Transmission Laser Beam Control Techniques for Active Free Space Optics Systems

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Abstract. This paper describes the laser beam alignment techniques for free space optical communication. Bilateral laser transmission system is designed between two active free-space-optical terminals, which are equipped with galvanic scanners, E/O and O/E converters and are able to control laser beam discharging directions. Two alignment strategies are proposed with regard to the transient and steady state of optical signal transmission. Search method for initial alignment is established based on the Gaussian beam optics, and a tracking control system is constructed for laser beam to maintain stable telecommunication between roaming transmission equipments. Experiments reveal that the proposed techniques enable the transmission laser beam to locate the target receiver accurately and to pursue the unstable transmission apparatus, and that the communication quality is as high as optical fiber network.

Keywords: Free space optics · Communication · Laser · Robot · Control · Alignment · Tracking · Gaussian beam

1 Introduction

User telecommunication network is mainly constructed by optical fiber and wireless local area network (WLAN) technologies at present. Optical fiber network is both time consuming and costly to install, though it transmits telecommunication signals safely and quickly. WLAN technology provides us with ubiquitous telecommunication services at relatively lower cost, whereas it involves risks of the wiretapping.

Free space optics (FSO) is an alternative to the main telecommunication technology such as optical fiber network or wireless local area network. It realizes telecommunication by transmitting collimated laser beam in the air [1–3]. FSO system is superior to optical fiber system in installation time and cost. It provides securer broadband communication than wireless LAN against phone tapping because laser beam does not spread like radio wave. On the other hand, conventional FSO is considered not to be ubiquitous but stationary telecommunication technology as it is designed for fixed point-to-point communication [4–14]. FSO terminal is rigidly attached to some stiff and sturdy structure enough to avoid vibration due to weather or traffic, even though the installation requires labor and time. Another weal point of conventional FSO is

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disconnection due to the obstruction of laser beam. If some obstacle happens to cross a line-of-sight of the laser beam, millions of data are lost in an instant.

We have proposed active FSO technology [15–17] to realize ubiquitous broadband communication in the user network where the transmission length is up to 100 meters. It can be improved to an optical mesh network that serves as a rural area network. The optical mesh network is established with ease by discharging a thin laser beam to transmit broadband signals in the air, and directing it to hit the receiver by motor-driven mirrors. We investigated, as well as short range FSO applications [18–23] and non-interruptive optical fiber line switching system [24–37], the optical alignment adjustment technique for actual fiber network [38–41].

The active FSO terminal contains a transmitter and a receiver. Laser beams transmit bi-directionally between two pieces of terminals. It is necessary to achieve long-distance transmission with thin laser beam from the transmitter to the receiver in the air. The positional relationship between the terminals is not always stationary but may shift by inches. One of remarkable features of active FSO system is the mobile terminal tracking technique. Laser beam alignment is essential to complete communication between remotely separated transmission terminals, and communication quality depends on the alignment accuracy.

This paper proposes an optical mesh network at first by applying active FSO technology that covers shorter range than conventional FSO, and designed the active FSO system. Bilateral free space optics terminal is designed and a prototype of the distributed control system is constructed using a galvanic scanner to steer the laser beam direction. The system is capable of controlling the transmission beam direction, and is intended to provide ubiquitous broadband telecommunications in user network areas, where the transmission length is up to tens of meters. Its principal features are laser beam tracking which is achieved by using a laser direction control technique.

Then we study a laser beam alignment method. Two types of laser beam alignment strategies, initial alignment scheme and tracking control technique, are proposed according to the transmission condition and the alignment procedure is established. Experiments confirm the validity of the proposed searching algorithm for optical signal connection and the tracking control system in the active free space optics communication. Communication quality of the proposed active FSO system is finally evaluated in terms of bit error rate to confirm its validity and usefulness.

2 Optical Mesh Network

Our proposed active FSO system receives laser beam and re-transmits it to an arbitrary direction in principle, whereas the conventional FSO system transfers optical signals between a pair of fixed terminals. Thus this technology can be applied to an optical mesh network such as a rural area network or an ad-hoc network in times of disaster. Figure 1 portrays a prospect of a free space optics cascade network to relay laser beam transmission. Each FSO terminal consists of a transmitter, a receiver, and a PC to control them. The feedback control signals are superposed on the optical signals transmitting communication data.

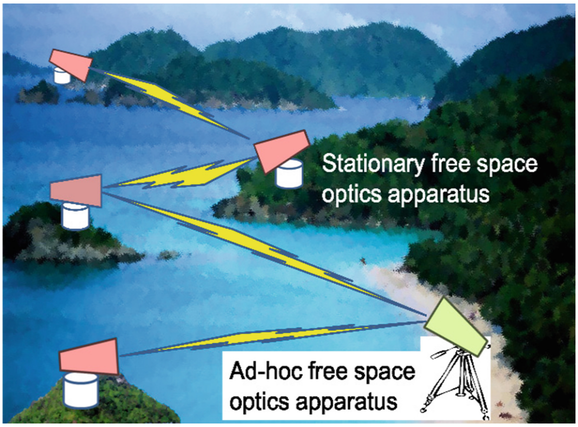


Fig. 1. Optical mesh network based on free space optics.

The mesh network is a type of communication networking, which consists of multiple network nodes. Each node serves as a relay for other nodes. Our proposed optical mesh network transmits a laser beam in the air between a pair of the nodes. A cascade transmission is established by relaying signals to the neighbor node in sequence.

The minimum configuration of the mesh network is illustrated in Fig. 2 with regard to single directional transmission, where two repeater nodes are allocated between a starting and a terminal node. Communication signals are carried from the starting node to the terminal by way of either repeater node. Each repeater node contains a photodiode and a laser diode. The former receives laser signals from the previous node, and the latter transmits the amplified signals to the next.

Accordingly, a partial transmission is achieved between the neighboring photodiode and laser diode. Conventional FSO system transmits laser beam between a pair of fixed FSO terminals. It uses a broad laser beam to prevent received signals from fluctuating owing to unstable transmission circumstances. The proposed active system casts a thin laser beam and thus succeeds in downsizing the terminal. In exchange for giving up the broad beam, it is equipped with a laser beam control system to guarantee stable transmission. The active free space optics system is applied to our system to keep the laser beam stable and to switch the transmission path.

The proposed active FSO system tracks a mobile terminal maintaining broadband communication using the laser positioning scheme. Positioning error of laser beam is detected by the dedicated sensor device and is transferred to the feedback controller carried upon the upstream transmission line directing from the opposite transmitter. The feedback control signals are superposed on the optical signals transmitting communication data.

The block diagram of the active FSO system is shown in Fig. 3 (a), where two FSO terminals discharge laser beam each other to realize bilateral optical communication. Each terminal is equipped with a PC to control both a receiver and transmitter. The galvanic scanner steers the laser beam direction based on the arrival point of the laser

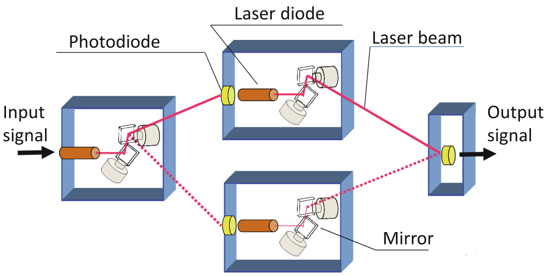


Fig. 2. Minimum configuration of optical mesh network.

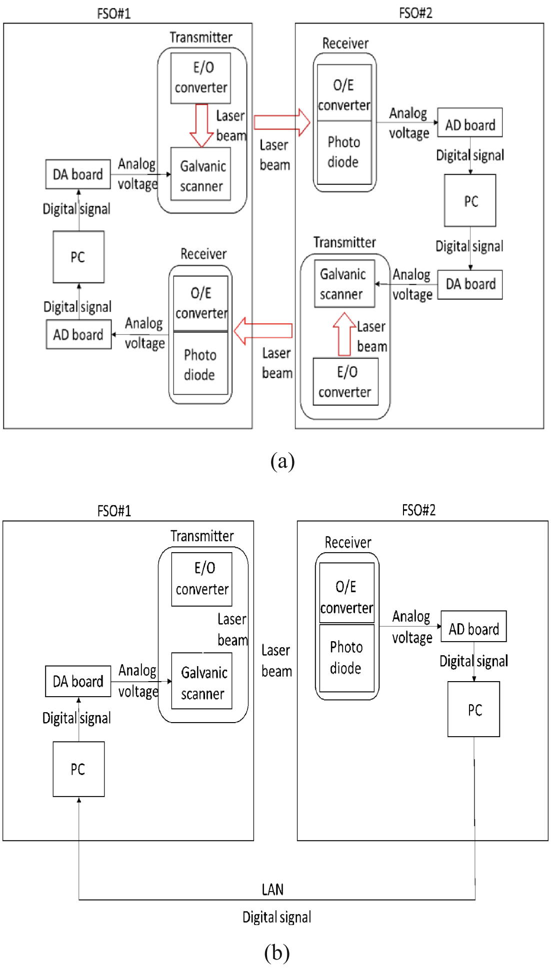


Fig. 3. (a) Distributed control system of bilateral FSO. (b) Distributed control system of unilateral FSO.

beam on the opposite receiver. Its positioning information is carried upon the optical signal sent from the opposite transmitter.

This paper deals with unilateral FSO system as shown in Fig. 3 (b), where the optical transmitter is applied only from FSO #1 to FSO #2. Reverse transmission line is established by electrical communication through LAN cable. The feedback signals are electrically transferred with TCP/IP by wire. When the positioning photodiodes receive a laser beam emitted from the transmitter, analog voltage are generated corresponding to the optical intensity and its data is introduced to the PC through the A/D board and transferred to another PC by wired LAN. Based on the data, the PC in FSO #1 calculates control commands and provides it to the galvanic scanner to correct the position of the laser beam.

3 Active Free Space Optics System

The active free space optics communication is achieved between a transmitter and a receiver as shown in Fig. 4, where FSO transmission is simplified and illustrated as a unilateral system. It consists of two pairs of servo motors and mirrors, and reflects laser beam to an arbitrary direction. Bilateral transmission at 1 Gbps is expected beyond 10 m in the air. Our proposed active FSO system transmits a thin laser beam discharged from a laser diode for broadband communication. The laser beam is created by AlGInP LD element and is several millimeters in diameters. Its wavelength is 658 nm, and frequency bandwidth is up to 1.2 GHz. The system is equipped with a galvanic scanner within the receiver to control the discharge direction of the laser beam. The laser beam reflects twice on the motor-driven mirrors, travels several meters, and reaches the receiver.

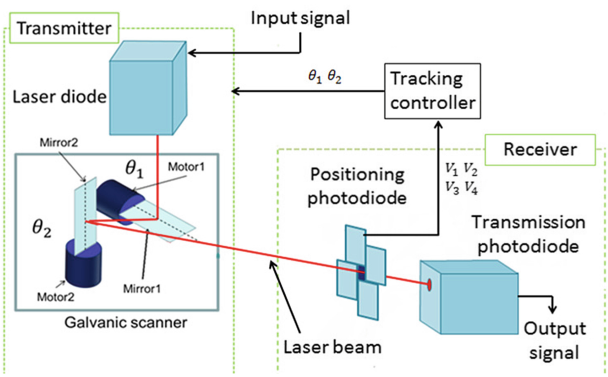


Fig. 4. Active free space optics system.

The receiver contains both a transmission photodiode and positioning photodiodes. The former catches transmission signals, while the latter detect the positioning error of the laser beam. The error is used to feedback control via the upstream transmission route. A laser beam controller provides the objective angles of the mirrors to the servo motors, based on the offset data detected by the positioning photodiodes.

The galvanic scanner is designed and fabricated to reflect laser beam and to spherically scan in the air. Two mirrors are attached to the orthogonal axes of motors as shown in Fig. 5 (a). They are controlled by servo motor drivers with a resolution of 4.77×10^{-4} degrees which is equivalent to an accuracy of 4.16×10^{-2} mm on the receiver.

We have also designed the dedicated receiver which is composed of two types of photodiodes for transmission and positioning as shown in Fig. 5 (b). An O/E converter for fiber optics is adapted for FSO transmission by arranging its optical system. The transmission photodiode contains SiPIN element and its wavelength range is from 400 to 1000 nm. Its frequency bandwidth is not more than 1 GHz.

Four other photodiodes surround the transmission photodiode as shown in Fig. 5 (c). They are not concerned in communication but only detect intensity of laser luminescence. They are SiPIN photodiodes whose cutoff frequency and wavelength range is 25 MHz, and from 320 to 1100 nm, respectively. The signal of these photodiodes is processed by an amplifier circuit [42] and introduced to a PC through an AD converter.

The positioning photodiode unit provides four output voltages depending on the laser spot position. When scanning the positioning photodiode unit with the laser beam in two-dimension, each photodiode element indicates its particular output pattern as shown in Fig. 6, where x-, and y-coordinates are determined in Fig. 5 (c).

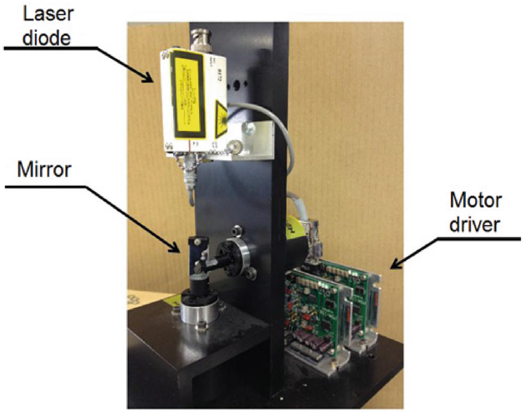
The experiment turns out that distribution of output voltage forms Gaussian distribution whose peak is in the center of each photodiode element. If the laser spot is placed just on the origin of the coordinate system, the output voltage of 4 channels, $V_1, V_2, V_3, \textit{and}\ V_4$, indicate approximately the same. They were 0.49, 0.23, 0.33, 0.40 V, respectively in this figure. The laser spot offset from the center of the transmission photodiode is deduced from those output voltage.

4 Laser Beam Control Techniques

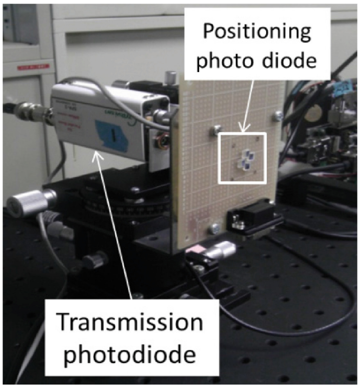
Free space optics communication is performed between two pieces of FSO terminals. A thin laser beam is introduced from a transmitter to an opposite receiver to realize broadband communication. The system keeps the laser spot within the sensible range of the receiver by controlling the discharge direction of the laser beam with a galvanic scanner. The scanner is equipped with two pairs of servo motor driven mirrors to reflect laser beam to a designating direction. The objective mirror angles are calculated based on the laser intensity measured by the positioning photodiode.

The receiver contains two types of detectors: the transmission photodiode and positioning photodiodes. The arrived laser beam is introduced to the transmission photodiode to catch the optical transmission signals. The function of the latter photodiodes is evaluation of positioning error of the laser beam. Their output data is transferred to the galvanic scanner to generate feedback control command. The thin laser beam is required to keep hitting the small receiver to maintain communication even if the target drifts.

We have prepared two modes of laser beam alignment: the transient and the steady state. In the former state, communication is not established yet, as the optical signals do



(a)



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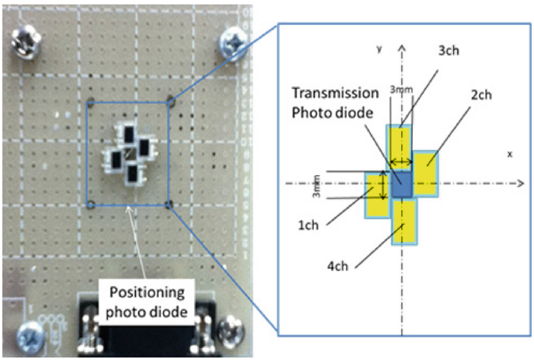


(c)

Fig. 5. (a) Transmitter. (b) Receiver (photodiode unit). (c) Positioning photodiode.

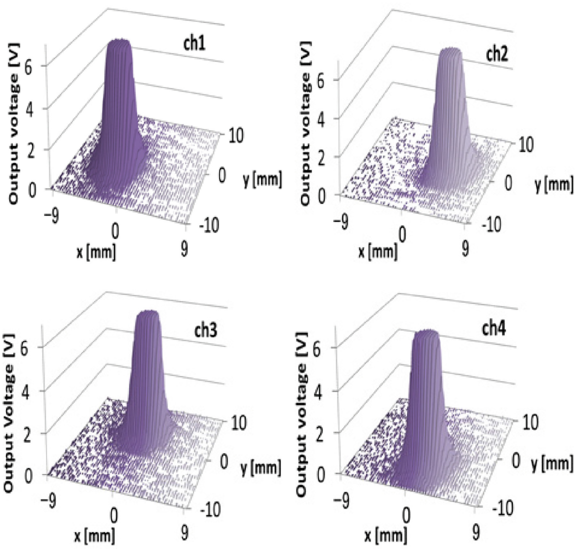


Fig. 6. Voltage distribution.

not successfully reach the receiver. It is necessary to find out precise travelling route of the laser beam from the transmitter to the receiver.

In the steady state, the laser beam arrives within the detection range of the positioning photodiodes. Based on the measured optical intensity, the tracking control is applied to adjust the laser hitting point onto the midst of the positioning photodiodes where the transmission photodiode is installed.

Each of two control schemes is applied according to the algorithm as shown in Fig. 7. It starts with the transient state in general as the laser beam is wide of

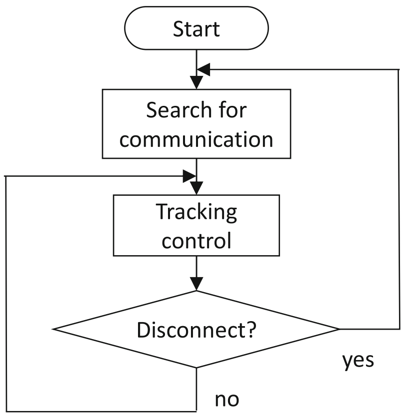


Fig. 7. Laser beam alignment procedure.

the receiver. Thus, the system scans the laser beam around over the area where the target receiver is possibly located, searching for the line-of-sight from the transmitter to the receiver. After monitoring the intensity of the received laser luminescence, the optimum physical relationship between the transmitter and the receiver is determined by adjusting the laser beam direction so that received signal intensity would be the highest.

Once the receiver detects the laser luminescence, a feedback control algorithm steers the laser beam direction so that the laser spot keeps within the sensible area on the receiver. In the steady state, the laser beam can track the receiver automatically. The target motion is estimated based on the output of positioning photodiodes that catch the laser luminescence discharged from the opposite transmitter.

If the laser beam misses reaching the target receiver by accident and the transmission is disconnected, the system is incapable of estimation and loses track of the target. Then the mode is turns to the transient state, and the system starts searching the receiver again.

4.1 Initial Alignment Scheme to Capture Optical Signals

The proposed system searches for the line-of-sight of the laser beam in the transient state. When the distribution of the laser beam intensity is previously known, it helps the search easier than observing all over the space. If the laser beam corresponds to Gaussian beam optics, it is possible to analytically estimate the peak of the distribution. That means we can adjust the optical axis of the laser beam just onto the receiver.

Let us consider the formulation of the laser beam in the x-y-z coordinate system, assuming the optical axis is parallel to the z-axis. When a laser beam hits at (a, b) on the x-y plane, the optical intensity, E_{xy} of a Gaussian beam at (x, y) on the x-y plane is theoretically formulated as

$$E_{xy} = E_0 \exp\left(-\frac{(x-a)^2 + (y-b)^2}{w^2} \right) \tag{1}$$

where E_0 is the maximum intensity, which is observed on the optical axis (a, b).

By locating the positioning photodiode at (x_0, y_0), we obtain the laser luminescence intensity, E_{x0y0} at that point. Then Eq. (1) gives the following equation.

$$(x_0 - a)^2 + (y_0 - b)^2 = -w^2 \log \frac{E_{x0y0}}{E_0} \tag{2}$$

Because this equation contains four unknown parameters, four independent conditions are necessary to solve the simultaneous equation in general. If we prepare four positioning photodiode at (x_0, y_0), (x_0, y_1), (x_1, y_0), (x_1, y_1), position (a, b) of the intensest laser spot is determined, by solving four simultaneous equations in terms of four variables, as

$$a = \frac{L_1^2\left(x_0^2 + y_0^2 - y_0 y_1\right)y_0 + L_1^3 x_1^2 y_0 + L_{23}^{14} x_1^2 y_1}{2\left\{L_1^2 x_0 y_1 + L_1^3 x_1 y_0 + L_{23}^{14} x_1 y_1\right\}} \tag{3}$$

$$b = \frac{L_1^2 x_0 y_1^2 + L_1^3\left(x_0^2 + y_0^2 - x_0 x_1\right)x_1 + L_{23}^{14} x_1 y_1^2}{2\left\{L_1^2 x_0 y_1 + L_1^3 x_1 y_0 + L_{23}^{14} x_1 y_1\right\}} \tag{4}$$

where $L_1^2, L_1^3, L_{23}^{14}$ represent

$$\log\frac{E_{x1y0}}{E_{x0y0}}, \log\frac{E_{x0y1}}{E_{x0y0}}, \log\frac{E_{x0y0}E_{x1y1}}{E_{x0y1}E_{x1y0}},$$

and E_{x0y1}, E_{x1y0}, E_{x1y1} are the laser luminescence intensity measured at (x_0, y_1), (x_1, y_0), (x_1, y_1), respectively.

We have carried out a fundamental experiment to confirm the analysis. The planar distribution of the laser beam intensity is actually measured by the positioning photodiode. It can be approximated by a Gaussian distribution at E_0 = 8.0 and w = 5.0.

The position (a, b) of the laser beam optical axis is evaluated by applying the measured values of the photodiodes to the Eqs. (3) and (4) with regard to various sensor placement. Figure 8 shows the estimation results on condition the photodiodes are arranged at four corners of 10 mm square. The vertical axis represents the estimation error of the optical axis position, while the horizontal axis denotes the distance between the photodiodes and the optical axis. It proves that the proposed method estimates the optical axis position of the laser beam within an accuracy of 10 mm.

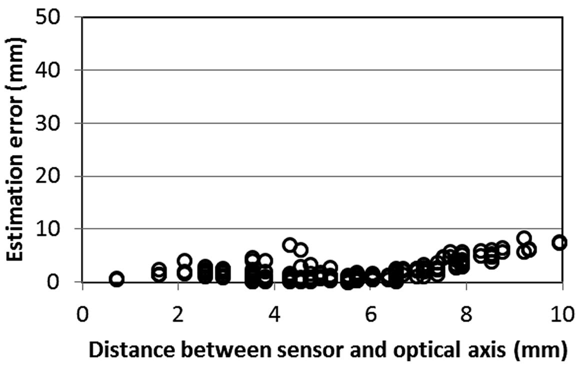


Fig. 8. Estimation results of optical axis.

4.2 Tracking Control Technique for Laser Beam

The tracking control is conducted in the steady state to steer the laser beam to the midst of four photodiodes. A feedback control system is established between the transmitter and the receiver. A block diagram of proportional control system is shown in Fig. 9.

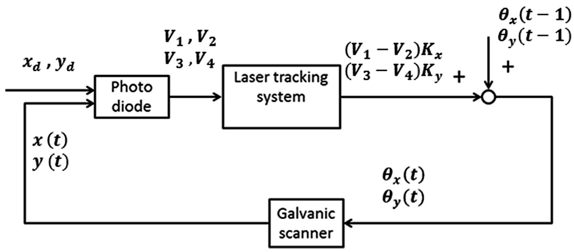


Fig. 9. Block diagram of laser tracking system.

Equations (5) and (6) express the proportional control formulations in terms of the command mirror angles for two-degree-of-freedom laser beam angles, where θx(t) and θy(t) represent the mirror angles, Kx, Ky do the feedback gains, V_1, V_2, V_3 and V_4 do the output voltages of the positioning photo diode, and θx(t-1), θy(t-1) do the previous angles.

$$\theta x(t) = (V_1 - V_2)K_x + \theta x(t-1) \tag{5}$$

$$\theta y(t) = (V_3 - V_4)K_y + \theta y(t-1) \tag{6}$$

This system controls the laser beam to make these four outputs equal. Each positioning photodiode covers a part of the laser spot, and generates voltage of the corresponding share of the laser intensity. When the laser beam shifts aside, the output voltages of four photodiodes increase or decrease with regard to the shift direction. The feedback controller directs the laser beam to compensate the gap based on the balance of the photodiode outputs. Thus, the proposed tracking system is able to chase the target belatedly.

We have examined the laser tracking system in chasing a fleer photodiode at the speed of 100 to 320 mm/s. Control responses are measured and evaluated, while the positioning photodiode unit is attached to a motorized slider and carried along a designated trajectory.

The figures expressing typical experimental results under the following conditions are shown below. The positioning photodiodes are guided to trace a vertically reciprocating trajectory, shown by a solid line in Fig. 10, on the condition that the target speed is 320 mm/s, the distance from the galvanic scanner to the positioning photodiode is 5 m, and its motion amplitude is 50 mm.

The amplified output voltages of the positioning photodiode, channels 1 to 4 are measured as shown in Fig. 11 (a) to (d), respectively. Channels 1 and 2 look constant as x-coordinate of the laser beam does not vary while the target heaves. Channel 3 and 4 fluctuate according to the target motion. When the target goes down, channel 3 detects higher intensity of the laser beam. When running up, output of channel 4 becomes intense.

Rotation angles of the vertical and horizontal mirrors are shown in Fig. 12 (a) and (b), respectively, as the command motor angles are calculated according to the control

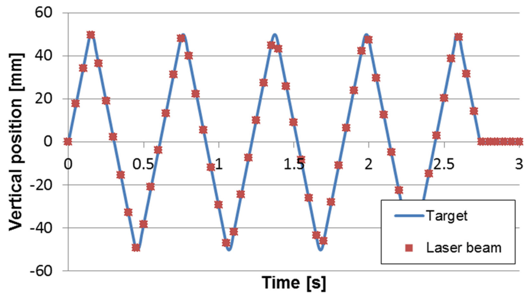


Fig. 10. Trajectory of target and laser beam.

algorithm. The vertical mirror moves as much as 6×10^{-3} deg, while the horizontal one indicates little movement.

Trace of the laser beam, represented by squares in Fig. 10, indicates that the proposed system successfully tracks the target photodiode unit. Reviewing the detail of the results, we have revealed that the positioning error between those trajectories subtly fluctuates within the range of less than 1 mm, and its peak is in a moment of return of the target as shown in Fig. 13 (a).

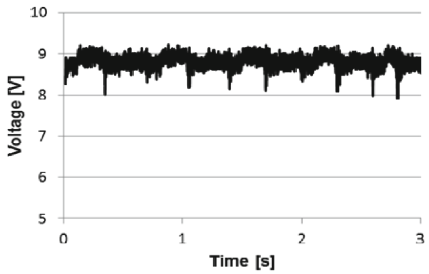
Such sensitive positioning error prevents the broadband communication from stable transmission condition. The input voltage of the transmission photodiode, i.e., intensity of the laser beam detected by the photodiode, conforms to the behavior of laser beam positioning error as shown in Fig. 13 (b). It is required to keep specified criteria of received laser intensity in order not to interrupt communications.

After executing laser beam tracking experiments with respect to several target speed and a couple of directions, we have confirmed that the positioning error is approximately proportional to the target speed as shown in Fig. 14 and that the proposed system is always successful in tracking the target.

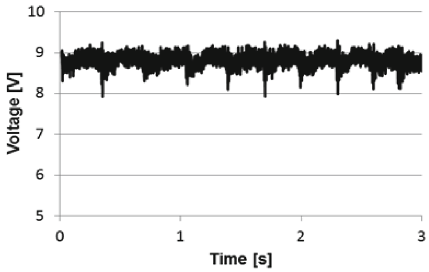
5 Communication Quality

The proposed tracking control technique makes it possible that the laser beam pursuits a roaming receiver by adjusting the optical axis of the laser beam to the center of the photodiode to guarantee stable communication.

Because the final purpose of the proposed system is to provide stable broadband communication, transmission quality is quantitatively evaluated while the laser beam is tracking the receiver. Bit error rate (BER) is one of popular indices to assess the digital transmission, which is calculated by dividing the number of bit errors by the total number of transferred data bits during a designated interval. It represents the influences of interference, noise or bit synchronization errors. The less BER is, the better communication is in quality. The BER of the commercial optical fiber telecommunication is regarded as being kept around 10^{-7} in general.



(a)



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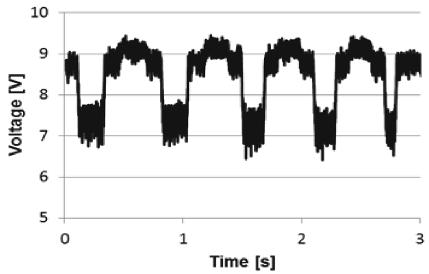

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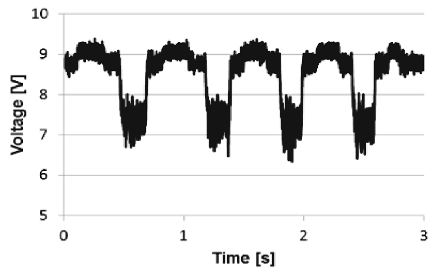


(d)

Fig. 11. (a) Output voltage of photodiode, ch. 1. (b) Output voltage of photodiode, ch. 2. (c) Output voltage of photodiode, ch. 3. (d) Output voltage of photodiode, ch. 4.

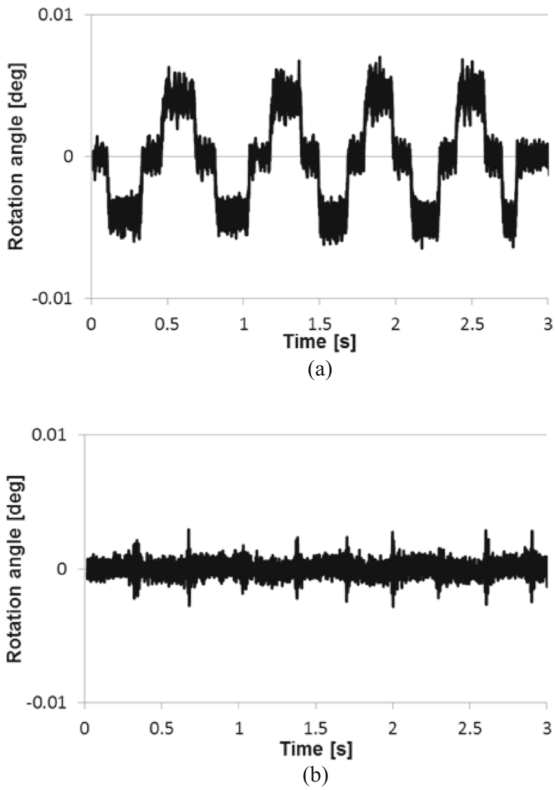
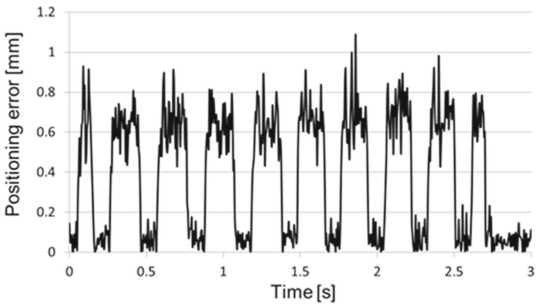


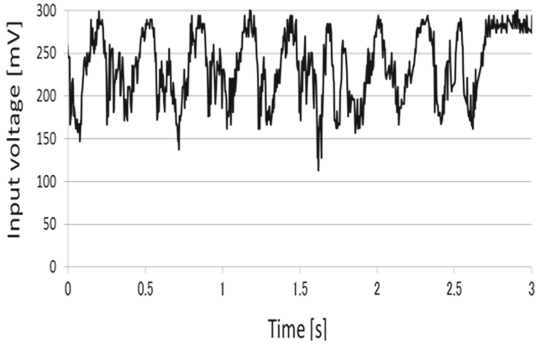
Fig. 12. (a) Motion of vertical mirror. (b) Motion of horizontal mirror.

We have conducted the laser tracking control chasing a roaming receiver. The positioning photodiode unit is attached to a motorized slider, and is carried in reciprocation motion with a swing of 50 mm at the speed of up to 300 mm/s. Meanwhile the transmission signals are carried upon the laser beam in the air at 0.5 Gbps. The quality of communication using our proposed active free space optics system is evaluated while chasing the photodiode unit. The bit error rate is measured using ANRITSU MP2100A bit error rate test set as shown in Fig. 15.

Figure 16 illustrates a block diagram of bit error rate measurement for the FSO transmission line. The bit error rate test set (BERTS) contains both a pulse pattern generator (PPG) and an error detector (ED). Input signals are introduced to the transmitter (LD) from the PPG. They are converted to optical pulses and transferred to the receiver (PD) through FSO system while the optical communication is maintained between two FSO terminals by tracking control. The arrived signals are detected by the ED and bit error rate is evaluated by comparing the original and arrived signals.



(a)



(b)

Fig. 13. (a) Tracking error. (b) Input voltage of transmission photodiode.

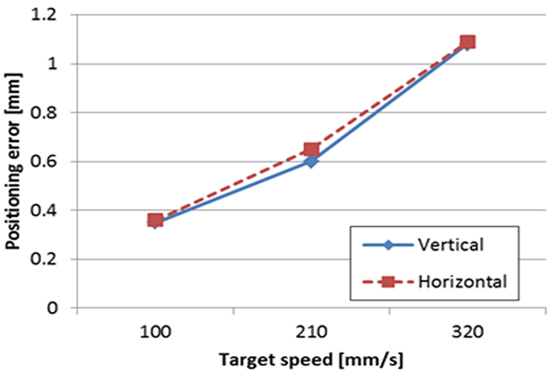


Fig. 14. Positioning error of laser beam.

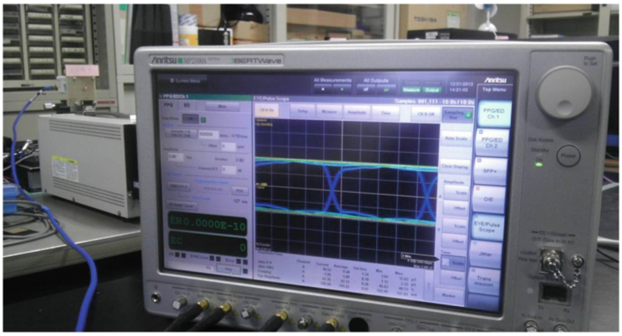


Fig. 15. Bit error test.

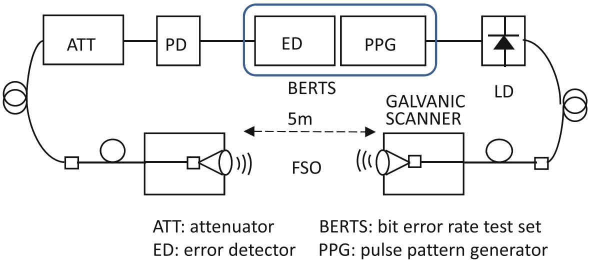


Fig. 16. Bit error rate measurement system.

The communication quality depends on the accuracy of optical axis alignment. Thus, we have measured the relationship between the BER and the laser beam offset from the center of the transmission photodiode. Results prove that broadband communication is valid in practice if the positioning error is less than 2.5 mm as shown in Fig. 17 (a), which indicates that the bit error rate becomes 10^{-7} when offset is 2.5 mm. It is noted that when the offset is smaller than 2.0 mm, a bit error rate becomes less

than 10^{-10}, which means practically error-free. The laser beam intensity detected by the transmission photodiode also depends on the positioning offset. The relation between the positioning error and the output voltage of the transmission photodiode is measured as shown in Fig. 17 (b). Based on these results, we have clarified the relationship between the output voltage of the transmission photodiode and BER as shown in Fig. 17 (c). As a result, successful FSO communication is expected in condition that the output voltage of the transmission photodiode is more than 20 mV.

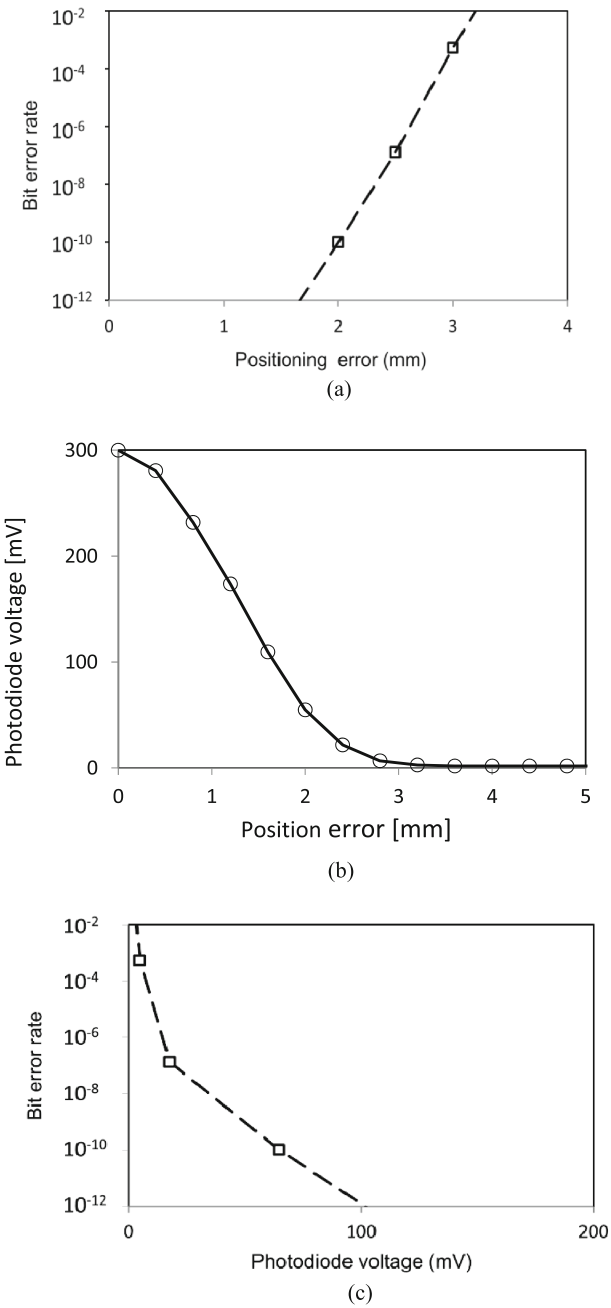


Fig. 17. (a) Bit error rate depending on positioning error. (b) Relationship between positioning error and photodiode voltage. (c). Bit error rate depending on photodiode voltage.

6 Conclusions

Bilateral telecommunication system of the active free space optics system is proposed which is equipped with distributed control system of the laser beam scanners to apply to optical transmission in the air. Dedicated apparatus is designed and prototyped both for communication and laser beam control. The feedback control system is also designed to adjust the laser beam travelling from the distant transmitter within the receiver by steering the laser beam direction based on the positioning photodiodes.

Two states are assumed with respect to optical signal transfer, and the alignment strategy is proposed according to the state. Searching method is investigated for the transient state, and its algorithm is established to determine the summit of the laser luminescent by analysing the Gaussian beam optics. It enables the galvanic scanner to efficiently hunt for the target receiver.

Tracking control is adopted for the scanning system to maintain optical communication in the steady state. It directs the laser beam to follow the target motion and to remain on the receiver. Experiments are conducted on the laser beam tracking for roaming receiver 5 m apart from the transmitter. Results reveal that the proposed active FSO system is successful in adjusting the laser beam destination in an accuracy of less than 1 mm to pursue the receiver swinging at up to 210 mm/s.

We finally evaluated the communication quality of the distributed processing FSO system. The bit error rate measurement at 0.5 Gbps transmission confirms that our proposed technique realizes broadband telecommunication in high quality with a bit error rate of 10^{-10}. The active free space optics is consequently proved to be successful in maintaining broadband free space transmission in high quality even when the receiver fluctuates, and also to be beneficial to the rural area network or the ad-hoc network.

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