A BI-DIRECTIONAL FREE-SPACE OPTICAL COMMUNICATION SYSTEM WITH MEMS SPATIAL LIGHT MODULATOR FOR AGLIE DATA LINK

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ABSTRACT

We report a free space optical (FSO) communication system for bi-directional passive optical network (PON) based on a MEMS spatial light modulator (SLM). A piezoelectric PZT scanner is used to display a marker image to invite a passive optical terminal (POT) and to keep the optical link even when the POT moves. Unlike wireless network that broadcasts radio signals, the FSO system in this work provides high security data transmission.

INTRODUCTION

Free space optical communication (FSO) is a line of sight (LOS) type optical link that transmits data through a collimated beam from a transmitter to a receiver aligned to each other. Various applications of FSO are studied in this several years, including chip-to-chip interconnection and satellite communication [1-3]. FSO inherently enables higher channel capacitance and high security compared to radio frequency (RF) system or visible light communication (VLC) [4]. It also can solve several problems that RF systems suffer such as bandwidth regulation and multipath interference [5]. However, wireless optical link can easily be lost by the motion of terminals or insertion of obstacles between the devices.

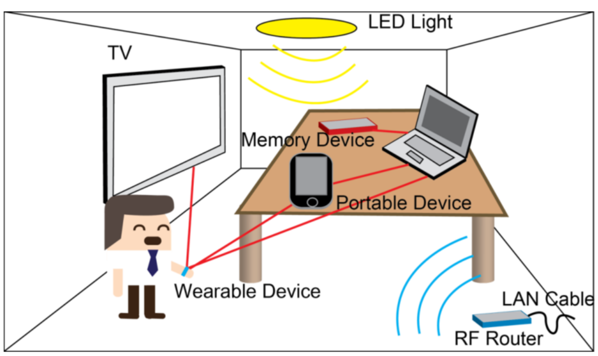

Figure 1: Concept of indoor wireless network. Free space optical communication enables fast and high security link with low power.

Figure 1 illustrates a use of IWON (indoor wireless optical network), which consists of RF system, VLC and FSO represented as blue wave, yellow wave, and red ray, respectively. In terms of mobility conventional RF system is the best and followed by VLC and FSO. However, in terms of data rate or security FSO is the best and followed by VLC and RF in order. Therefore, we think that using 3 methods depending on the purpose is a useful strategy.

Here, to use the FSO not only to the communication between fixed devices but between mobile or wearable devices, we present an optical system to search and track the position of a mobile PON (passive optical terminal) placed in free space by using a MEMS-SLM (spatial light modulator) [6]. Based on the image projection system and our previous optical system, we report the constructed optics and control system along with the experimental results of passive optical terminal (POT) tracking operation [7-8].

DESIGN

Figure 2 schematically illustrates the design of optical system in this work. This system applies MEMS spatial light modulator (SLM) to the passive optical network (PON) to connect two terminals automatically and to keep the connection while transmitting data to each other. Active optical terminal (AOT) consists of a light source, a MEMS-SLM, lenses for magnifying the deflection angle, a beam splitter and a quadrant photodiode (QPD) for sensing the beam returned back from the POT. The POT consists of a beam splitter, a photodiode for receiving the downlink data, a liquid crystal shutter (LCS) and a corner cube reflector (CCR) for returning the beam from the AOT with data on it. The incident and reflected beam by the CCR are center symmetry to each other so the position displacement between beam and CCR is detected by the QPD.

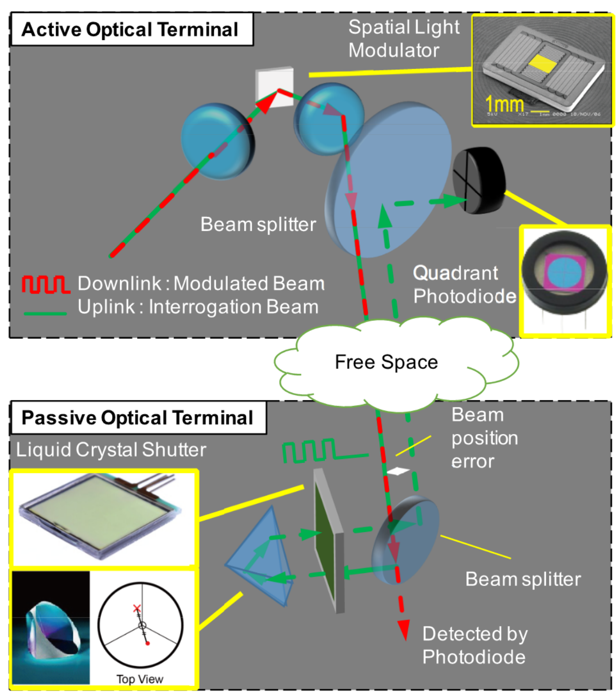

Figure 2: Optical system design. Red laser uplinks data from AOT to POT, and green laser downlinks data while SLM controls the beam direction to maintain the link.

A pair of lens installed in AOT to enlarge the deflection angle follows the design shown in Figure 3. Focusing lens of focal length f_1 and spreading lens of focal length f_2 are placed at intervals of f_1+f_2 to prevent blurring the collimation. The magnification ratio of deflection angle is calculated by thin lens equation as

$$\frac{\theta_2}{\theta_1} = \frac{d_m - f_2}{f_2}, \tag{1}$$

where d_m is the distance between the SLM and spreading lens. Even though the collimation is not broken by this two lens system, it is inevitable to enlarge the beam divergence around f_1/f_2 times.

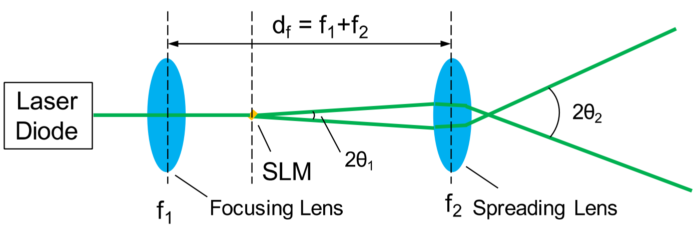

Figure 3: Schematic draw of two lenses system for enhancing beam deflection angle without blurring the collimation.

The optical system is controlled by the control system shown in Figure 4. When the system starts, the SLM in the AOT scans the laser to search for the POT, which we call the scan-mode. We used a circle of changing radius as a scan pattern for covering the whole area with applying low frequency voltage to MEMS-SLM. When the beam hits the CCR on the POT, the "scan mode" stops and the "tracking-mode" starts.

The signal from the QPD has two functions: one is acquisition of the timing that beam encounters the POT, and the other is creating beam spot error for proportional-integral-derivative (PID) control. Therefore, after amplified by the non-inverse amplifier, the signals from the QPD are split into two beams. One beam of signals is summed by the adder and goes into comparator input voltage (V_{IN}). When the V_{IN} exceeds the reference voltage (V_{REF}) the comparator voltage goes down to zero and tracking mode starts.

The other beam is converted into digital signals and used to calculate the beam spot errors, which are variables for deciding control variable in the PID controller. Low pass filter (LPF) before the analog to digital converter (ADC) reduces the high frequency noise of the signal. It also cuts the high frequency signal so the cut-off frequency is set to lower than PID controller loop-time.

Generated signal by scan generator or PID controller is adjusted and amplified to the appropriate level to drive MEMS scanner (V_G and H_G) through the MEMS driver in the FPGA and analog amplifier shown in upper part of Figure 4. LRF is installed to avoid higher parasitic oscillation modes of the MEMS-SLM.

While the laser of the AOT tracks the POT in this way, intensity of the laser is directly modulated for the downlink. For uplink, the plain laser sent from the AOT is modulated by the liquid crystal shutter (LCS) in the POT.

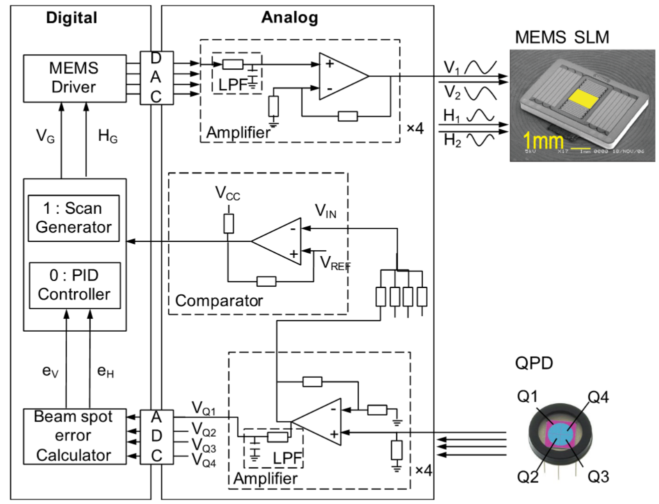

Figure 4: Control system design in this work. FPGA is used to implement the controller for POT search and track. Analog amplifiers and comparator are separately constructed.

EXPERIMENT

This system can be diversified by the number of laser diodes that are used. A system with one laser using time-division multiplexing (TDM) for bidirectional communication is less expensive and small but transmits at a low data-rate. The data rate increases with the number of laser diodes by using wavelength division multiplexing (WDM). Here, we constructed a system with two lasers.

The AOT of this system is constructed on the optical test bench as shown in Figure 5. The traces of the laser are represented by the arrows. A red (power 1mW, wavelength 635nm) and green (5mW, 532 nm) laser are combined by a dichroic mirror and reflected by the SLM surrounded by two lenses of focal length of 100 mm and 6 mm. The distance between the spreading lens and MEMS-SLM (d_m) is 54 mm. The POT constructed by placing a CCR and a dichroic mirror on the 3D-printed holder is shown in the right-hand side of Figure 5. The photodiode and LCS have not been implemented yet.

The digital circuit is programmed by the LabVIEW on the MyRIO that is a device with a field programmable gate array (FPGA) made by National Instrument, while peripheral analog circuits are assembled on an electronic breadboard following the design shown in Figure 4. The V_G and H_G that are set to be limited from -1.5 V to 1.5V are converted to the voltage that controls the MEMS-SLM (V_1 and V_2) by the MEMS driver and amplifiers as

$$V_1 = 7.25 \times (1.5 + V_G) \tag{2}$$

$$V_2 = 7.25 \times (1.5 - V_G) \tag{3}$$

The coefficient 7.25 is the gain of the amplifier, and the constant 1.5 is added to make the signal positive all the time. H_G is also converted to H_1 and H_2 in this way. In the scan mode, V_G and H_G are generated to be a sinusoidal wave with changing amplitude expressed by

$$V_{GS} = 1.5 \times \sin(\frac{2\pi t}{2.3}) \times \sin(\frac{2\pi t}{33.3}) \tag{4}$$

$$H_{GS} = 1.5 \times \sin(\frac{2\pi t}{2.3}) \times \sin(\frac{2\pi t}{33.3} + \frac{\pi}{2}) \tag{5}$$

The beam spot of the laser draws an ellipse with changing radius with these signals. While scanning a target marker, the comparator waits until the comparator input or intensity factor of the light measured by the QPD (V_{IN}) exceeds the threshold voltage (V_{REF}) which is set by referring the measurement data. When the intensity of the light (V_{IN}) is high enough, the "tracking mode" starts, where the MEMS-SLM is controlled by the PID controller. The manipulated variable (MV) is calculated by the equation

$$MV(t) = K_p \left\{ e(t) + \frac{1}{T_i}(t) + \int_0^t e(\tau)d\tau + T_d \frac{d}{dt} e(t) \right\}, \tag{6}$$

where e is the vertical and horizontal beam spot errors, which corresponds to e_V and e_H, respectively. Those signals are calculated from the QPD signal expressed as

$$e_V = (V_{Q1} + V_{Q4}) - (V_{Q2} + V_{Q3}) \tag{7}$$

$$e_V = (V_{Q3} + V_{Q4}) - (V_{Q1} + V_{Q2}) \tag{8}$$

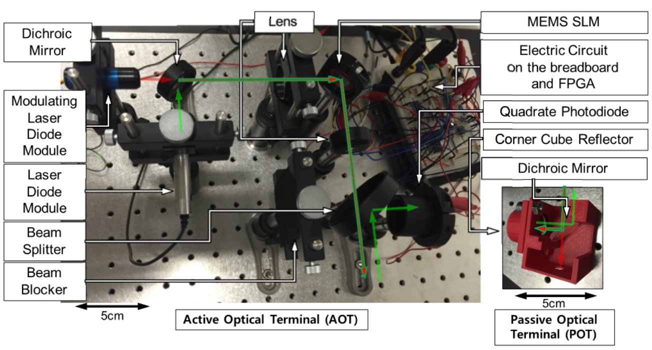

Figure 5: Experimental setup. The optical system shown in Fig. 1 is constructed on the optical board, while digital and electric circuits shown in Fig.2 are implemented on the MyRIO by National Instrument and breadboard.

RESULTS

The field of view (FOV) for this system was measured while drawing an ellipse pattern by applying sinusoidal wave of 10.71V amplitude to both axes, as shown in Figure 6. The maximum deflection angle is enhanced to 14.3 degrees for horizontal direction, and 10.7 degrees for vertical direction from the initial values of 1.38 degrees and 1.06 degrees, respectively.

Figure 7 shows the signals used for the acquisition and tracking. The comparator input signal (V_{IN}), which is the intensity of the light is used to judge whether the laser beam spot is on the POT or not. The intensity of the light coming into the QPD can be calculated by integrating the Gaussian distribution in the area of QPD. The calculation result is expected to be a hill-shape as measurement result shown in Figure 7a. Beam spot error for the vertical and the horizontal direction are shown in Figure 7b and 7c, respectively. The area that can be used for tracking is limited to the area that the signal changes linearly. Comparing those signals, we could see that the linear region is where the intensity factor (V_{IN}) is over 2V. Considering the response time of this system, we set to start "tracking mode" when V_{IN} > 1.4 V. Also, we set a hysteresis to prevent the effect of the chattering noise so the mode is converted to "scan mode" when V_{IN} < 0.4 V.

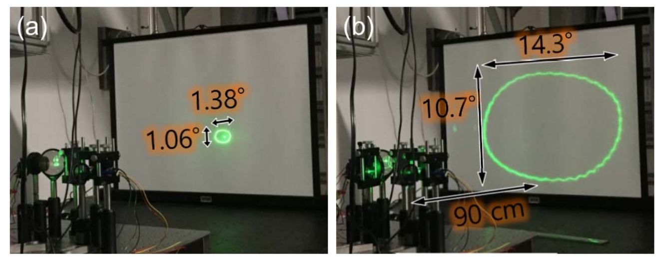

Figure 6: Ellipse patterns for measuring FOV with (b) and without (a) using two lens system.

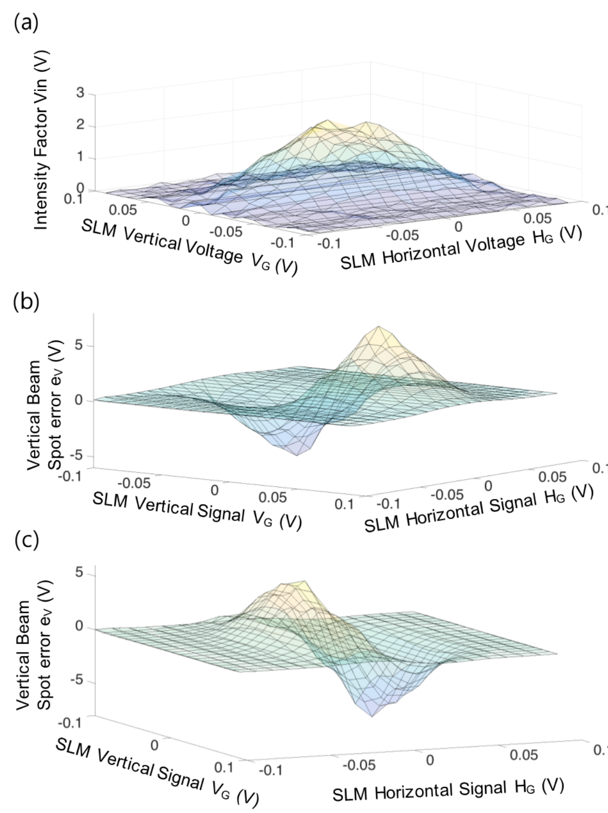

Figure 7: Signals used in this system. (a) The intensity for acquisition of POT, (b) horizontal and (c) vertical beam spot error for PID control.

We demonstrated the find & tracking system. The distance from the AOT to the POT was 65 cm. The system could track the POT successfully until a 1.5 m distance. The PID parameters K_p, T_i and T_d are set to be 200×10^{-6}, 1×10^{-6}, and 100×10^{-6}, respectively. As shown in Figure 8, the POT was brought into the scanning area and moved around in the area. At around 1.2 seconds, the laser beam is locked in the POT and tracks the movement of the POT until 2.0 seconds.

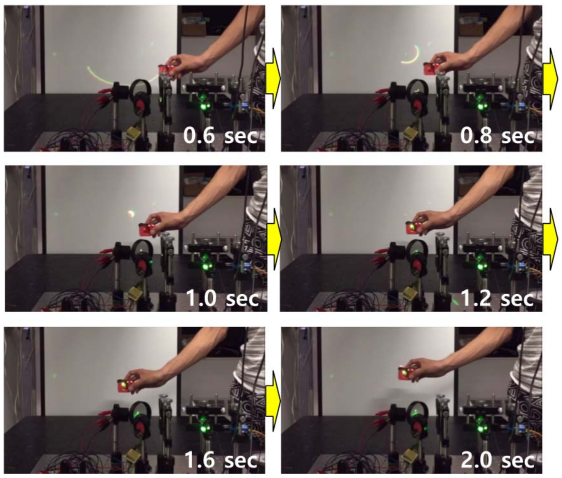

Figure 8: Snapshot images from POT acquisition and tracking system. System displays a spiral for 1.2 second before the POT is locked, after which the system follows the POT motion.

Performance of this system is measured by data acquisition device (DAQ) by national instrument and shown in Figure 9. When the beam hits the outer part of the CCR the beam is leaded to the center by PID control. It took 8 ms and the angular change was calculated to be 0.15-degree change from the voltage change as shown in Figure 9a. The fluctuation of the beam angle is less than 0.05 degrees, as shown in Figure 6b. PZT actuators in general are known to have displacement drift but the developed system gives compensation to the drive voltage to keep track on the POT.

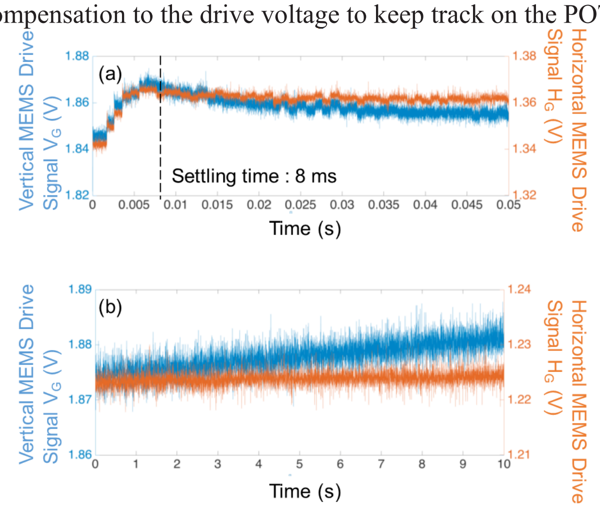

Figure 9: MEMS Drive signal for various situations. (a) Right after the system finds the still POT and (b) When the POT is still for 10 seconds.

CONCLUSION

We proposed a bi-directional FSO or VLC for indoor wireless optical network as a supplement of RF system. We also noted that using a MEMS-SLM, FSO could be used for mobile or wearable devices by connecting two terminals automatically and keeping the connection even when the terminals are moved.

As an example of the lab-level experimental system, we constructed and demonstrated a system with stationary AOT that scans the laser to find the POT and tracks the POT after finding it. This is possible because the beam from the AOT comes back to the AOT after reflected the CCR on the POT which reflects the beam back to its original direction with a beam displacement proportional to the center of the CCR and incident beam. This error is used to PID control the MEMS SLM.

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