Full-duplex FSO Communication System utilizing Optical Image Stabilizer and Free-Space Optical Circulator

Abdelmoula Bekkali(*), Hideo Fujita and Michikazu Hattori

TOYO Electric Corporation, Japan. (*) e-mail: bekkali_a@toyo-elec.co.jp

Abstract *We developed a novel full-duplex FSO transceiver with optical-image stabilizer (OIS) and free-space-optical circulator. The OIS technology, which is widely used by smartphones cameras, was successfully implemented to expand the transceiver field-of-view (FOV) and maintain laser beam alignment with efficient seamless coupling to fiber core.*

Introduction

Free space optics (FSO) have been recognized as a promising, cost-effective, and energy-efficient wireless technology for high-capacity communication networks. In fact, FSO can guarantee data-rate similar to optical fiber links, but at a fraction of their deployment cost[1, 2]. Despite their potential advantages, FSO links face some inherent challenges, that should be addressed for a reliable communication links. These challenges include losses due to weather conditions, and atmospheric turbulence induced beam wander and scintillation effects. Moreover, FSO links are restricted to stringent line-of-sight requirements, which necessitates advanced pointing, acquisition, and tracking techniques[3].

In this paper, we introduce a newly developed FSO transceiver (TRx.), incorporating two main components, i.e., cost-effective 3-axis voice-coil motors (VCMs) lenses to guide the optical beam from/to the fiber core, and an integrated free space-based optical circulator (FSO-C) to control efficiently and independently the transmitting and receiving beams. Similar to their application in the current smartphone and digital cameras for auto-focus (AF) and optical image stabilization (OIS) functionalities[4], the VCM lenses are used in this newly designed TRx. to expand both the transmitter and receiver field of view (FOV), control the incident beam alignment, suppress the effects of random beam angle-of-arrival (AOA) fluctuations induced by the atmospheric turbulence, and maintain a direct coupling to fiber core at the receiver. Unlike the existing alignment and steering technologies, such as fast steering mirrors (FSM)[2, 5], the use of VCM lenses can not only maintain the beam alignment but also control the beam collimation and adjust the difference between the lens focal plane and projection plane to achieve a higher fiber coupling efficiency. Since the laser beam is seamlessly coupled to the optical fiber, a bandwidth and data-rate transparent communication link can be realized. Moreover, the developed FSO-C can ensure similar flexibility as the binocular TRx., by controlling the transmitted and received beam independently.

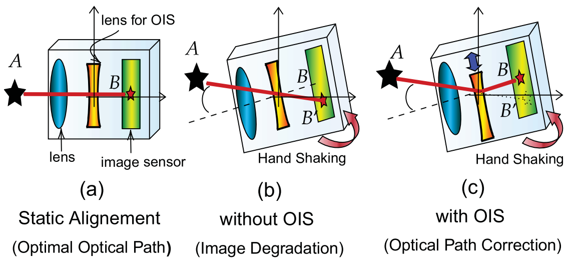


Fig. 1: General concept of OIS

Optical Image Stabilizer

In smartphones and digital cameras systems, the OIS technique consists of physically moving the camera lens to compensate for the image quality degradation and blurring, induced by the natural hand jitter and camera motion. Fig.1 illustrates the basic principle of the OIS technique. By moving the lenses, the OIS can control and adjust the optical path between the target and image sensor, and thus the received image can be kept steady.

To enable the OIS feature, VCMs are widely used owing to their low cost, low power consumption, quick response and small size. In general, VCM actuators consist of two main modules. The first module is fixed and includes two magnets, known as yoke and base, while the second module is moving and has the lens with holder attached using coils[4]. Thus, based on the Lorentz-Force principle, the lens can be moved by a distance that is directly proportional to the current applied to the coil.

Description of the Proposed FSO Transceiver

We developed an all-optical and full-duplex FSO transceiver based on FSO-C and OIS technolo-

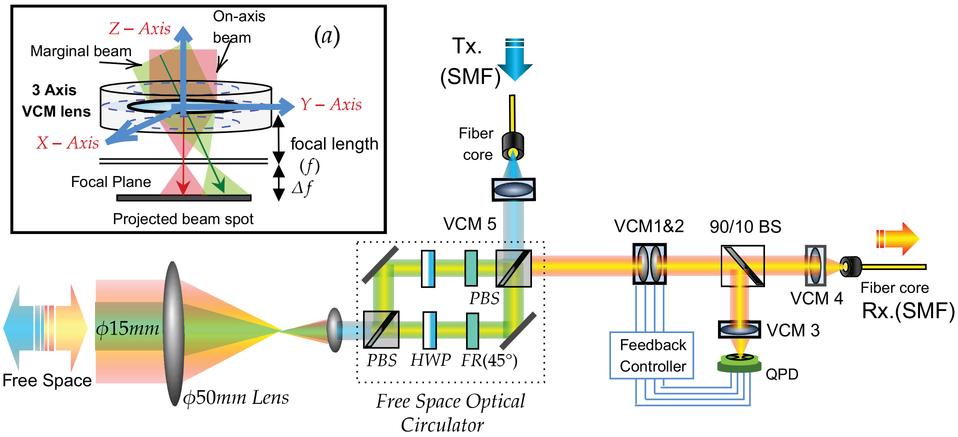


Fig. 2: Our proposed FSO transceiver optical path and system layout

gies. The concept of FSO-C is based on the widely used polarization-independent optical circulators. Utilizing a single transmitting/receiving lens, the FSO-C will not only enable full-duplex transmission but also eliminate the impact of the optical antenna *roll*, in particular for narrow beam FSO links and moving platforms. On the other hand, the OIS system incorporates different modules and components for sensing, compensation, and control to accurately correct the incoming beam on-axis deviation, as well as the optical antenna movement, such as the *pan-tilt* deviation.

The optical path and layout of our proposed FSO TRx. is depicted in Fig. 2. The incoming laser beam transmitted from the SMF is aligned and expanded to ϕ2mm beam, by controlling the 3D position of the VCM5 lens. The collimated beam will then pass through the FSO-C, which consists of four main components, i.e., 45° Faraday rotator (FR), half-wave plate (HWP), a polarizing beam splitter (PBS), and prism mirror. In this circulator, the isolation between the three ports was about 25 dB. Before being transmitted through the air using the ϕ50mm lens, the ϕ2mm beam will undergo a 1:7.5 beam expansion process, so that the collimated beam size is ϕ15mm and the beam divergence equals to 120μrad.

At the receiver side, after the beam passes through the FSO-C, it is aligned and seamlessly coupled to the fiber core using VCM1&2 and VCM4. As illustrated in the Fig.2, inset (a), by changing the 3D position of the lens, the received light deflection angle changes, and the beam spot size/position moves on the focal plane. Hence, to allow maximum coupling efficiency, the VCM4 z-axis was used to control the focusing lens focal plane with the fiber core plane, so that the focused spot size becomes comparable to the fiber

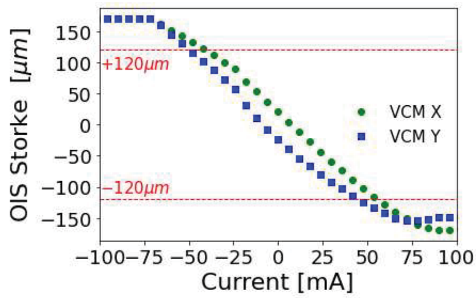
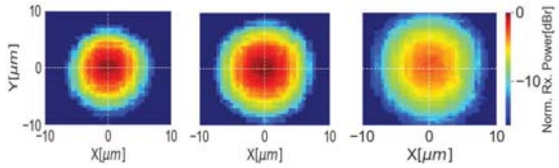


Fig. 3: VCM stroke vs. applied current

core size. According to Gaussian optics, in order to couple a collimated laser beam with wavelength λ and diameter D_B into a fiber of mode field diameter d_F, the coupling lens focal length should be $f = \frac{\pi D_B d_F}{4\lambda}$. To implement the fine tracking mechanism, we used a 10:90 IR beamsplitter (BS) and a quadrant photo-detector (QPD) as a tracking sensor. Here, the VCM3 is implemented to adjust both the beam initial center position and size at the QPD aperture. The tilted angle of the received wavefront was estimated and used by the proportional-integral-derivative (PID) controller to order the beam-steering device, i.e., VCM1&2, to minimize the deflection angle. Our tracking subsystems ensure that the received light can be accurately aligned and focused into the fiber.

Results and Discussion

Fig.3 shows the response of our spring-preloaded VCM stroke (μm) with the applied current (mA). When the applied current lies between -50mA and $+50$mA, the VCM shows a linear response with $\pm 120 \mu m$ linear shift. Hence, by maintaining the VCM x and y positions at the linear region, we can easily control the movement of the lenses. To highlight the impact of the VCM x,y and z movement, we plotted the Rx. optical power profile for VCM 4 that is used for fiber coupling. The plots



(a) (b) (c)

Fig. 4: Opt. pw. profile for different VCM4 x,y and z : (a) $z = 0$, (b) $z = -90\mu m$ and (c) $z = -175\mu m$

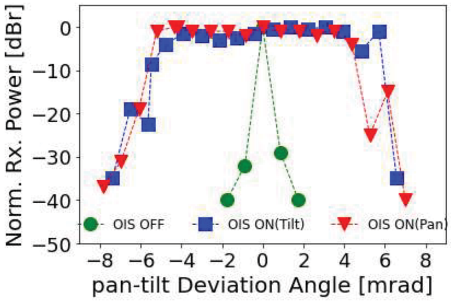


Fig. 5: OIS control performance

are obtained by moving the positions x and y in a spiral way and for different z positions (i.e. $0\mu m$,$-90\mu m$ and $-175\mu m$). Thanks to the VCM linearity, we can easily control the fiber coupling efficiency for better system performance. Indeed, for the incident collimated beam, the power profile at the fiber core also shows Gaussian behavior. Furthermore, by modifying the z value (i.e AF), the power profile size and peak power can be controlled efficiently.

In order to investigate the performance of our fine tracking system using the OIS and the close loop feedback control mechanism, we changed the laser beam angle of incidence by adjusting the *pan-tilt* angles of the antenna. Fig. 5 shows the norm. Rx. optical power for different *pan-tilt* deviation angles. When the OIS control is OFF, the optical power drops by 30 dBr for a deviation angle less than ± 0.8 mrad. On the other hand, by applying the OIS control, a *pan-tilt* deviation exceeding ± 6 mrad can be successfully controlled. Our fine tracking system ensures a significant improvement of the Rx. FOV with less complexity and minimum electronic overhead.

Using a bit error rate tester (BERT), we demonstrated 10-Gbit/s transmission over a looped-back 2×6m FSO link. The experimental setup is shown in Fig.6. The BERT was equipped by a standard 10-GbE small-form-factor-pluggable (SFP+) interface, where the generated PRBS length was $2^{31} - 1$ and the output optical power was about 0 dBm. The optical signal was then amplified by an Erbium doped fiber amplifier (EDFA) and directly plugged to the fibre connector of the 1st FSO TRx.. Here the transmitted optical power was $+10$

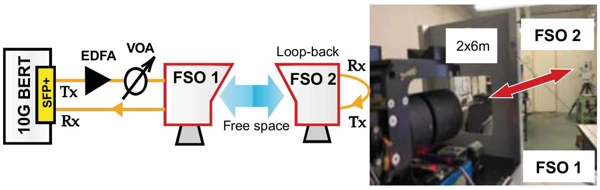


Fig. 6: Experimental setup for evaluation

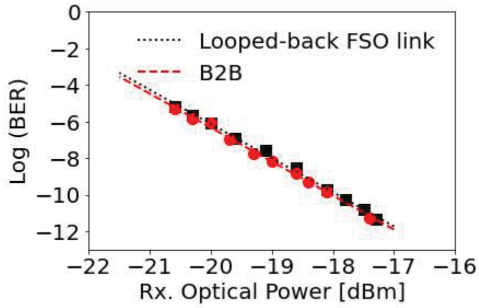


Fig. 7: BER performance

dBm. At the 2nd FSO TRx., the optical beam was received, directly coupled to the SMF and then looped-back to the Tx. port without being processed or amplified. Finally, the output laser beam was transmitted back to the 1st FSO TRx., seamlessly coupled to the SMF and then received by the BERT for evaluation. The Rx optical power was about -6 dBm, and thus the total loss of end-to-end optical link was about 16 dB. Fig. 7, shows the BER curves generated for back-to-back (B2B) and after transmission over 2×6m looped-back link. From the figure, The BER curves are identical and demonstrate that our system performance is similar to B2B scenario, where error-free transmission was confirmed.

Conclusions

We introduced a novel FSO transceiver utilizing FSO-C and OIS technologies. Owing to the transceiver optical design and the OIS-based fine-tracking control, a wider FOV is achieved and BER similar to B2B transmission at 10Gbit/s capacity were demonstrated. Since our transceiver relies on the seamless coupling to the SMF core, it is bandwidth and data-rate transparent, and thus suitable for high-capacity future networks.

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