4-3 Experiment of the Fiber Coupling Efficiency for Satellite Downlinks

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The results are shown of experiments to measure fiber coupling efficiencies using the fine pointing mechanism in ground-to-satellite optical communications by utilizing the optical inter-orbit communications engineering test satellite "OICETS". First, the fiber coupling theory of spatial optical communication in horizontal propagation is extended to a fiber coupling theory of optical communication in space which takes into account changes in altitude. Further, in the present experiments a fast fine pointing mechanism was used to enable the tracking of variations in atmospheric turbulence, and thus the fiber coupling experiments of ground-to-satellite optical communications were conducted by suppressing the effects of atmospheric turbulence. Finally, the results of the actual fiber coupling experiments using OICETS are compared with the results of simulations using the fiber coupling theory of optical communication in space which takes into account changes in altitude.

Keywords
Laser communication, Fiber coupling efficiency, Atmospheric turbulence, Fast steering mirror

1 Introduction

In recent years, due to significant increases in the functionality of satellites, there have been many opportunities to process a large volume of data. Therefore large capacity and high-speed communications linking between a satellite and a ground station are in demand. Radio frequency (RF) communications using radio waves would be unable to realize the communication speed in the gigabit class demanded now because radio frequencies are severely regulated by radio wave laws. In addition, when we try to realize some multi-transmitting schemes with high speed, the size of the whole satellite system including its larger antenna-diameter and its increased power consumption would be problematic to the RF communications. Thus, RF communications have some restrictions for development in space because power resources are limited in space [1].

On the other hand, attention is now being given in research and development to satellite laser communications technology. This technology can easily realize baseband transmission in the gigabit class because in laser communications, a laser is used at frequency regions of several hundred tera (10^{12}) Hz. An ideal feature of satellite laser communications is that the size of the antenna becomes smaller because of the high frequency of the optical wave, and both the size and weight of the satellite onboard optical transceiver would be small. However, in order to apply the optical communications to the satellite communications, there are still some challenges to overcome. First of all, some satellite onboard components need fine acquisition and tracking performance because the divergence angle of a laser beam is narrow. In addition, since there is atmosphere between a satellite and the ground, a communication signal is degraded by the generation of scintillation or variations in an arrival angle caused by changes in the refractive index generated by atmospheric turbulence. This scintillation is a main factor of disturbance when laser communications are implemented between a ground station and a satellite, and the variation frequency of atmospheric turbulence becomes more than 1 kHz when the satellite moves on the Earth orbit with 7 km/sec and an optical link cuts across the Earth's atmosphere with high speed. Moreover, an Optical received from the satellite must be led into a single mode fiber because an optical fiber amplifier is necessary to apply laser communications to satellite communications.

In this paper, the following sections describe the measurements of fiber couplings using optical from the actual satellite, the Optical Inter-orbit Communications Engineering Test Satellite (OICETS). In Section **2**, the equation for fiber coupling theory in horizontal propagation is extended in order to be able to correspond with the changes in altitude. Using the extended equation, simulations can be performed for the fiber coupling efficiency in ground-to-satellite optical communications based on an arbitrary zenith angle. Section **3** gives an explanation of the experiment of actual fiber coupling experiments using the OICETS. Section **4** shows the results of fiber coupling experiments in ground-to-satellite optical communications using the OISETS. In Section **5**, the measured values obtained from the actual OICETS experiments are compared to the theoretical values of fiber coupling efficiency in ground-to-satellite optical communications.

2 Fiber coupling theory

In this research, the fiber coupling theory in horizontal propagation is extended to show how fiber coupling efficiency is affected when the structural parameters of refractive index change as the altitude changes in the propagation path such as ground-to-satellite optical communications. The efficiency of the fiber coupling theory in horizontal propagation under atmospheric turbulence is obtained by Equation (1) [2].

$$\eta_c = 8a^2 \int_0^1 \int_0^1 exp\left[-\left(a^2 + \frac{A_R}{A_C}\right)(x_1^2 + x_2^2)\right] \times I_0\left(2\frac{A_R}{A_C}x_1x_2\right)x_1x_2dx_1dx_2 \tag{1}$$

$$a = \frac{D_R}{2}\frac{\pi W_m}{\lambda f} \tag{2}$$

$$A_C = \pi\rho_c^2 \tag{3}$$

$$A_R = \pi D_R^2/4 \tag{4}$$

$$\rho_c = (1.46C_n^2k^2L)^{-3/5} \tag{5}$$

where, D_R is the diameter of the reception lens, W_m is the radius of the fiber mode field, λ is the wavelength, f is the focal length of the lens, L is the communication distance, and k is the wave number of beam wave.

In order to extend Equation (1) corresponding to changes in the altitude, it is necessary to use the following structural parameters of atmospheric detraction of the Hufnage-Valley (H-V) model [3].

$$C_n^2(z) = 0.00594(v/27)^2(10^{-5}z)^{10}\exp\left(-\frac{z}{1000}\right) + 2.7\times10^{-16}\exp\left(-\frac{z}{1500}\right) + A\exp\left(-\frac{z}{100}\right) \tag{6}$$

After adapting Equation (6) to ρ_c, the fiber coupling efficiency corresponding to the altitude change is obtained as follows:

$$\rho_z = \left[1.46k^2\frac{1}{\cos(\zeta)}\int_{h_0}^{H} dz\, C_n^2(z)\right]^{-3/5} \tag{7}$$

In addition, for H,

$$H = h_0 + L\cos(\zeta) \tag{8}$$

where, h_0 is the height of the telescope and ζ is the zenith angle. The C_n^2 (z) parameter, v is the rms value under the Bafuton wind speed model, and averaged coefficient A by an aperture is a measured value, $1.2\times10^{-13}m^{-2/3}$ which was measured by the optical ground station of National Institute of Information and Communications Technology (NICT) in Koganei City. In addition, h_0 is 122 meters [4]. Figure 1 shows a graph of the detraction index of atmospheric turbulence when z altitude in these parameters changes. This graph clearly shows that the structural parameters of atmospheric detraction caused by the atmospheric turbulence become smaller as the altitude becomes higher.

Figure 2 shows the fiber coupling efficiency when changing the distance L, assuming that $D_R = 0.318$, $W_m = 5.2$ μm, $\lambda = 850$ nm, $f = 0.1$ m, $h_0 = 122$ m, $\zeta = 58°$, and $A = 1.2\times10^{-13}\mathrm{m}^{-2/3}$. The graph shows that the fiber coupling efficiency becomes smallest when the distance reaches 10 km. This happens when the altitude is high and the atmospheric effect is suppressed.

3 Configuration of experimental system

Experiments of ground-satellite laser communications were performed using the OICETS. One of the experiments was performed to determine how well a fine pointing mechanism could couple to the single mode fiber, absorbing variations in atmospheric turbulence. The summary of this experiment was shown in Fig. 3. First, in advance, a control command is transmitted from the Tsukuba Space Center to OICETS in order to set up the experiment. Then, mutual laser communications were enabled when the optical ground station transmitted laser to OICETS and OICETS responded to the laser after the OICETS became visible in the sky at the optical ground station at NICT.

The laser received from a telescope was then led into an optical bench through the Coudé Path. The configuration of the fine pointing mechanism (FPM) is shown in Fig. 4. The received laser is split into two and the mirror of the fine pointing mechanism reflects each split light. A closed loop is integrated into the fine pointing mechanism and a tracking sensor (QD), and the pointing mechanism is controlled so that the laser enters through the center of the tracking sensor. In addition, a beam splitter is placed between the fine pointing mechanism and the tracking sensor, and a lens and a single mode fiber are placed at the subsequent stage. The fine pointing mechanism is adjusted so that the laser is led into the single mode fiber when the laser enters through the center of the tracking sensor.

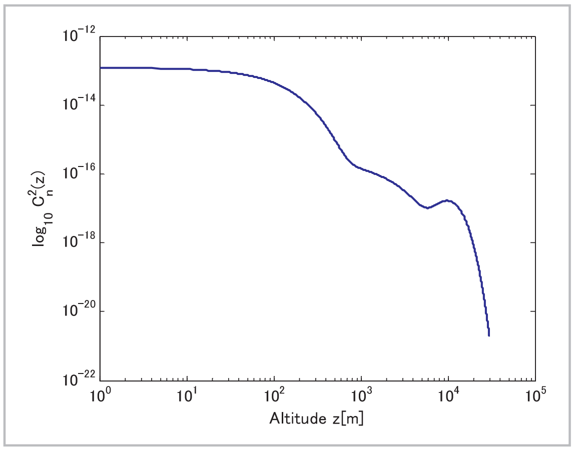

Fig.1 Changes in the structural parameter caused by atmospheric turbulence

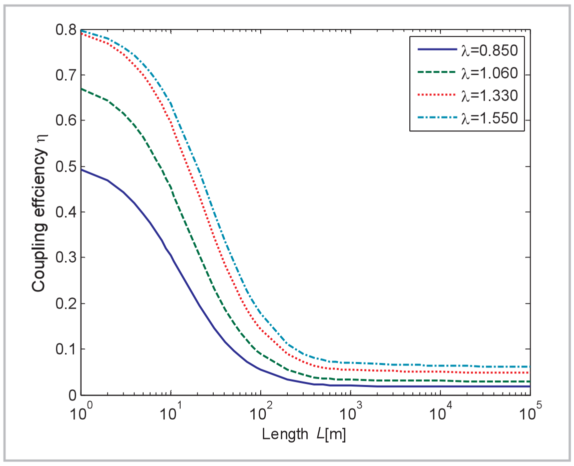

Fig.2 Fiber coupling efficiency when Communication distance L changes

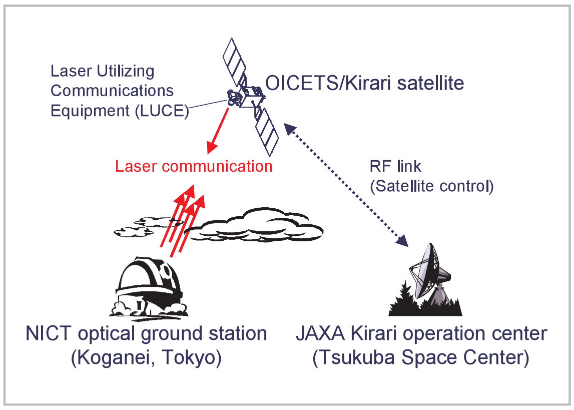

Fig.3 Summary of OICETS experiments

As for the received level through the fiber coupling, the received power of the single mode fiber using a stable local source is compared to the received power using the actual OICETS. The received power is measured by a sensor of the single mode fiber PD_a and a reference sensor PD_b. In addition, both the loss of the optical system and the power before entering the single mode fiber have been obtained by the reference sensor PD_b in advance.

Figure 5 shows the fine pointing mechanism utilized for this experiment. A fine pointing mechanism is used that is designed to have more than 4 kHz of frequency response (Table 1).

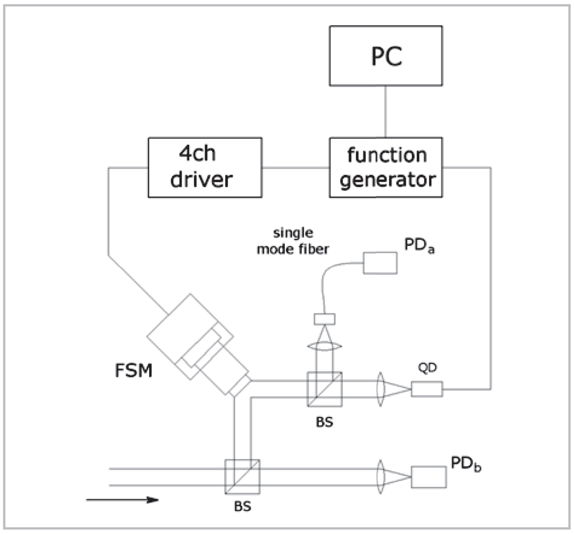

Fig.4 *Experiment configuration of Fine pointing mechanism*

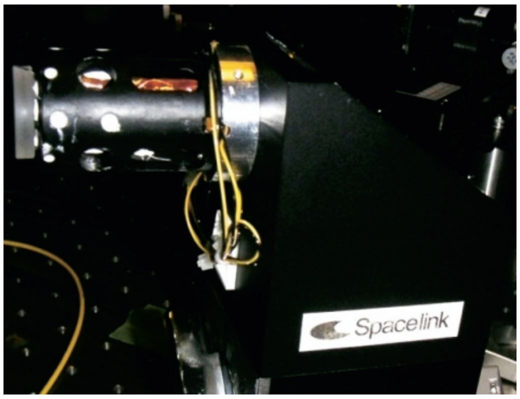

Fig.5 *Fine pointing mechanism*

4 Experiment results

Figure 6 shows the experiment results of communicating with the OICETS. These graphs show the amount of received laser and the ON-OFF status of the fine pointing mechanism from the experiment of communicating with the OICETS. In both graphs, the vertical axis indicates voltage and the horizontal axis indicates elapsed time. The elapsed time in these graphs shows the experiment time in the experiment of ground-to-satellite optical communications.

During the experiment, the fine pointing mechanism repeated ON-OFF operations on purpose. The fine pointing mechanism turns ON when its power voltage becomes 5 volts. It was found that the amount of received laser led into the single mode fiber was increased when the fine pointing mechanism was ON and the atmospheric turbulence could be re-

Table 1 *Specification of Fine pointing mechanism*

item	value
Drive element	Piezoelectric
Drive voltage	0-150 V
Pre-road	900 N
Diameter of Mirror	20 mmφ
Angular range	±2.7 mrad
Frequency response	> 2 kHz

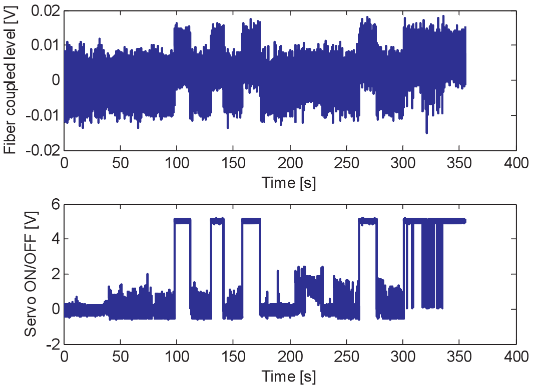

Fig.6 *Fiber coupling values and ON-OFF status of Fine pointing mechanism*

duced by the fine pointing mechanism.

Figure 7 shows the fiber coupling loss when the fine pointing mechanism operates during the 100-to-110 sec period. When the fiber coupling efficiencies measured using the local laser source are compared to those measured using the laser from OICETS, the graph clearly shows that the fiber coupling loss stays on attenuation levels between –11 dB and –18 dB.

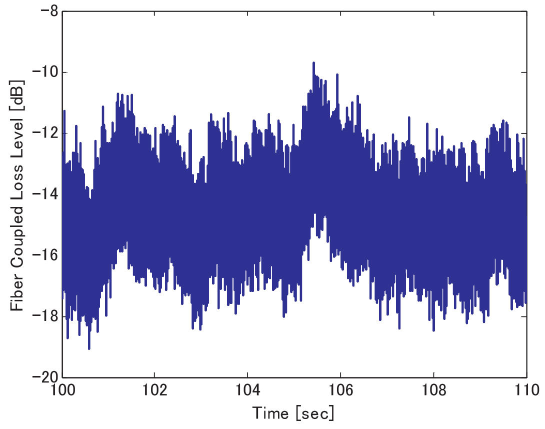

Fig.7 Fiber coupling loss

Table 2 Simulation parameters

parameter	value
h_0	122 m
L	1000 km
A	1.2E-13 m$^{-2/3}$
W_m	5.2 μm
v	90 m/s
D_r	0.318 m
λ	847 nm
f	0.1 m
ζ	58 deg

5 Consideration of experiment results

The fiber coupling efficiency is calculated when the effect of atmospheric turbulence is included. After the laser passes through the atmosphere, the optical coherence is collapsed and speckle pattern are generated. The fiber coupling efficiency is degraded according to the number of speckles. Using ρ_z in Equation (7) in Section **2**, which is the extended equation corresponding with changes in the altitude, we calculated ρ_z to show how the fiber coupling efficiency degraded. Table 2 shows the parameters used for this calculation.

The satellite altitude was about 1,000 km during the 100-to-110 sec period. In this situation, it was found that the fiber coupling efficiency was –17.05 dB at the altitude of 1,000 km. Since the fiber coupling loss is from –11 to –18 dB, which is obtained in Section **4**, this result shows that the theoretical value is very close to the experiment value.

6 Conclusion

In this paper, the theoretical equation for horizontal propagation has been extended and the fiber coupling efficiency including the effect of atmospheric turbulence was calculated. It was found that the theoretical value of fiber coupling loss is very close to the experiment value when compared.

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