Application of Compact Optical Duplicate System as a Multi-beam Generation Device for Satellite–Ground Laser Communications

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Abstract—**Satellite-ground laser communication has been of particular interest because of increase in the quantity of data exchanged between satellites and the ground. It is necessary to improve the quality of data communication, because laser communication is vulnerable to air fluctuation. This paper reports on a simulation conducted to reduce the efficiency loss due to air fluctuations. The simulation used data from a beam transmission experiment in the atmosphere. We propose an optical duplicate system for a multi-beam generation device for satellite–ground laser communications. This is a device that generates many reproduction images for optical computing and optical information processing, the validity of which has been proven and is widely known. This device enables more efficient miniaturization and weight saving than previous techniques, and it is flexible in terms of the number of optical beams. We designed the optical duplicate system for satellite–ground laser communications, and proved the validity of this system by simulations.**

Keywords—Satellite–Ground Laser Communication; Optical Duplicate System; Air Fluctuation; Multi-Beam Generation

I. INTRODUCTION

Recently, space optical communications have attracted attention because of the increased demand for data volume transfer between artificial satellites and ground stations for media broadcasting, GPS, positioning, earth observation, and space observation [1]. Space laser communications use high-frequency subcarriers, and because the wavelength is short and diffraction is small, even if the diameter of an antenna is small, propagation loss and interference between systems can be suppressed. Moreover, the frequency band for optical communications is presently not subject to international regulations; therefore, frequency resources can be utilized without prior authorization.

However, in order to improve the quality of modulated laser data communications, reducing the influence of air fluctuation is of primary importance. That is, degradation of signal quality and intensity due to air fluctuation must be reduced. In the past, (a) wavefront correction of light according to the influence of atmospheric distortion, and (b) method for averaging effect of light intensity by stacking multi-beams to compensate for the influence of atmospheric distortion have been examined [2].

In this paper, we focus on a method for intensity averaging effect. Although methods (1) and (2), which are shown in Table 1, have been proposed as for multi-beam generation, which is key to any averaging technique, they have not been established in practice. Thus, a small, lightweight, and highly efficient technique is still sought after.

Through a numerical analysis, we demonstrated that the averaging effect for reducing air fluctuation can be achieved by superposing multi-beam with spatial division of laser beam intensity in a simulated medium-distance propagation experiment in the atmosphere. Based on this result, as shown in Fig. 1, we propose a duplicate system as a spatial division device with multiple output beam can be adapted to an established optical satellite–ground station. The system is small and lightweight, and its number of beam branches is variable branches.

A duplicate optical system proposed for beam generation device was built in 2003 by the present authors as an image input device for the parallel optical operation of a hybrid face recognition system (optical computer), which was the first optical system of its type to be put to practical use. The highly efficient formation of two or more images has been confirmed by evaluation experiments using modulation transfer function analysis and other methods [3]. The design of a duplicate optical system and the performance analysis by the ray tracing method are examined on the basis of this these track record, and the possibility of a trial production is also suggested.

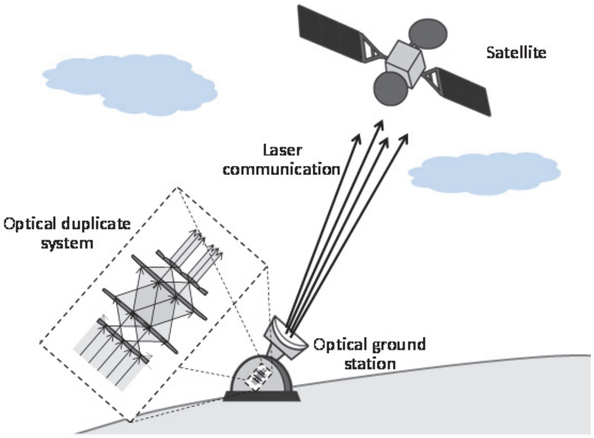


Fig. 1 Satellite laser communication.

II. Verifying The Averaging Effect of Spatially Split Multi-Beam

First, we examined how air fluctuation can be reduced by superposing two or more beams [4]. The laser beam intensity distribution, after transmitting one beam at a certain time, is

$$g_1(x,y) = f(x,y) + n_1(x,y) \tag{1}$$

where $f(x, y)$ is the signal component without the noise component after transmitting a single beam, and $n_1(x, y)$ is the noise component. The atmospheric distortion, i.e., the noise, arises because of changes in the angle of arrival of the beam or wavefront distortion in the atmosphere. This is caused by fluctuations of the refractive index of air caused by changing temperature, air currents, convection, and turbulence, etc. Only the noise components differ when m laser beams are transmitted with mutual separations greater than the atmospheric coherence length r_0. Then, the intensities of the laser beams are expressed as follows:

$$\begin{aligned} g_2(x,y) &= f(x,y) + n_2(x,y), \\ g_3(x,y) &= f(x,y) + n_3(x,y), \\ &\vdots \\ g_m(x,y) &= f(x,y) + n_m(x,y). \end{aligned} \tag{2}$$

The average intensity of each beam is shown in Eq. (3). Because the noise component of each beam is averaged, the atmospheric distortion can be suppressed by superimpositions of multi-beams.

$$\begin{aligned} \bar{g}(x,y) &= \frac{1}{m}\sum_1^m g(x,y) = \frac{1}{m}\sum_1^m f_i(x,y) + \frac{1}{m}\sum_1^m n_i(x,y) \\ &= f(x,y) + \frac{1}{m}\sum_1^m n_i(x,y) \end{aligned} \tag{3}$$

In this paper, we attempted to prove by numerical analysis that the averaging effect of reducing the atmospheric distortion is achieved by a superimposed image of multi-beam intensity distribution for spatial division using the beam intensity image in a medium-distance laser beam propagation experiment in the atmosphere.

As shown in Fig. 2, the transmission experiment was performed at a distance of 7.5 km between 2 location, A and B, using a laser of wavelength 1.55 μm as the light source. The transmitted beam was detected at point B, and the intensity distribution of the acquired beam is shown in Fig. 3(a). The divergence angle of the beam was 0.2 mrad at point A, indicating that it had spread to a full width at half maximum of 1.6 m. The intensity distribution in the center section of the beam was acquired in real time using a video camera with a pixel size of 300 μm. A 200-pixel-square image was cut from the center area of the acquired image, and the atmospheric distortion in one beam was evaluated from the histogram of the beam intensity distribution. The result is shown in Fig. 3(b). The probability density distribution calculated from that histogram is shown in Fig. 3 (c). The normalized intensity value of 1 is the average intensity value of the image shown in Fig. 3(a). Although the probability density is mostly distributed in the region where the normalized intensity is ≤1, it is widely distributed over the region where the normalized intensity is ≥2. It is shown that the change of detected intensity of a transmitted beam is large owing to atmospheric distortion.

Next, the averaging effect by superposition of multi-beams by spatial division of a single beam image was verified. One beam was divided into four beams of equal size, as shown in Fig. 4 (a). The obtained images ①–④ can be thought of as corresponding to $g_1(x, y) – g_4(x, y)$ shown in Eqs. (1) or (2). The histogram of the intensity distribution of images ①–④ is shown in Fig. 4 (b), as in the above case of a single beam. The probability density distribution by superimposing images ①–④ calculated using each histogram is shown in Fig. 4 (c). The probability density values acquired by stacking images ①–④ are shown in the figure. The distribution width of the probability density becomes small with the increase in the number of stacked spatially divided beams as compared with one beam shown in Fig.3 (c). The fluctuation of the received intensity due to atmospheric distortion was controlled, and it was confirmed that reduction was achieved.

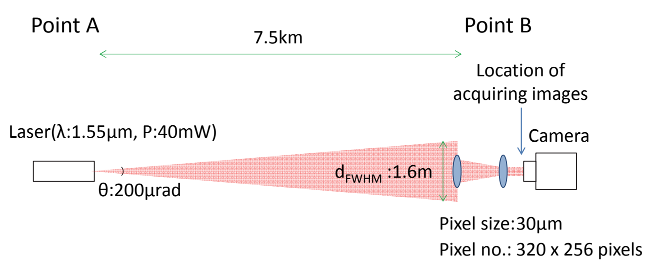
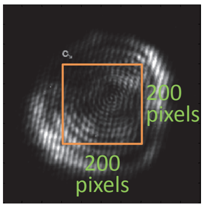
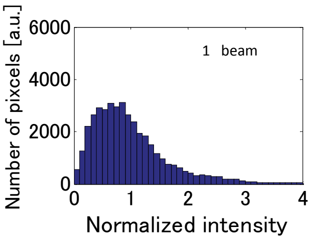


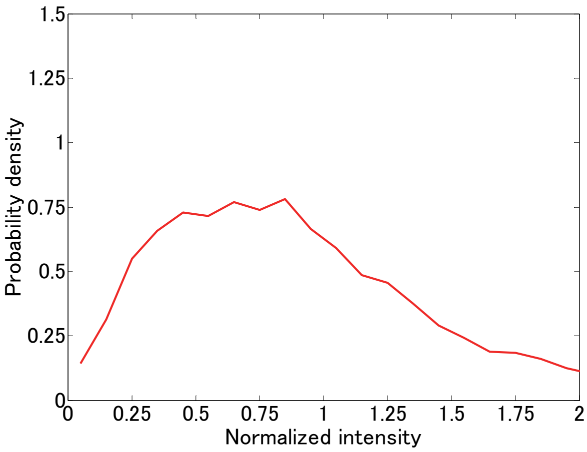
Fig. 2 Schematic diagram of the medium-range transmission experiment.



(a)

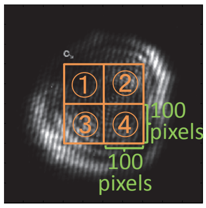


(b)

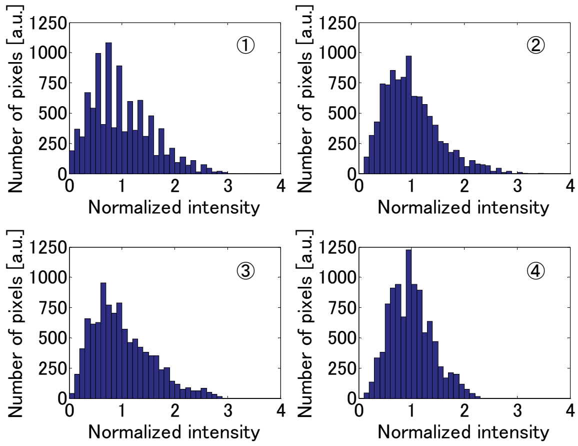


(c)

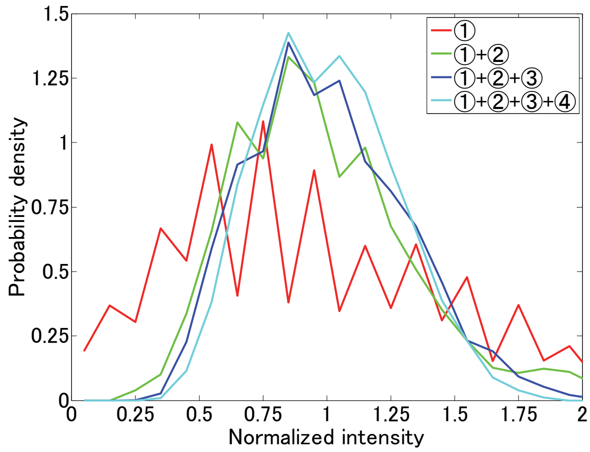
Fig. 3 (a) Image of one beam obtained in the beam transmission experiment in the atmosphere and (b) intensity distribution of a single. (c) Probability density distributions of the single beam. The intensity is normalized by the average value.



(a)



(b)



(c)

Fig. 4 (a) Single beam divided into four beams and (b) intensity distribution of each of the four beams. (c) Probability density distributions of spatially superimposed beams. The intensity is normalized by the each average value.

III. Compact Optical Duplicate System for a Multi-Beam Generation Device for Space Laser Comunications

A. Principle of optical duplicate system

An arrangement of an optical duplicate system is shown in Fig.5. The incident wavefront is split by array lens AL1 into a number of wavefronts equal to the number of lenses in the array. Each divided beam enters lens L1. AL1 and L1 form the focal system, and the beams split by AL1 are collimated in different directions and overlapped on the input plane (IP). When the transparent pattern is incident on the IP, each collimated beam forms a Fourier transform on the focal plane of lens L2. A number of Fourier-transformed images equal to the number of lenses constituting the AL are generated. The images are Fourier-transformed again by array lens AL2, and the pattern displayed on the IP is duplicated on the output plane (OP), which is the focal plane of AL2 [5].

Because the position of the lens comprising AL1 and AL2 corresponds to the position of a duplicate image, the position of a duplicate image can be changed by changing the position of each lens in AL1 and AL2. A Fourier-transformed image and a duplicate image can be simultaneously obtained on the same plane by adjusting the focal length of each lens constituting AL1 and AL2. That is, different designs corresponding to various array lenses are possible. Moreover, an additional process using a duplicate image as an input image, i.e., a cascade process, is easy to perform because the output plane crosses the optical axes of AL1, L1, L2, and AL2.

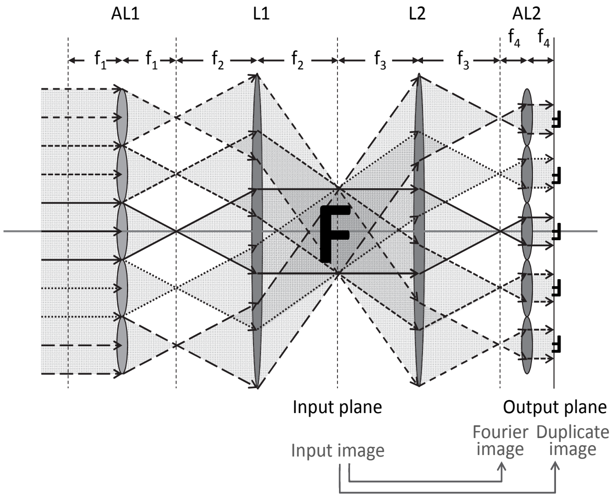


Fig. 5 Optical duplicate system.

B. Design of the optical duplicate system for a multi-beam generator

The numerical values required for the design of an optical duplicate system were calculated using geometric optics. The size d_i of the input plane that can input the beam to be duplicated is calculated from the following:

$$d_i = d_1 f_2 / f_1 \, . \tag{4}$$

The magnification β of a duplicate image is calculated from the following:

$$\beta = - f_4 / f_3 \, . \tag{5}$$

The length of one side of an output beam d_o is calculated from the following:

$$d_o = d_1 f_2 f_4 / f_1 f_3 \, . \tag{6}$$

The distance between output beams p_o is calculated from the following:

$$p_o = d_1 f_3 / f_2 \, , \tag{7}$$

where, d_1 is the diameter of the lenses in AL1, and f_1, f_2, f_3, and f_4 are the focal lengths of AL1, L1, L2, and AL2, respectively. The number of duplicate beams is the same as the number of lenses in AL1 and AL2.

The designed optical duplicate system will be used to split 1 beam into 4 beams with the following design condition, and it is assumed that the system will be installed in the telescope at the National Institute of Information and Communications Technology (NICT) ground station for space laser communication. Further, it is assumed that the system will be used in urban areas, with a 10× telescope, and a predetermined distance between output beams. L1 and L2 were of the same specifications. For the case of entering the collimated beam, in order to suppress the spherical aberration of each lens, the incidence side of a lens was made convex. For the same reason, when a collimated beam is output, the output side of lens is also convex. In order to condense an incident beam efficiently, AL1 and AL2 were from 2 × 2 square lenses; however, since the incident beam was circular, AL2 was made circular. Only the domain of 2 × 2 square lenses contributes to the output of a beam.

[Design condition]

- Number of output beam: 4
- Distance between output beams: p_o = 3 mm
- Length of one side of an output beam: d_o = 1.5 mm
- Wavelength of the input beam: 1.55 μm
- Diameter of the input beam: < 10 mm
- Form of the lenses in AL1 and AL2: square
- Form of AL1 and AL2: circular
- Material of AL1, AL2, L1, and L2: NBK-7 (index: n = 1.50)
- Thickness of AL1, AL2, L1, and L2: 5 mm
- Length of one side of a lens in AL1: d_1 = 3 mm
- Focal length: f_1 = 50 mm, $f_2 = f_3$ = 100 mm, f_4 = 25 mm

C. Examination of the optical duplicate system for space laser communication with a compact multi-beam generator by simulation

As summarized in Table 1, the conventional multi-beam generation method for space laser communications includes (1) installing the optical system composing beam splitters and mirrors with reflectance distribution in the telescope of the existing ground station, and (2) producing a new system comprising a laser and a telescope for projecting multi-beams. It is necessary to produce a new system that allows for changing the number of beams from each element comprising the optical system. However, the optical duplicate system proposed in this paper can be miniaturized independently of the number of beam branches by controlling the input pattern without changing the composition of each element. It is necessary to change the output beam size and the interval between output beams. Because the degree of atmospheric distortion depends on the position of a ground station and the time taken for communication with a satellite, the optical duplicate system with an easily controlled number of beams is useful in space laser communication.

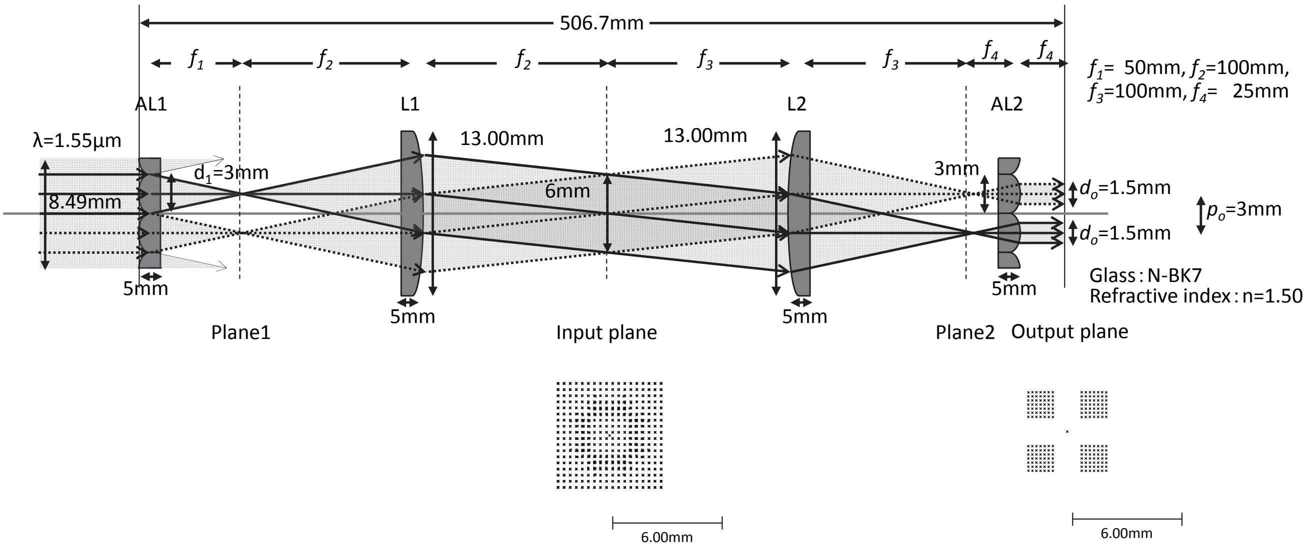


Fig. 6 Designed optical setup and spot diagrams at the input plane and output plane for the optical duplicate system functioning as a multi-beam generation device for satellite–ground laser communications.

Table 1 System for generating multi-beams.

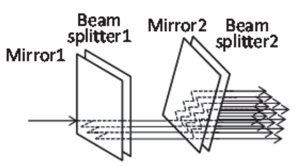
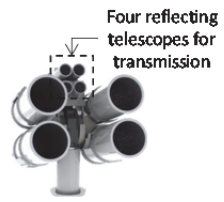
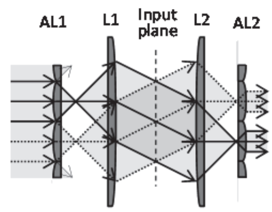
Method of generating multi-beams	(1) Two bulk optical devices [6] (Amplitude splitting)	(2) Co-boresighted telescopes on a single gimbal [7]	(3) The proposal technique Optical duplicate system (Wavefront splitting)
Group	M. Toyoshima [NICT]	D. M. Boroson [MIT]	Authors
Optical setup			
Size of system	About 150mm × 150mm × 400mm	The telescopic Aperture is 150mm.	Palm-sized (6mm × 6mm × 54mm*)
Principle of system	The intensity of the transmitted beam is equalized using the reflectance distribution of a beam splitter.	Multiple telescopes with identical parallel lasers.	The incident wavefront is split by array lens into a number of wavefronts equal to the number of lenses in the array.
Number of beams	Depends on the reflectance distribution of the beam splitter.	Telescope and laser must be prepared for each beam.	Increasing the number of beams is easy by simply controlling the input plane.)
Alignment and adjustment	Simple	It is required to align each telescope individually.	Alignment is easy by adjusting the optical axis.
Use of existing optical ground stations	Possible	It is necessary to replace.	Possible

Figure 6 shows the designed optical duplicate system as a multi-beam generator for space laser communication, and the spot diagram obtained in the simulation by ray-tracing software "CODE V®" [8].

In the input plane, the collimated beam enters tilted from four different directions. All of the beams centering on an optical axis are square in form, and they overlap each other. It was confirmed that the length of a side of the square in the simulation was nearly equal to the value d_i = 6 mm calculated from Eq. (4). Moreover, it turned out that it is necessary to input the beam into this square.

In the output plane, it was confirmed that 4 branch beams had been generated from a single input beam, as designed. The length of a side of the generated square beam was nearly equal to the theoretical value d_o = 1.5 mm calculated using Eq. (6). The theoretical value of the interval of the output beam calculated Eq. (7) was p_o = 3 mm, and it was nearly equal to the value estimated from the spot diagram in the simulation. The square spot (6 mm × 6 mm) on the input plane was considered to have been reproduced by a magnification $\beta = -1/4$ of the duplicated beam calculated using Eq. (5) corresponding to the number of the square lenses that constitute the AL.

As mentioned above, the optical duplicate system can flexibly control the number of beams according to the number of branch devices inserted image in the input plane without changing the specifications of the array lens or its arrangement. However, the output beam interval becomes small when inputting a beam onto the input plane and increasing the number of output beams. In order to reduce the influences of atmospheric distortion by multi-beam transmission, the interval between beam needs to be longer than the coherence length of air. This interval can be adjusted by changing the magnification of the telescope arranged behind the optical duplicate system.

IV. Conclusion

As a multi-beam generator for reducing the influence of atmospheric distortion in satellite–ground laser communications, a small and lightweight optical duplicate system was newly proposed. We proved that the averaging effect reduced atmospheric distortion by superimposing multi-beams in space through the calculation of probability density distributions using beams obtained in transmission experiments in the atmosphere. On the basis of this result, the small optical duplicate system was proposed as a spatial division multi-beam generator that can flexibly control the number of output beams. Furthermore, it is assumed that an optical duplicate system is to be installed in the telescope of the ground station of NICT after determining the size and the output pattern of the output beam, the size of the array lens, the lenses constituting the optical duplicate system, the arrangement of the optical system, etc., and a realizable optical duplicate system was designed. In the future, we will produce a prototype optical duplicate system based on this design and prove the reduction of the atmospheric distortion using multi-beams.

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