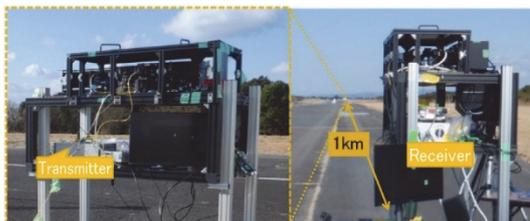


# Development of a Free-Space Optical Communication Device Capable of High-Speed, High-Capacity Transmission Over Distances Exceeding 1 km in Outdoor Environments



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*This report focuses on free-space optical (FSO) communication as a next-generation high-speed communication technology to meet the rapidly increasing demand for data traffic, and examines the challenges and solutions for its practical application. While FSO communication can achieve high-speed, large-capacity and secure communication by leveraging the straight-line propagation and wideband characteristics of light, it faces the problem of degraded communication quality due to transceiver installation errors and minute optical axis fluctuations caused by atmospheric turbulence. To address these issues, Mitsubishi Heavy Industries, Ltd. (MHI) developed acquisition and tracking technology for installation errors and optical axis compensation technology for axis fluctuations, achieving high-speed and high-precision optical axis control. Furthermore, in collaboration with NTT, Inc., which possesses optical fiber communication expertise, MHI confirmed that a maximum transmission rate of 100 Gbps can be achieved even in outdoor environments over a distance of 1 km with strong atmospheric turbulence, maintaining an average transmission rate of 93 Gbps per unit time. These results represent a significant outcome toward the practical application of FSO communication and demonstrate its potential for use in disaster-affected areas, regions with undeveloped infrastructure, and mobile-to-mobile communications.*

## 1. Introduction

In recent years, data traffic has continued to increase year after year with the rapid spread of video streaming services, cloud computing, and IoT devices. As a result, it is becoming increasingly difficult to meet this demand using only conventional wireless communication and wired infrastructure, leading to a growing need for new communication methods. Against this background, free-space optical (hereinafter referred to as FSO) communication is attracting attention as a next-generation high-speed communication technology that leverages the straight-line propagation and wideband characteristics of light<sup>(1)</sup>.

FSO communication is a technology that enables high-speed, large-capacity communication comparable to optical fiber communication by collimating the communication light emitted from an optical fiber within the transmitter, re-focusing the light at a distant receiver, and coupling it back into an optical fiber. This allows for the construction of flexible networks without using physical media such as optical fibers as the transmission path. It is expected to be applied particularly in scenarios where communication infrastructure needs to be established during disasters, as well as in situations where laying infrastructure is difficult, such as satellite communications and mobile-to-mobile communications.

FSO communication has several distinct advantages compared to radio frequency communication. First, FSO communication using communication light enables high-speed communication ranging from several gigabits per second (Gbps) to as fast as several terabits per second (Tbps). In radio frequency communication, frequency resources are limited, and increasing communication speeds involves issues with regulations and interference. Additionally, communication light has very high directivity and does not spread spatially, which minimizes leakage and makes eavesdropping difficult, thereby ensuring high security. Furthermore, frequency

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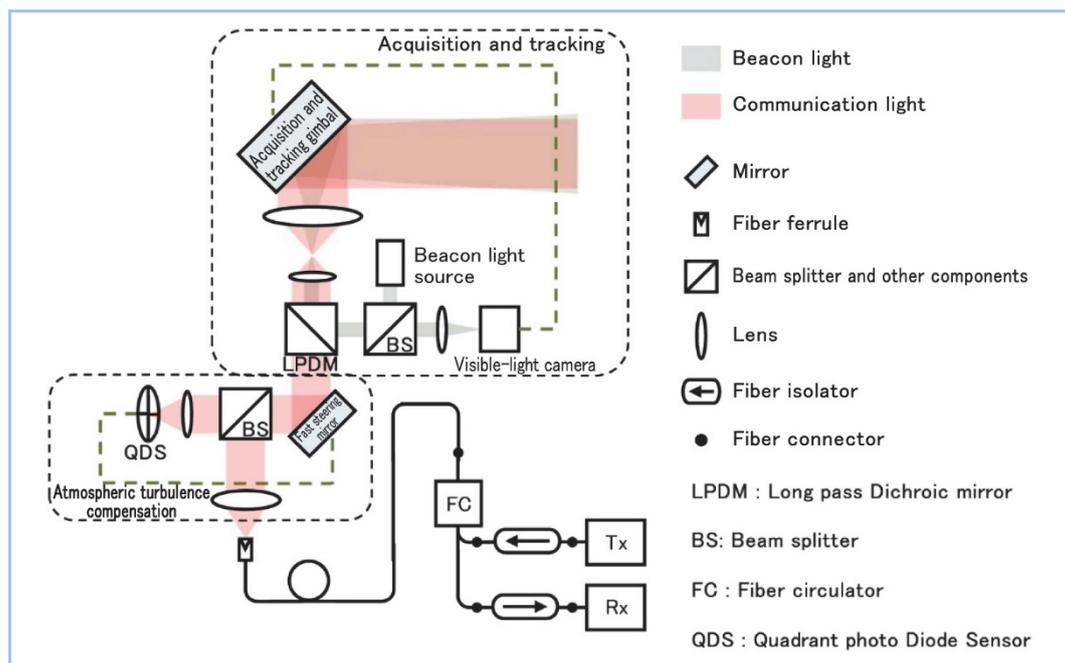
licensing and notifications are not required for its use.

On the other hand, there are specific challenges associated with the use of communication light toward its practical application <sup>(2)</sup>. For example, communication light is affected by atmospheric turbulence during propagation through the atmosphere. Atmospheric turbulence is a refractive index fluctuation caused primarily by non-uniformity in temperature and pressure, and these fluctuations disturb the optical axis. Because atmospheric turbulence causes temporal variations in the intensity of the light coupled into the optical fiber at the receiver, it consequently leads to communication disruptions and increased error rates. The effects of atmospheric turbulence become prominent during long-distance propagation or when communication light passes near the ground surface. To ensure stable communication in FSO communication, technology to compensate for atmospheric turbulence is essential. Furthermore, because communication light has high directivity, installation errors significantly degrade coupling efficiency. Therefore, precise optical axis alignment is indispensable in FSO communication.

## 2. System overview

As explained in the previous chapter, the optical axis of the communication light in FSO communication fluctuates due to transceiver installation errors and atmospheric turbulence along the transmission path, leading to communication disruptions and increased error rates. To overcome this challenge, technology to detect and compensate for installation errors and optical axis fluctuations is essential. This report presents the details of the acquisition and tracking technology developed for installation errors, and the optical axis compensation technology for optical axis fluctuations caused by atmospheric turbulence and other factors.

**Figure 1** shows the overall conceptual diagram of the FSO communication system. When transmitting data from this system, as shown in Figure 1, communication light is emitted from the light source (Tx) via an optical fiber. The communication light passes through a fiber circulator (hereinafter referred to as FC<sup>\*1</sup>) and is emitted into space from the fiber end. It then sequentially passes through a beam splitter (hereinafter referred to as BS<sup>\*2</sup>), a fast steering mirror (hereinafter referred to as FSM<sup>\*3</sup>), a long-pass dichroic mirror (hereinafter referred to as LPDM<sup>\*4</sup>), and an acquisition and tracking gimbal mirror before being emitted to a distant location. Conversely, when receiving data, the communication light follows the opposite path and reaches the receiving optical device (Rx) from the FC outlet different from Tx.



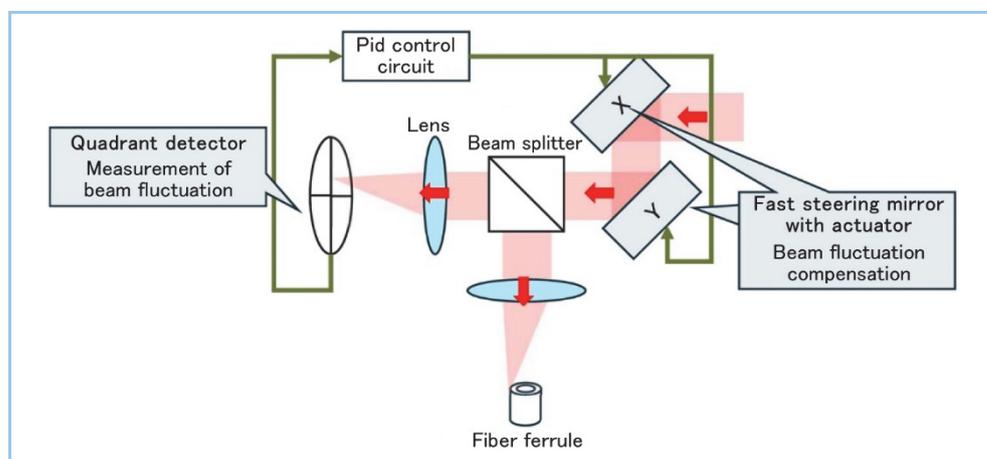
**Figure 1 Overall conceptual diagram of FSO communication system**

The developed acquisition and tracking technology described in this report aligns the communication light and beacon light coaxially, as shown in Figure 1. Specifically, the system is configured to combine the communication light and beacon light using an LPDM and emit them

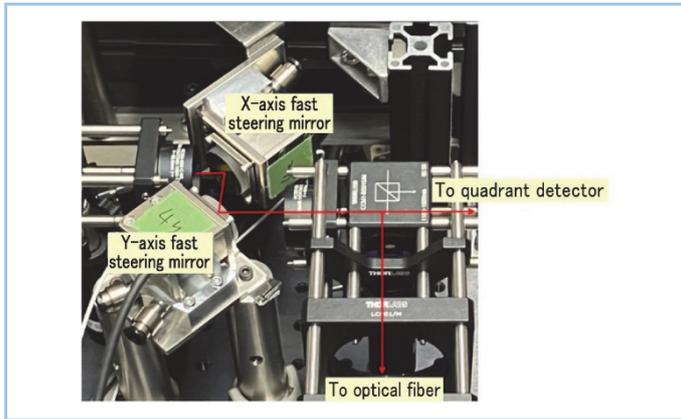
from a single optical axis. By selecting a visible wavelength for the beacon light, it can be easily detected at the receiving side. The receiving side uses a visible-light camera to capture an image of the communication device emitting the beacon light. The system calculates the deviation of the communication device's position from the center of the camera's field of view. This deviation information is fed back to the control system of the acquisition and tracking gimbal mirror shown in Figure 1. The acquisition and tracking gimbal mirror can adjust its angle with high precision using electric actuators, and by compensating for the mirror angle according to the amount of deviation, it performs tracking so that the communication device is positioned at the center of the visible-light camera image. By implementing this operation at both the transmitting and receiving stations, it has become possible to mutually compensate for installation errors and stably guide the communication light into the optical fiber. In the future, this technology is expected to be utilized for mobile communications through high-speed and high-precision control.

Next, the developed optical axis compensation technology described in this report consists of a quadrant detector, an FSM, and a beam splitter, as shown in Figure 2. A quadrant detector is a photodetector with a light-receiving surface divided into four regions, capable of detecting the center-of-gravity position of the incident light intensity distribution with high precision. When the communication light is displaced from the ideal optical axis, the direction and amount of optical axis fluctuation are calculated by analyzing the difference in light intensity incident on each region. Optical axis fluctuations can be detected at speeds of several kHz or higher, and optical axis fluctuations caused by turbulence or mechanical vibrations can also be detected. The FSM is a steering mirror that tilts minutely and at high speed using piezoelectric elements. Figure 3 shows the developed FSM. The FSM incorporates a small mirror with a diameter of one inch, and is configured with separate units for the X and Y axes to achieve higher speeds. By feedback-controlling the FSM's tilt angle in real time based on the optical axis fluctuation information from the quadrant detector, the communication light can be accurately guided to the center of the quadrant detector. Then, a beam splitter is placed between the FSM and the quadrant detector to couple the branched communication light into an optical fiber. The branched communication light is in an optically conjugate relationship, where it converges at the same position in both the quadrant detector and the optical fiber. Therefore, when the communication light is guided to the center of the quadrant detector by controlling the FSM, it is also inevitably guided to the center of the optical fiber. With this configuration, it has become possible to consistently couple the communication light into the optical fiber even in the presence of optical axis fluctuations, leading to improved communication quality.

- \*1 Device capable of extracting optical signals propagating in the opposite direction in an optical fiber
- \*2 Optical element capable of reflecting part of incident beam power and transmitting the rest
- \*3 Mirror capable of being controlled at any angle of up/down/left/right at high speed by an actuator
- \*4 Optical element capable of transmitting communication light of longer wavelength than visible light and reflecting visible light



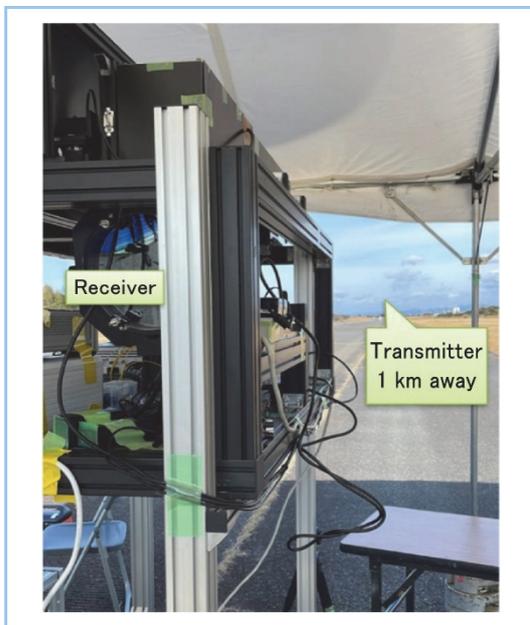
**Figure 2 Atmospheric turbulence compensation technology**



**Figure 3** Developed fast steering mirror and surrounding FSO communication optical system

### 3. Outdoor 1-km transmission experiment and results

The developed FSO communication systems were placed facing each other over a distance of 1 km to conduct demonstration experiments in an outdoor atmospheric turbulence environment (Figure 4). In the experiments, 100-Gbps optical signals were transmitted to measure the transmission rate per unit time (throughput) and the refractive index structure parameter (hereinafter referred to as  $C_n^2$ ). The optical transmitter and receiver used were 100 Gbps-digital coherent transceivers commonly used in optical fiber communications (wavelength: 1,550 nm, modulation format: Dual Polarization-Quadrature Phase Shift Keying), and throughput was measured for 30 seconds at 0.1-second intervals using a Viavi 100G optical tester. For the measurement of  $C_n^2$ , a scintillometer (BLS900) was used to detect refractive index fluctuations caused by atmospheric turbulence as intensity fluctuations of light received from a remote light source.



**Figure 4** Outdoor 1-km test setup

$C_n^2$  is a critical factor affecting the stability and quality of communication, and is a parameter that needs to be considered particularly when evaluating communication performance in environments with atmospheric turbulence. Specifically, a smaller  $C_n^2$  value indicates a smaller effect of refractive index fluctuations, enabling more stable communication. It is generally known that  $C_n^2$  values range from approximately  $1 \times 10^{-14} \text{ m}^{-2/3}$  to  $1 \times 10^{-13} \text{ m}^{-2/3}$  for strong turbulence occurring near the ground surface during the day, and from  $1 \times 10^{-17} \text{ m}^{-2/3}$  to  $1 \times 10^{-15} \text{ m}^{-2/3}$  for weak turbulence occurring at night or at high altitudes<sup>(3)</sup>.

$C_n^2$  in the outdoor experiment was confirmed based on the daytime measurement results to

fluctuate within the range of  $1 \times 10^{-14} \text{ m}^{-2/3}$  to  $1 \times 10^{-12} \text{ m}^{-2/3}$ , and was approximately  $1 \times 10^{-13} \text{ m}^{-2/3}$ , which corresponded to an environment with generally strong atmospheric turbulence.

**Figure 5** shows the results of throughput measurements for 30 seconds in the outdoor 1 km, 100-Gbps transmission experiment. As a result of the measurements, a maximum of 100 Gbps was achieved even in a strong atmospheric turbulence environment. Additionally, according to Figure 5, the throughput decreased temporarily. This stems from instantaneous communication disruptions caused by communication light failing to couple into the optical fiber end temporarily due to residual atmospheric turbulence and device vibrations that persist even after the aforementioned atmospheric turbulence compensation. Throughput measurements were conducted at 0.1-second intervals; for example, if a communication disruption of 0.02 seconds occurred, the throughput would be  $(0.1-0.02)/0.1 \times 100 \text{ Gbps} = 80 \text{ Gbps}$ . Furthermore, the average throughput over the 30-second measurement period was 93 Gbps.

