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COUPLING EFFICIENCY OF LASER BEAM TO MULTIMODE FIBER FOR FREE SPACE OPTICAL COMMUNICATION

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I. INTRODUCTION

Recently, the free space optical (FSO) communications have been widely studied as an alternative for large capacity communications and its possible implementation in satellite and terrestrial laser links. In satellite communications, clouds can strongly attenuate the laser signal that would lead to high bit-error rates or temporal unavailability of the link. To overcome the cloud coverage effects, often site diversity technique is implemented [1]. When using multiple ground stations though, simplified optical system is required to allow the usage of more flexible approaches [2]. In terrestrial laser communications, several methods for optical system simplification by using a multimode fiber (MMF) have been proposed [2, 3].

In the case of the FSO communications, however, the atmospheric turbulence causes wavefront distortion of the propagation light. As a result, angle-of-arrival fluctuations of the laser beam are observed at the focal plane of the optical receiving system [4]. In order to solve these problems, one method is to use a high accuracy tracking system or a wavefront correction system [5, 6].

Another popular method is to use a photodetector (PD) with large receiving area in order to cover the movement of the beam spot without using tracking system [7, 8]. However, PD with large receiving area have narrow bandwidth due to high capacitance. An outdoor optical receiving system can be simplified significantly by replacing the PD in the receiving antenna directly with an optical fiber. Thus it is not necessary to supply electricity for the PD outdoors. Furthermore, such design is independent on link parameters, such as operation wavelength, bit-rate and modulation. An optical system with simple structure will contribute to the easy usage and to the wide spread of FSO communication systems, which can be used for satellite and terrestrial optical communication.

When an optical fiber is used as a receiver though, there is a coupling loss due to the angle-of-arrival fluctuations. Therefore, the received power is attenuated as the atmospheric turbulence becomes stronger. The atmospheric turbulence can be expressed with the refractive index structure parameter Cn^2, which is a very important parameter for the measurement of atmospheric turbulence.

In this research, we derive a closed form equation to estimate the coupling loss when the FSO receiver uses direct coupling of optical fiber. Our theoretical model is evaluated by comparison with the experimental results of our FSO system setup. We are aiming at the contribution to design a receiving optical setup with an optical fiber for satellite laser communications and terrestrial laser communications.

In Section 2 we introduce an optical wireless transmission system without tracking or wavefront correction systems, designed by using a MMF with different core diameters. In Section 3 we derive a closed form equation for calculation of coupling efficiency of laser beam to a MMF from Cn^2. In Section 4 we compare the theoretical and experimental results for coupling efficiency. Finally, we conclude the paper in Section 5.

II. OVERVIEW OF THE EXPERIMENT

In order to measure the optical turbulence and show the relationship between the turbulence characterization and the coupling efficiency of laser beam to a MMF, we setup a pair of optical transmission systems between two buildings - a building of NICT and of UEC in Tokyo. The aerial photo of propagation path of FSO communication is shown in Fig. 1.

The laser propagates in the center of Tokyo. We transmit a laser with 1.5 μm wavelength from UEC to NICT and the link distance is 7.8km. Fig. 2 shows the container, which we set on the roof of the building in UEC (Fig. 2a) and the view from the container to NICT. You can see a part of the transmitting system in Fig. 2b, and there is no obstacle to intercept the laser transmission path.

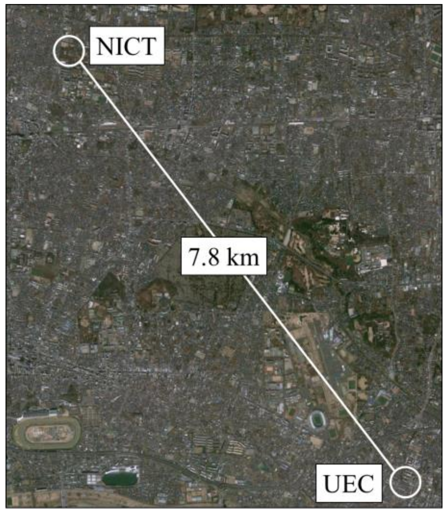


Fig. 1. An aerial photo of the propagation path (data from google.com)

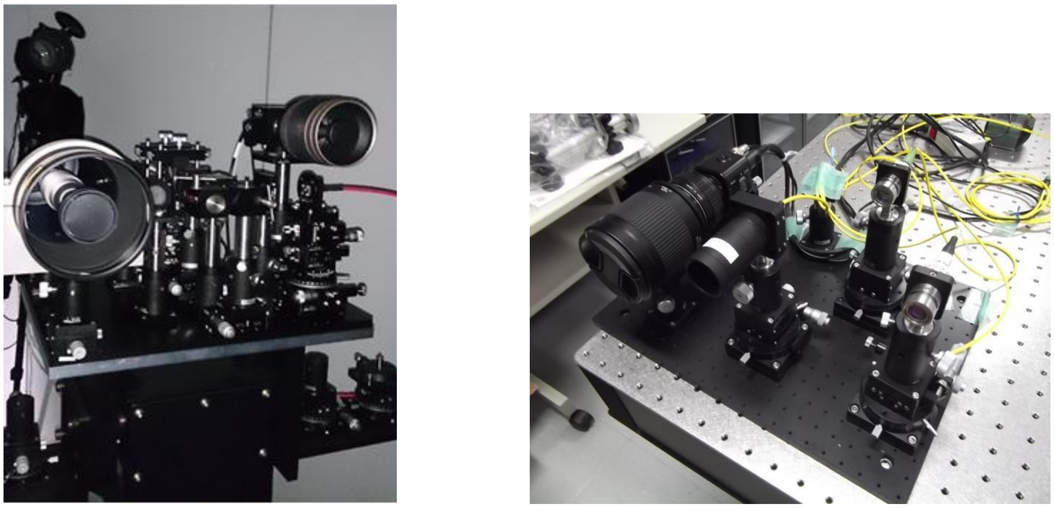
(a) (b)

Fig. 2. The communication facility in UEC: a. dome on the building roof; b. view of the container from inside

The optical receiver and transmitter are shown in Fig. 3 and the link parameters are shown in Table 1. The laser, transmitted from UEC is received by a mirror lens, attached to the receiving system. The aperture size of the mirror lens is 111 mm and the focal length is 800 mm. The received laser is separated into two different beams by a beam splitter, one of the beams propagates to PD_1 to measure the receiving power, and the other one propagates to MMF and through it reaches PD_2. We regard coupling efficiency as the ratio of the received power in the two PD's.

TABLE 1 Characteristics of optical communication system

Optical receiving system	
Aperture size of the mirror lens	111 mm
Focal length of the mirror lens	800 mm
Effective radius of PD	2 mm
Communication distance	7.8 km
Optical transmitting system	
Communication wavelength	1.5 μm
Divergence angle	0.2 mrad
Communication distance	7.8 km



(c) (d)

Fig. 3. Photo of the optical system setup: c. receiver module; d. transmitter module

III. THEORY OF ATMOSPHERIC TURBULENCE AND COUPLING EFFICIENCY

A. Atmospheric Turbulence

The local density of the atmosphere is always changing because of temperature, pressure fluctuations and presence of wind [9, 10]. When a laser beam propagates through the atmosphere the randomly varying spatial distribution of the refractive indexes that it encounters can cause a number of effects, including scintillation - a fluctuating intensity observed with an optical detector at the end of the path. In the late 1960's Tatarskii developed the Rytov method [9], which it is widely used in calculations of the effect of the atmospheric turbulence on optical wave propagation. The method provides a solution for the intensity fluctuations of a plane wave in weak turbulence conditions,

$$\sigma_I^2 = \left\langle \left(\ln I - \left\langle \ln I \right\rangle\right)^2 \right\rangle = 1.23 Cn^2 k^{7/6} L^{11/6}, \tag{1}$$

where L is the propagation distance, $k=2\pi/\lambda$ is the wave number, λ is the wavelength and I is receiving power. σ_I^2 shows the intensity fluctuation and it will be measured by a receiving aperture with a small diameter.

The amount of intensity fluctuations varies with the size of the receiver aperture. This effect of the receiver size on the intensity variance is called aperture averaging. The aperture averaging factor A is defined as the ratio of the normalized intensity variance of fluctuations of a receiver with diameter D to that of a point receiver. For a plane wave with small inner scale, $l_0 << (L/k)^{1/2}$ the aperture averaging factor is approximated by [11]:

$$A = \frac{\sigma_I^2(D)}{\sigma_I^2(D=0)} = \left[1 + 1.07\left(\frac{kD^2}{4L}\right)^{7/6}\right]^{-1}. \tag{2}$$

From (1) and (2) the intensity fluctuations in an aperture with diameter D are shown in [12]:

$$\sigma_I^2(D) = A\sigma_I^2(D=0) = \left[1 + 1.07\left(\frac{kD^2}{4L}\right)^{7/6}\right]^{-1} \times 1.23 k^{7/6} Cn^2 L^{11/6} \tag{3}$$

And Cn^2 can be indicated from the received power of the optical measure devices by [12]:

$$Cn^2 = \frac{\sigma_I^2(D)\left[1 + 1.07\left(\frac{kD^2}{4L}\right)^{7/6}\right]}{1.23 k^{7/6} L^{11/6}}. \tag{4}$$

$\sigma_I^2(D)$ is the variation of intensity fluctuations with aperture averaging. We use (4) to calculate the Cn^2 from the received power in the experiment.

B. Coupling Efficiency

The beam quality factor M^2 is important to measure the coupling efficiency when the beam after atmospheric propagation is coupled into the optical fiber [13]. We focus on the M^2 to estimate the coupling efficiency of laser beam to a MMF, and the M^2 of the beam after atmospheric propagation is calculated by the following formula [2, 14]:

$$M^2 = \sqrt{\left(M_0^2\right)^2 + 2\omega_0^2 k^2 TL + \frac{8}{3\omega_0^2} TL^3 + \frac{4}{3} k^2 T^2 L^4}\ , \tag{5}$$

where ω_0 is the beam waist of the laser emitted, and T is

$$T = \pi^2 \int_0^\infty k^3 \Phi(k) dk\ . \tag{6}$$

$\Phi(k)$ is the power spectrum of refractive index, and (6) can be determined from the Tatarskii spectrum by

$$T = 7.6113 Cn^2\ . \tag{7}$$

M_0^2 is

$$M_0^2 = \frac{\pi}{\lambda} w\phi\ , \tag{8}$$

where w is a beam radius and ϕ *is* angle of incidence before the incidence in a fiber. In the case of geometrical optics, the coupling efficiency of laser beam to multimode fiber is given by the factor M^2 [13]:

$$\eta = \left[1 - \exp\left(-\frac{2M_F^2}{M^2}\right)\right]^2 \tag{9}$$

An equivalent factor M_F^2 for the multimode fiber is introduced to characterize the fiber coupling capability. M_F^2 is defined by the core radius a and the maximum accepted angle θ that corresponds a numerical aperture (NA) for a MMF:

$$M_F^2 = \frac{\pi}{\lambda} a\theta\ . \tag{10}$$

The value of w is found to be 74.5 μm by using a laser beam profiler. We consider that the reflection loss on the input surface and the output surface affected the result of the estimating coupling efficiency. So we can rewrite (9) into η' by geometrical optics:

$$\eta' = \alpha \times \eta \tag{11}$$

$$\alpha = (1 - R_1) \times (1 - R_2)\ . \tag{12}$$

R_1 and R_2 are the reflections from air to silica and from silica to air, respectively. We calculate the reflection by the Fresnel equations [15]. Fig. 4 shows the theoretical coupling efficiency, calculated by (11), for core diameters of MMF of 200 μm or 600 μm and both of the NA are 0.37. Wavelength is 1.5 μm and the propagation distance L is 7.8 km. R_1 and R_2 are 0.034 when the refractive index of air is 1 and the refractive index of silica is 1.45. From Fig. 4, the coupling efficiency with 600 μm is a constant when Cn^2 is less than 10^{-15} and the value of 200 μm decrease from Cn^{-16}.

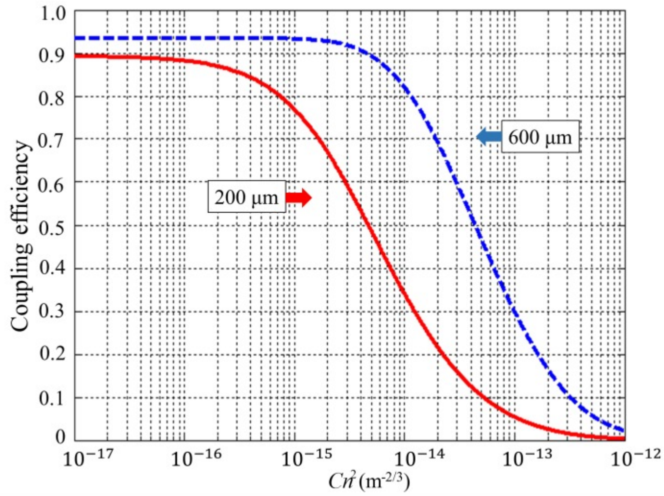


Fig. 4. The coupling efficiency as a function of the

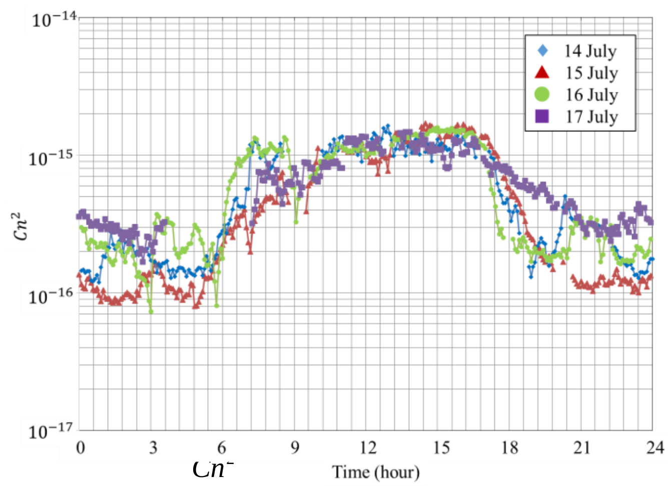


Fig. 5. Cn^2 fluctuations in time for different dates

IV. EXPERIMENTAL RESULTS

We introduce the daily fluctuations of atmospheric turbulence between NICT and UEC in Tokyo. We use (4) to calculate the Cn^2 from the receiving power of optical communication systems. Fig. 5 shows the daily fluctuations of Cn^2 for four different dates with good weather in July, 2014. Table 2 shows the weather data and the Cn^2. The sample frequency of the data is 20 kHz. In Fig. 5, one dot indicates the average data for 5 min.

As it is widely known, Cn^2 in the daytime is larger than at night. And we can see that Cn^2 fluctuates almost identically for the same time of the day. From previous work it is known that the Cn^2 in a rainy or cloudy day is weaker, compared to the one in a sunny day [9]. Furthermore, the Cn^2 in the city is also stronger than in the country [9]. We evaluate the coupling efficiency during a period of time when the values of the Cn^2 vary from 10^{-15} to 10^{-17} m$^{-2/3}$.

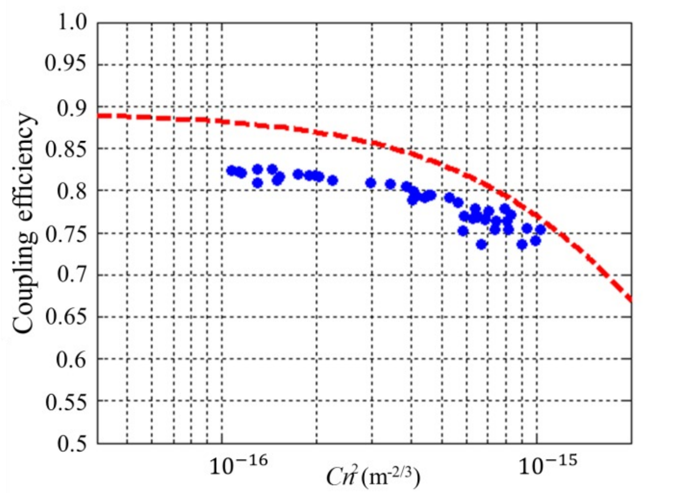
TABLE 2 Weather data and Cn^2

Data	Temperature (°F)		Wind speed (m/s)	Hours of sunlight (h)	Cn^2	
	High	Low			High	Low
14 July 2014	92.6	72.5	1.5	4.8	1.63×10^{-15}	1.00×10^{-16}
15 July 2014	90.3	74.8	2.2	7.0	1.71×10^{-15}	8.03×10^{-17}
16 July 2014	92.3	73.9	1.8	9.8	1.58×10^{-15}	7.30×10^{-17}
17 July 2014	88.5	75.5	2.2	4.3	1.48×10^{-15}	1.68×10^{-16}

We introduce the measurement results of the coupling efficiency when a MMF is implemented. The core diameters used in the optical setup are 200 μm and 600 μm, each used in a different day. Both NA are 0.37. Fig. 6 shows the coupling efficiency for both theory and experimental results for two different days. The dotted line shows the theoretical coupling efficiency, and dots show the experimental results. We regard the coupling efficiency as a ratio of the received powers measured by MMF and PD. The sample frequency of the data is 20 kHz and one dot indicates the average of 5-min data. The measurement time is about 3 hours, and it is measured from 3:30 pm to 7:00 pm when the Cn^2 largely changed.

When a MMF with core diameter 200 μm was used, we could measure the Cn^2 value from 10^{-15} to 10^{-16} $m^{-2/3}$. In case of 600 μm, we calculated the Cn^2 value from 10^{-15} to 6×10^{-17} $m^{-2/3}$. We can see coupling efficiency attenuates as the Cn^2 increases, as well as the theoretical coupling efficiency in the data for 200 μm. In the case of 600 μm, the coupling efficiency is almost constant between 6×10^{-17} and 3×10^{-16} $m^{-2/3}$. The theoretical coupling efficiency with 200 μm have a maximum of 8 % error in comparison with the measurement results. Similarly, the theory in the case of 600 μm the error is around 8 %. All measurement results have a range of about 5 % error at the same value of Cn^2. The theory (11) used in this evaluation is considered as geometrical optics for simple estimation. We can conclude that there is about 8 % error that is independent on the atmospheric turbulence in the considered Cn^2 range.

According to this result, the theory indicated in this paper contributed to design of a receiving optical setup using MMF with core diameter 200 μm and 600 μm in consideration of errors when the value of the refraction structure Cn^2 is from 10^{-15} to 10^{-16} $m^{-2/3}$. For example, if a step-index MMF with core diameter 600 μm is used and NA is 0.37 and a core refractive index is 1.45, an upper bound of data transmission band is 1.27 GHz in case of fiber length 5 m [16].



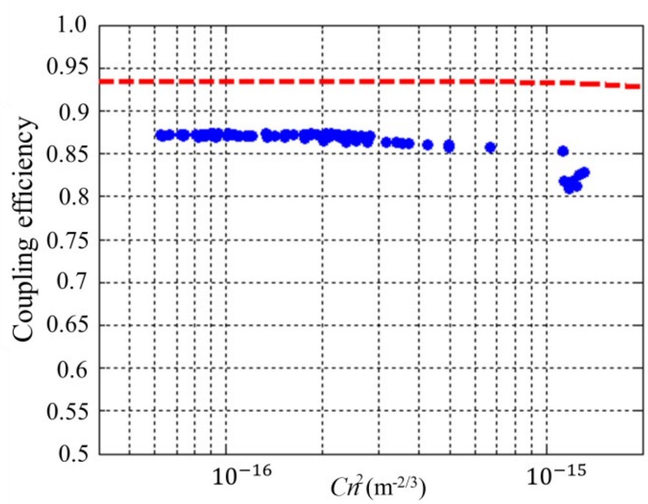


Fig. 6. The coupling efficiency of laser beam to MMF
The core radius of the MMF (top: 200 μ, bottom: 600μ)

V. CONCLUSION

In this paper, we report the FSO coupling to the MMF to simplify an optical system under the atmospheric turbulence environment for the FSO communications. We setup an optical communication system to measure the refraction parameter Cn^2 and the coupling efficiency between two buildings on 7.8 km distance. We calculate Cn^2 from the experimentally received optical power and observe the daily fluctuations of atmosphere turbulence between NICT and UEC in Tokyo. Further, we discussed the theory of coupling efficiency by using M^2 and M_F^2. The comparison between the theory and the experiment results shows that they match within 8 % error when the value of the refraction structure Cn^2 is from 10^{-15} to 10^{-16} $m^{-2/3}$. From this result, this theory contributes to design of an optical communication systems using MMF under the value of Cn^2 from 10^{-15} to 10^{-16} $m^{-2/3}$ for satellite and terrestrial laser communications.

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