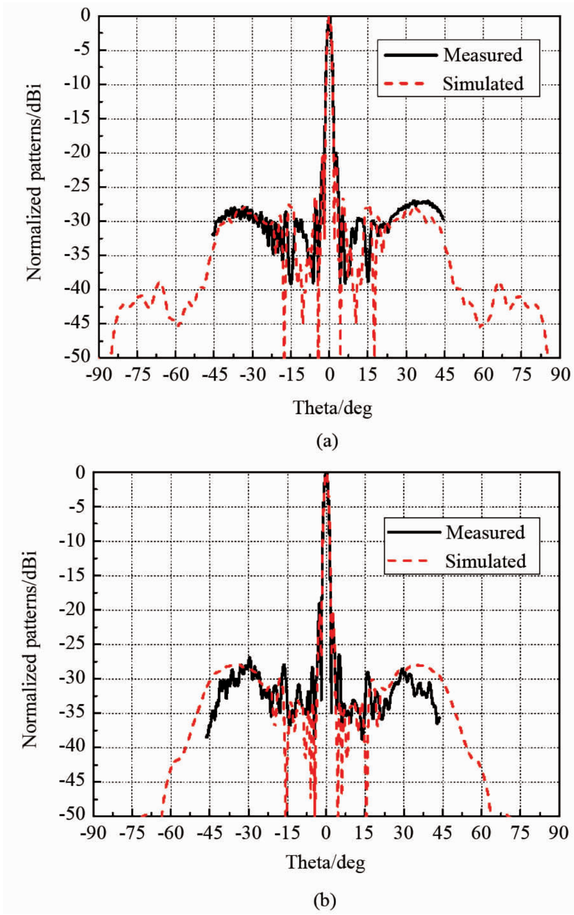

Fig. 6　The measured and simulated normalized sum radiation patterns of the proposed antenna (a) H-plane, (b) E-plane
图 6　研究的天线归一化和方向图测试与仿真结果对比 (a) H 面, (b) E 面

Fig. 7. The null-depth is −25.3 dB in H-plane and −24.7 dB in E-plane. The amplitude balance between the two peaks is less than 0.5 dB both in H and E-plane. The gain ratio of sum- and diff-beam is 3.6dB in H-plane and 3.4dB in E-plane. It should be pointed out that the first side-lobe level unbalance of measured patterns is mainly because of the sub-reflector departing from axis. The distal side-lobe level of measured difference radiation patterns is superior to simulated ones. This is probably due to some reasons, including connection loosening between test components, harmonic mixer working unstably, turntable jitter. In addition, the measured radiation patterns are only from −45° to 45° due to the measurement system. The plotted patterns show good agreement between the measured and simulated results.

Figure 8 shows the H and E-plane voltage ratio between difference and sum beams. Firstly, the two curves are almost overlapping, indicating good symmetry of the proposed antenna. Secondly, the two curves have larger slope, which will bring about the better angle measuring accuracy of the target. In general, the antenna proposed

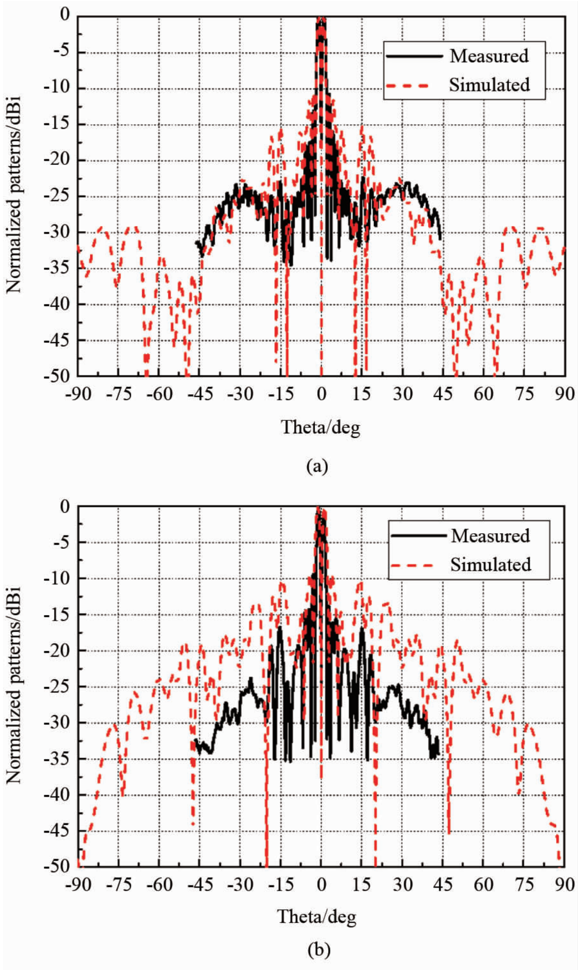

Fig. 7 The measured and simulated normalized difference radiation patterns of the proposed antenna (a) H-plane, (b) E-plane

图 7 研究的天线归一化差方向图测试仿真结果对比(a)H 面,(b)E 面

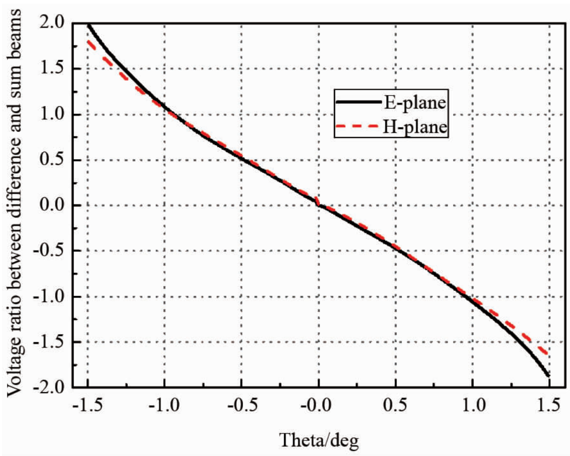

Fig. 8 The measured E- and H-plane voltage ratio between difference and sum beams

图 8 E 面与 H 面角误差测试曲线

in our paper presents an excellent candidate in the W-band monopulse system.

3 Conclusion

In this paper, a W-band high aperture efficiency monopulse Cassegrain antenna has been proposed for the helicopter collision avoidance radar. The parameters of the proposed Cassegrain antenna were designed based on the aperture field approach instead of traditional method. The antenna has been fabricated with integration and its radiation characteristics have been demonstrated. Both simulated and measured results have shown that the proposed Cassegrain dual-reflector antenna based on aperture field approach is a promising candidate for W-band antennas with high gain, high aperture efficiency and low side-lobe levels.

References

[1] Kumar B A, Ghose D. Radar-assisted collision avoidance/guidance strategy for planar flight[J]. *IEEE Trans. Aerospace Electronic Systems*, Jan. 2001, **37**(1): 77-90.

[2] Mangogna A J. Development of a helicopter obstacle detection and air data system[C]// In 20th *Digital Avionics Systems Conference in Daytone Beach*, Oct. 2001, **1**: 1A4/1-1A4/7.

[3] Gandhi T, Yang M T, Kasturi R, *et al*. Detection of obstacles in the flight path of an aircraft[J]. *IEEE Trnas. Aerospace Electronic Systems*. 2003, **39**(1):176-191.

[4] Kwag Y K, Kang J W. Obstacle awareness and collision avoidance radar sensor system for low-altitude flying smart uav[C]. In 23^{r}d *Digital Avionics Systems Conference*, Oct. 2004, **2**:12. D. 2-10.

[5] Black D N, Wiltse J C. Millimeter-wave characteristics of phasecorrecting fresnel zone plates[J]. *IEEE Trans. Microw. Theory Tech.*. 1987, **35**(12):1122-1129.

[6] Hristov H D, Herben M H A J. Millimeter-wave fresnel-zone plate lens and antenna[J]. *IEEE Trans. Microw. Theory Tech.*. 1995, **43**(12): 2779-2785.

[7] Migliaccio C, Dauvignac J Y, Brochier L, *et al*. W-band high gain lens antenna for metrology and radar applications[J]. *Electronics Letters*, 2004. **40**(22):1394-1396.

[8] Tienda C, Arrebola M, Encinar J A. Recent developments of reflectarray antennas in dual-reflector configurations[J]. *Hindawi International Journal of Antennas and Propagation*, 2012, Article ID 125287.

[9] Nguyen B D, Migliaccio C, Pichot C, *et al*. W-band fresnel zone plate reflector for helicopter collision avoidance radar [J]. *IEEE Trans. Antennas Propagat.*,. 2007, **55**(5):1452-1456.

[10] Hu W, Arrebola M, Cahil R L, *et al*. 94 GHz dual-reflector antenna with reflectarray subreflector[J]. *IEEE Trans. Antennas Propagat.*,. 2009, **57**(10): 3043-3050.

[11] PENG Shu-Sheng, WU Li, LI Xiang-Qin. Design of 300 mm W band radiometer offset-feed reflector antenna[J]. *Journel of Infrared and Millimeter Waves*(彭树生,吴礼,李向芹. 300 mm 口径 W 波段辐射计偏馈反射面天线设计,**红外与毫米波学报**) 2013, **32**(6): 545-549.

[12] Chantalat R, Menudier C, Thevenot M, *et al*. Enhanced EBG resonator antenna as feed of a reflector antenna in the Ka band[J]. *IEEE Antennas Wireless Propagat. Lett.*, 2008, **7**: 349-353.

[13] Hannan P. Microwave antennas derived from the cassegrain telescope [J]. *IEEE Trans. Antennas Propagat.*. 1961, **9**(2):140-153.

[14] Padman R, Murphy J, Hills R. Gaussian mode analysis of cassegrain antenna efficiency[J]. *IEEE Trans. Antennas Propagat.*. 1987, **35**(10): 1093-1103.

[15] Booker H G, Clemmow P C. The concept of an angular spectrum of plane waves, and its relation to that of polar diagram and aperture distribution[J]. *Proceedings of the IEE - Part III: Radio and Communication Engineering*. 1950, **97**(45):11-17.

[16] Zheng P, Sun H-J, Luo M-J, *et al*. W band waveguide 3db directional coupler based on e-plane branch line bridge[C] \\In *Asia-Pacific Microw. Conf.* in Seoul, Nov. 2013: 279-281.