3-D simulation research for off-axis Cassegrain optical antenna and coupling systems

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Cassegrain antenna has excellent transceiver characteristics, it is widely used in inter-satellite optical communication. The coupling system is also an important component of the whole system. Most of the researches are only based on the optical antenna, but coupling efficiency is also an important parameter that affecting the performance of the optical system. Therefore, the whole optical system including the coupling system and its off-axis performance are studied in this paper.

(Received November 28, 2011; accepted February 20, 2012)

Keywords: Cassegrain antenna, Off- axis, Coupling efficiency

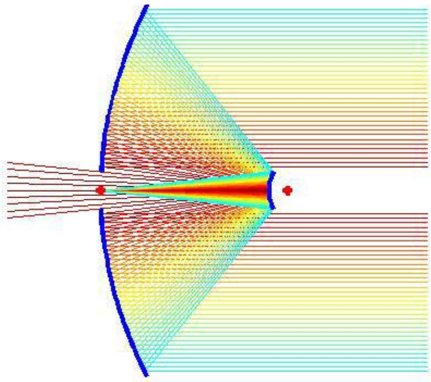
1. Introduction

With the development of the times, the optical fiber communication and the inter-satellite optical communication technology has been developed rapidly. The Cassegrain antenna has some characteristics, such as the aperture can be very large, no chromatic aberration and has wide range of available band. When using the aspherical lens, it can eliminate the aberration greatly, and it can be a transceiver [1]. So the Cassegrain antenna is widely used in satellite communications stations and single-pulse radars.

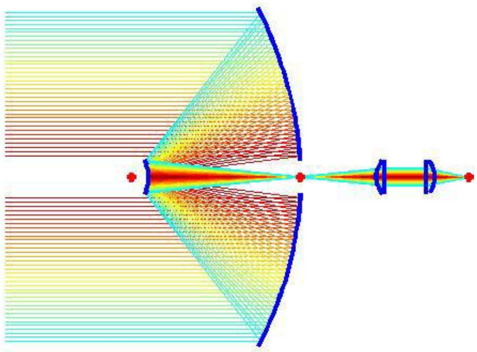
But up to now, the studies of the Cassegrain antenna system are mainly based on the optical system itself. In fact, the Cassegrain antenna system is just one part of the whole system, the coupling system also plays a key role in the optical fiber communication. So it is necessary to study the whole system, including the coupling system.

2. Research about Cassegrain antenna and off-axis analysis

Since the receiving optical antenna system and the launching optical antenna system structure are similar and symmetric, shown as Fig. 1. So when considering the characteristics of the system, we can only take one part into consideration. A coupling system is added in the receiving optical antenna.



(a)



(b)

Fig. 1. Launching system and receiving system.

The Cassegrain antenna comprises of two mirrors, the secondary mirror with small aperture is hyperboloid, and primary mirror with bigger aperture is paraboloid. Take the receiving system, the illuminant is placed on the vertex of the paraboloid. But there is an aperture on the parabolic reflector; as a result, part of the light is reflected back to the back of the antenna, some light energy is lost here. The emitted laser beam is Gauss laser beam. By theoretical analysis, the electric field distributing of Gaussian beam can be described as [2]:

$$E(z)=\frac{C}{\omega(z)}\exp\left(-\frac{r^2}{\omega^2(z)}\right)\exp\left\{-\mathrm{i}\left[k\left(z+\frac{r^2}{2R}\right)-\arctan\frac{z}{f}\right]\right\} \quad (1)$$

The power of the beam in the cross section is

$$\left|E(r)\right|^2=C^2/\omega^2(z)\exp\left[-2r^2/\omega^2(z)\right] \quad (2)$$

Where $\omega(z)=\omega_0\sqrt{1+\left[\lambda z/\left(\pi\omega_0^{\,2}\right)\right]^2}$, λ is the wavelength of the beams, f is the focal length of the coupling lens, and C is a constant coefficient.

The aperture of the primary mirror is 150 mm, and the aperture of the secondary mirror is 30 mm, the distance between vertexes of two mirrors is 240 mm. According to the structure and calculation results, only about 72.86% of the light energy is emitted.

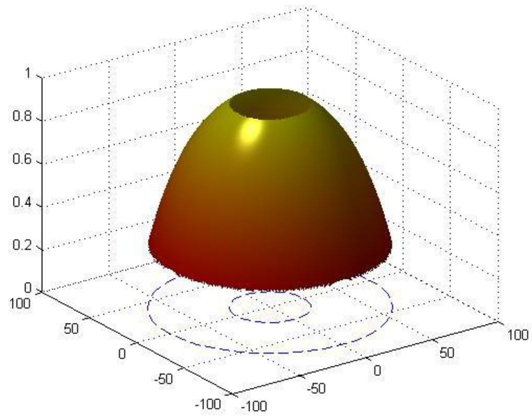
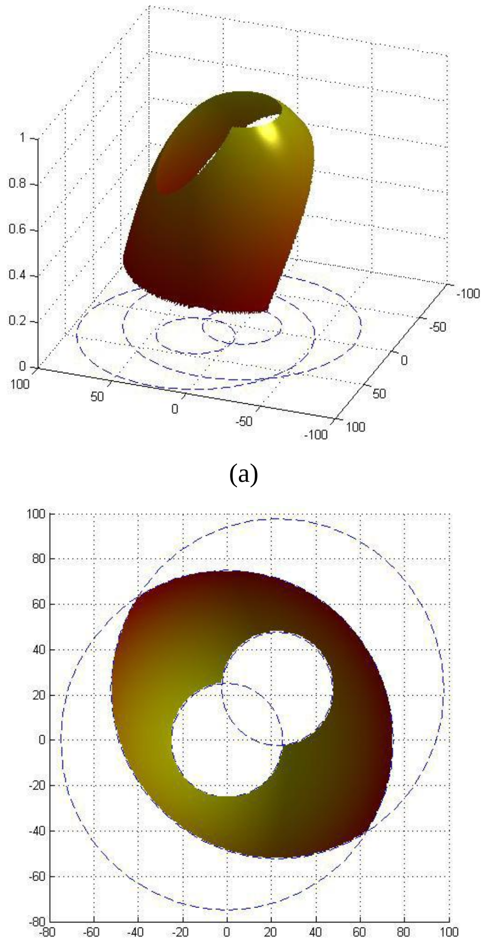


Fig. 2. Light intensity without off-axis.

Fig. 2 shows that the light intensity is satisfied with Gaussian distribution, and the light intensity is normalized. Due to affects of secondary mirror Cassegrain antenna, there is no intensity in the central part of the laser beam. Then, laser beam will be parallel and then enter the coupling system.

Above is the situation that the receiving system and the launching system are aligned. In practical situation, the receiving system and the launching system are not aligned, there exists deflection angle. Here is the intensity distribution and its 2D shape on the off-axis condition, which is shown in Fig. 3.



(a) (b)

Fig. 3. Light intensity with off-axis and its 2D shape.

We can see that because of the deflection angle, part of the light cannot be received. And the light energy received varies with the deflection angle. In 3D case, we can decompose the deflection angle into two directions. They are X and Y. The relationship between the light energy received and the defection angle is showed in Fig. 4:

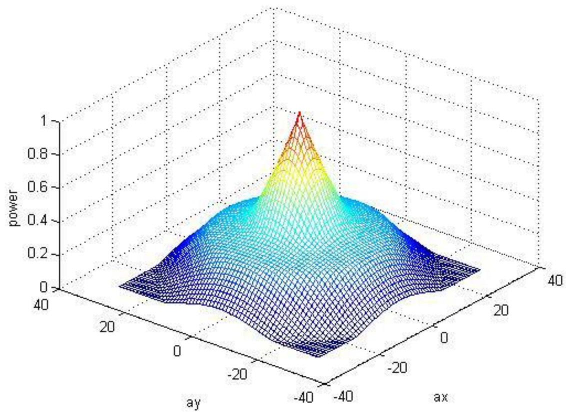


Fig. 4. Light energy received and the defection angle.

When the deflection angles of two directions are zero, that is, completely aligned, the light intensity is normalized. With the increase of the deflection angle, the light energy received decrease. When the deflection angle is about 35 degree, the light energy received is almost zero. So if the deflection angle is bigger than 35 degree, we can consider that no light energy is received.

On the off-axis condition, the propagation direction of the light received does not parallel to the antenna axis. The laser beam will still go through two reflections. Fig. 5 shows the result when the deflection angle is 0.5 degree.

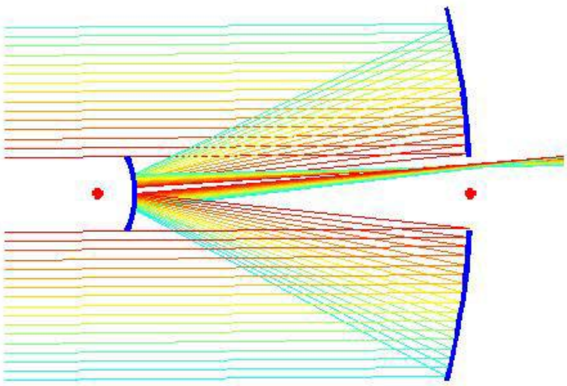


Fig. 5. The transfer of laser beam with off-axis.

We can see that laser beam will finally converge. But the convergence point is not the vertex of the paraboloid.

3. Research about coupling system and off-axis analysis

The coupling system can be simply considered as a lens. According to the characteristics of Gaussian beams, the beams here are spherical waves. But because the distance between the antenna and the coupling system is very small, the radius of the Gaussian beams has little change, so they can be considered as plane wave. Beams through the coupling system will converge. But because of the Fraunhofer diffraction, the beams do not completely converge on the focus of lens, but form a diffraction spot on that point. The thickness of the lens we designed is 0.5 cm, the diameter of the lens is 5 cm, The wavelength of the beams we used is 1550 nm, we can obtain the diameter of the Airy spot is 5.8 μm.The diameter of the fiber we used is 10 μm. After coupling system converge the beams, the laser beam will enter the fiber for further processing.

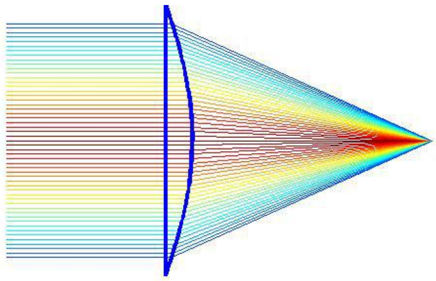


Fig. 6. Laser beam without off-axis.

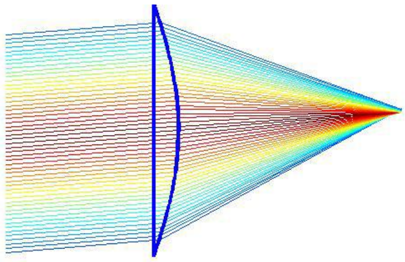


Fig. 7. Laser beam with off-axis.

Fig. 6 shows that when there is no off-axis, the laser beam enters the coupling system. After going through the coupling system, the laser beam completely enter the fiber. Fig. 7 shows that when there exists off-axis, the laser beam enters the coupling system, but they do not converge. Because the diameter of the fiber is limited, so part of the light energy is lost, and the coupling efficiency will be reduced.

The light intensity at the boundary of the fiber is expressed as: [3]

$$\Psi(r) = \exp\left[-\left(r/r_0\right)^2\right] \tag{3}$$

The light intensity distribution on the receiving lens focus is:

$$U(r) = \exp(\mathrm{i}kf)\exp(\mathrm{i}kr^2/2f)\pi a^2\left[2\mathrm{J}_1\left(\frac{2\pi ar}{\lambda f}\right)\right]\Big/(\mathrm{i}\lambda f) \tag{4}$$

The coupling efficiency of spatial light - single-mode fiber is:

$$\eta = \iint U^*(r)\Psi(r)rdrd\theta \Big/ \sqrt{\iint U(r)U^*(r)rdrd\theta \iint \Psi(r)\Psi^*(r)rdrd\theta} \tag{5}$$

Taking equations (4), (5) into equation (6), and we can get the coupling efficiency for spatial light to single mode fiber

$$T = \eta\eta^* = |\eta|^2 = \frac{\left|\int_0^{+\infty}\exp\left[-\left(r/r_0\right)^2\right]\exp\left(-\mathrm{i}kr^2/2f\right)\left[2\mathrm{J}_1\left(\frac{2\pi ar}{\lambda f}\right)\Big/\left(\frac{2\pi ar}{\lambda f}\right)\right]r\mathrm{d}r\right|^2}{\int_0^{+\infty}\exp\left[-2\left(r/r_0\right)^2\right]r\mathrm{d}r\int_0^{+\infty}\left[2\mathrm{J}_1\left(\frac{2\pi ar}{\lambda f}\right)\Big/\left(\frac{2\pi ar}{\lambda f}\right)\right]^2 r\mathrm{d}r} \tag{6}$$

We assume that when there is no off-axis, the coupling efficiency is normalized. The relationship between defection angle and the coupling efficiency is showed in Fig. 8.

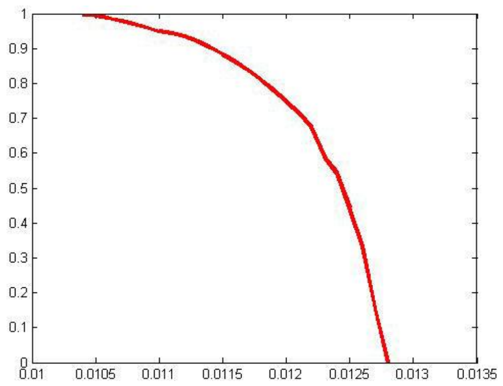


Fig. 8. Defection angle and coupling efficiency.

The calculation results show that when the angle between laser beam and the horizontal line is 0.012 degree, the coupling efficiency drop to only 74.95%.

4. Conclusion

Because of the structure, the Cassegrain antenna will lose part of light energy when transmitting laser beam. When the axis is completely aligned, the transceiver has a good performance. But when there exists off-axis, the loss of light energy will increase. When the deflection angle is about 35 degree, the light energy received is almost zero. Because of off-axis, the laser beam will continue to lose energy when going through the coupling system, thus influence the coupling efficiency. When the angle between laser beam and the horizontal line is 0.012 degree, the coupling efficiency drop to only 74.95%.Considering the lost light energy in the Cassegrain antenna, the coupling efficiency of the whole system is only 54.61%.So the Cassegrain antenna needs good alignment system to perform well.

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