An Optimal Match between the Ground-based Laser and a Relay Mirror System

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Abstract— Based on the application of a relay mirror system, we study the intensity distribution and receiving efficiency of laser beams through a relay mirror system. When Fresnel number is big, this studies shows that the coupling efficiency of power between ground-based telescope and relay mirror is high for collimated beams. Due to small spot and high intensity concentrated on central obscuration, beams focusing to relay mirror is not suitable. For the reason that the distance between the laser source and relay mirror is fixed, and the distance from the relay mirror to a target is various, the intensity distribution is changed with different target. It is impossible to keep in high coupling efficiency when beams focus to target directly through a relay mirror system.

1. INTRODUCTION

With the use of a relay mirror system, the effects of atmosphere on the propagation of laser beams can be significantly reduced. Meanwhile, the obscurations at the propagation path, such as buildings, mountains can be avoided. In military, a relay mirror system can be not only used as a ballistic missile defense system to attack the air and ground targets, but also used for the space surveillance and space control [1–5]. In optical communication, the propagation distance can be significantly enhanced with the help of a relay mirror system [6].

There are many factors that will affect on the propagation of a laser beam through a relay mirror system, such as diffraction, turbulent atmosphere [7–9], thermal blooming [10, 11], different types laser beams [12–14] and its focal length. In this paper we will study the optimal match between ground-based telescope and receiver of relay mirror for flattened beams with different focal length.

2. THEORY STUDY

In the absence of atmosphere, the propagation of laser beams through a relay mirror system can be shown as Figure 1. A laser beam is projected by a Cassegrain telescope from a ground-based laser source. A relay mirror system with two-Cassegrain telescope receives the beam and focuses it on a target [15]. z_1 denotes the distance between laser source and the relay mirror. z_2 is the distance from the relay mirror to a target.

In practice, the propagation of beams in a relay mirror system without correction can be treated with geometry optics. Therefore, the propagation in Figure 1 can be simplified into three cases. The first one is focus transmitting, shown as Figure 2. Namely, the based-ground telescope focuses the beam to the relay mirror. The second one is collimated transmitting, see Figure 3. The based-ground telescope project a collimated beam to relay mirror. The third one is directed transmitting, illuminated as Figure 4. The based-ground telescope focuses a beam to a target through a relay mirror directly.

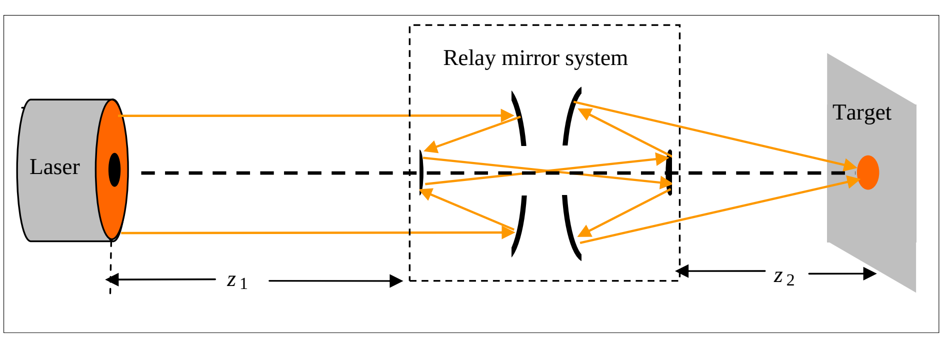

Figure 1: Configuration for beams through a relay mirror system.

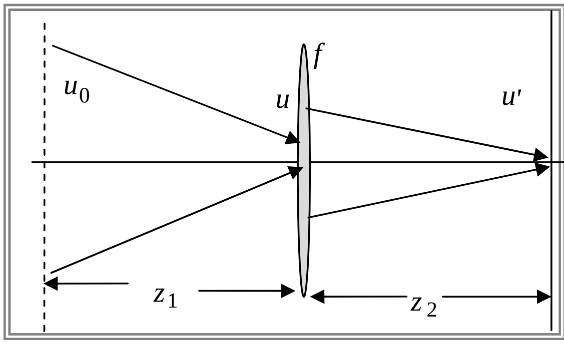

Figure 2: Laser beam focusing to relay mirror.

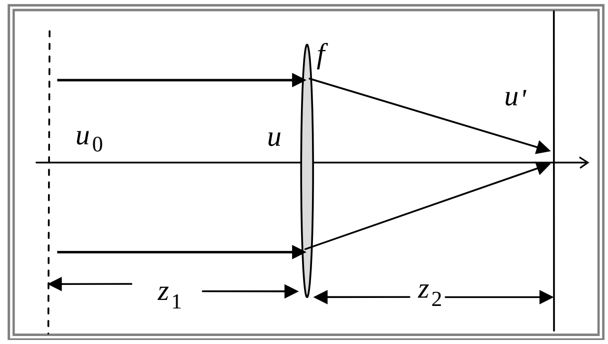

Figure 3: Propagation of collimated beams through relay mirror system.

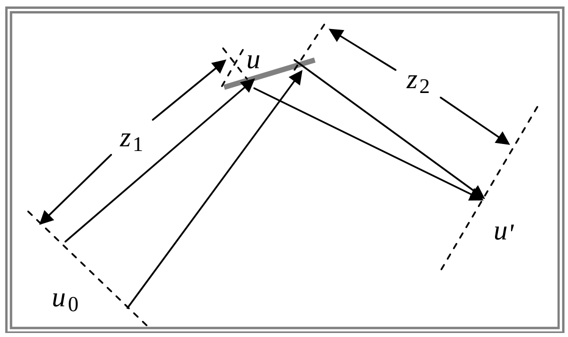

Figure 4: Laser beam focusing to target directly through relay mirror system.

In Figures 2–4, u_0, u and u' denote the optical field at the source plane, relay mirror and target, respectively. We assume that a laser source is located at the plane ($z = 0$) and propagates along z-axis in a cylindrical coordinates system. r_0 and r are the radial coordinates at source plane ($z = 0$) and receiver plane ($z = z_1$), respectively. $\rho_0 = r_0/a$, $\rho = r/a$ are the normalized transverse coordinates. a and ε are the radius and obscuration ratio of the transmitter aperture. The optical field of high power laser projected by ground-based telescope is chosen as the form:

$$u_0(\rho_0) = \begin{cases} A_0 & \varepsilon^2 \le \rho_0^2 \le 1 \\ 0 & \text{others} \end{cases} \tag{1}$$

where A_0 is the amplitude. Therefore, with the use of Fresnel diffraction integration, the optical field at z_1 plane can be expressed as

$$u(\rho, N_F) = -iA_0 N_F \exp\left(iN_F\rho^2/2\right) \int_{\varepsilon}^{1} J_0(N_F\rho\rho_0) \exp\left[iN_F\rho_0^2(1 - 1/\delta)/2\right] \rho_0 d\rho_0 \tag{2}$$

where $N_F = ka^2/z_1$ is Fresnel number, $k = 2\pi/\lambda$ is wave number, λ is wavelength, $\delta = f/z_1$, f is the focal length. For the case that the beams focusing to the relay mirror ($\delta = 1$), the field at z_1-plane can be expressed as

$$u(\rho, N_F) = \frac{1}{i\rho} A_0 \exp\left(iN_F\rho^2/2\right) \left[J_1(N_F\rho) - \varepsilon J_1(N_F\varepsilon\rho)\right] \tag{3}$$

The intensity is

$$I(\rho, N_F) = A_0^2 \left[J_1(N_F\rho) - \varepsilon J_1(N_F\varepsilon\rho)\right]^2 / \rho^2 \tag{4}$$

If $\varepsilon = 0.25$, from Eq. (4) we can obtain that the 84% encircled power is concentrated on the aperture with $3.83/N_{F1}$ normalized radius. Therefore, the loss of power due to central obscuration is big in the near field. For example, $a = 0.5$ m, $\lambda = 1.06$ μm and $z_1 = 30$ km, the normalized radius is 0.13. So concentrated laser beam not only cause big loss of laser energy due to central obscuration, but also destroy the secondary mirror. From the studies above we can see that to focus a beam to a relay mirror is not suitable when the Fresnel number is big.

If a collimated beams ($\delta \to \infty$) are projected to relay mirror, from Eq. (2) the intensity distribution with different Fresnel number can be calculated numerically (see Figure 5). I_n in Figure 5 denotes the intensity divided by A_0^2.

Figure 5 shows that when $N_{F1}(1-\varepsilon^2) = 4n\pi$ (n is integer), the on-axis intensity is equal to $4A_0^2$ when $N_{F1}(1-\varepsilon^2) = (2n+1)2\pi$ (n is integer), the on-axis intensity is equal to zero. The on-axis intensity can be expressed in the form

$$I(0, N_F) = 4A_0^2 \sin^2\left[\frac{1}{4}N_F\left(1-\varepsilon^2\right)\right] \tag{5}$$

If the radius and obscuration ratio of receiver telescope is as the same as the ground-based telescope, the receiving efficiency with different Fresnel number are listed in Table 1.

From Table 1 we can see that the receiving efficiency is high when the Fresnel number is big. With Fresnel number degreasing, the receiving efficiency degreases.

Figure 6 shows the intensity profiles for the case that the beam focus to a target directly through a relay mirror, i.e., the relay mirror is equal to a reflective mirror. For the reason that the distance between the laser source and relay mirror is fixed, and the distance from the relay mirror to a target is various, the intensity distribution is changed with different target. Namely, the coupling efficiency is different with different target (see Table 2). In Table 2, we also assume that the radius and obscuration ratio of receiver telescope is as the same as the ground-based telescope. Therefore,

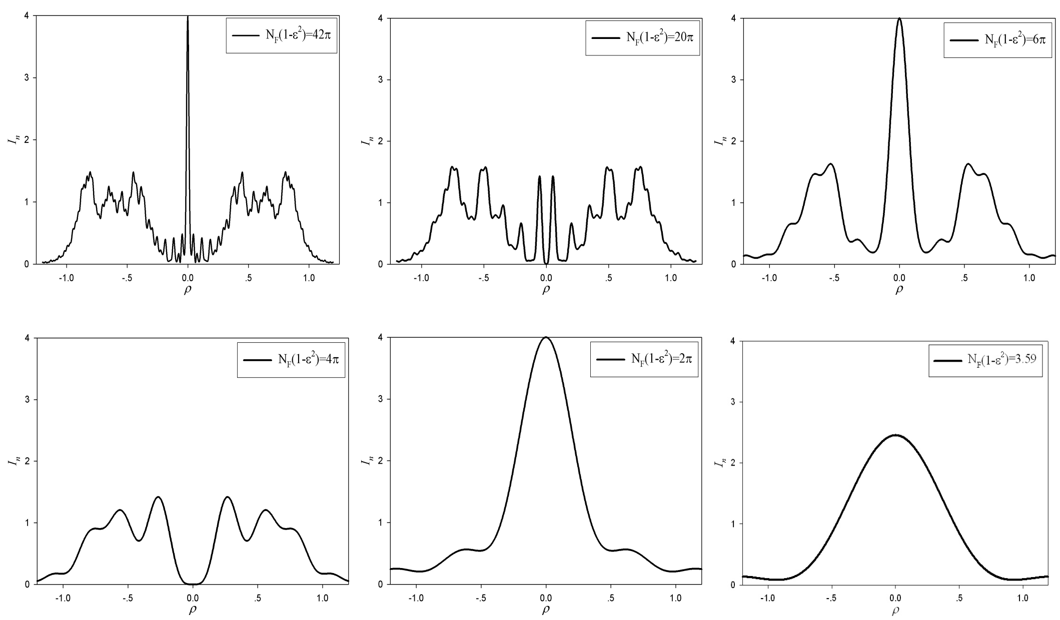

Figure 5: Intensity distribution of collimated beams with different Fresnel number.

Table 1: Receiving efficiency with different Fresnel number.

$N_{F1}\ (1-\varepsilon^2)$	42π	20π	6π	4π	2π	3.59
Encircled power (%)	93.0	87.5	86.0	83.2	67.5	62.9
Loss due to obscuration (%)	1.4	3.0	4.5	4.9	18.6	18.7
receiver efficiency (%)	91.6	84.5	81.5	78.3	48.9	44.2

Table 2: Receiving efficiency with different δ.

δ	1.25	1.5	1.75	2
Encircled power (%)	94.2	93.4	92.9	92.4
Loss due to obscuration (%)	84.6	59.7	27.7	15.1
receiver efficiency (%)	9.6	33.7	65.2	77.3

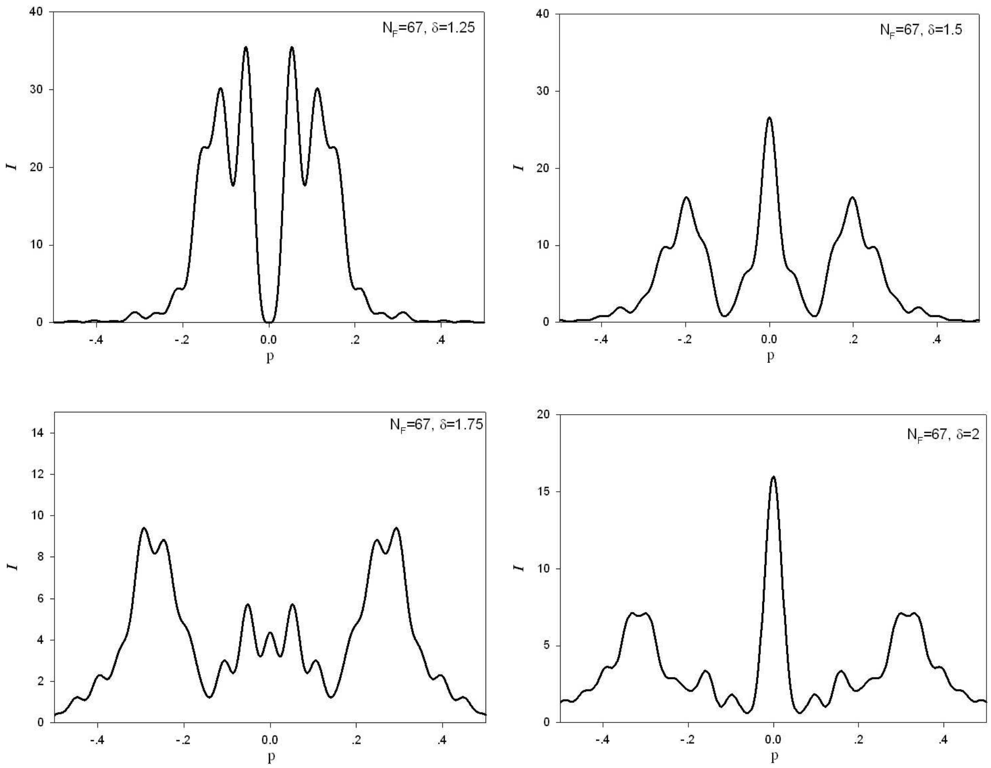

Figure 6: Variations of intensity profiles with different δ.

it is impossible to keep in high coupling efficiency when beams focus to target through relay mirror directly.

From the studies we can see that the coupling efficiency is high when a collimated beam is projected to a relay mirror.

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