Variable Focus Lens-Based Beam Steering and Divergence Control for WDM Free-Space Optical Communication

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Abstract: We investigate through experiments the wavelength dependence of optical beam steering and divergence control technique realized by variable focus lenses (VFLs). We also transmit 4×10-Gb/s signals over a 104-m free-space link using the VFL-based system. © 2021 The Author(s)

1. Introduction

Free-space optical communications (FSOC) are now expanding their applications to the data interconnection between airborne platforms, which could be an essential part of flexible, high-capacity, free-space fronthaul/backhaul networks in beyond 5G era [1-3]. A major technical challenge associated with such FSOC systems is the pointing, acquisition, and tracking (PAT).

Optical beam steering is a crucial function to realize the PAT. The optical beam steering has long relied on the mechanical mechanism. Some examples of mechanical beam steering include a two-axis gimbal, fast steering mirrors (FSMs), and micro-electro mechanical system-based mirrors [2, 3]. There have been some studies on non-mechanical beam steering techniques based on, for example, liquid crystals [4], optical phased arrays [5], and decentered variable focus lenses (VFLs) [6, 7].

The adaptive beam divergence control (ABDC) has been recently proposed and demonstrated to improve the performance of FSOC systems in the presence of pointing errors and angle-of-arrival (AoA) fluctuations [8-11]. The mechanical vibrations and movement of airborne platforms on the transmitter side give rise to the pointing errors, while the optical axis of the receiver aperture deviates from the direction of optical beam impinging onto the receiver due to the movement of the receiver. The ABDC mitigates the impacts of pointing errors and AoA fluctuations by changing the beam divergence angle adaptively to the channel conditions. It was shown that the ABDC can be realized non-mechanically by using a VFL and this system improves the outage probability of airborne FSOC systems in comparison with the system using a fixed beam size [9].

We have recently demonstrated a simultaneous realization of optical beam steering and ABDC using VFLs [11]. In this system, two decentered VFLs are used to steer the optical beam in two-dimensional directions, whereas one on-axis VFL is utilized to resolve the defocusing problem and also to implement the ABDC. The major benefits of this system include a wide range of beam steering/divergence control, a fast response time, low insertion loss, lightweight, and long lifetime [10, 11].

In this paper, we explore the possibility of using the VFL-based optical beam steering and divergence control system for the realization of wavelength-division-multiplexed (WDM) FSOC. To the best of our knowledge, this is the first study on a WDM FSOC system capable of non-mechanical optical beam steering and divergence control realized by VFLs. The WDM technique is perceived as the most promising and practical way to increase the capacity of FSOC systems. However, since the decentered VFL behaves similarly to a prism, the optical beam steering and divergence control characteristics could be a function of wavelength. We characterize the wavelength dependence of VFL-based beam steering and divergence control technique experimentally. Also, we carry out an experimental demonstration of 40-Gb/s (=4×10 Gb/s) WDM transmission over a 104-m long free-space optical link using the VFL system.

2. Experiment and Results

Fig. 1 shows the experimental setup. The outputs of two tunable lasers are coupled and sent two an electro-absorption modulator (EAM) for 10-Gb/s modulation. Another two tunable lasers are also modulated by using an EAM. The four-channel on-off-keying (OOK) optical signals are combined by using a 50:50 optical coupler and then fed to an erbium-doped fiber amplifier (EDFA). Since the even and odd channels are modulated by the same pseudo-random binary sequence, we insert a 5-meter long decorrelation fiber before they are combined.

The VFL system for simultaneous realization of optical beam steering and divergence control is composed of three VFLs packed in optical cages, as shown in the inset of Fig. 1. The VFL consists of an elastic polymer membrane-based container filled with an optical liquid. There is an electromagnetic actuator controlled by an electric current. The actuator exerts pressure on the container to control the curvature of lens, and thus its focal length. The main difference between these three lenses is their relative positions to the optical path of the beam. There is one on-axis

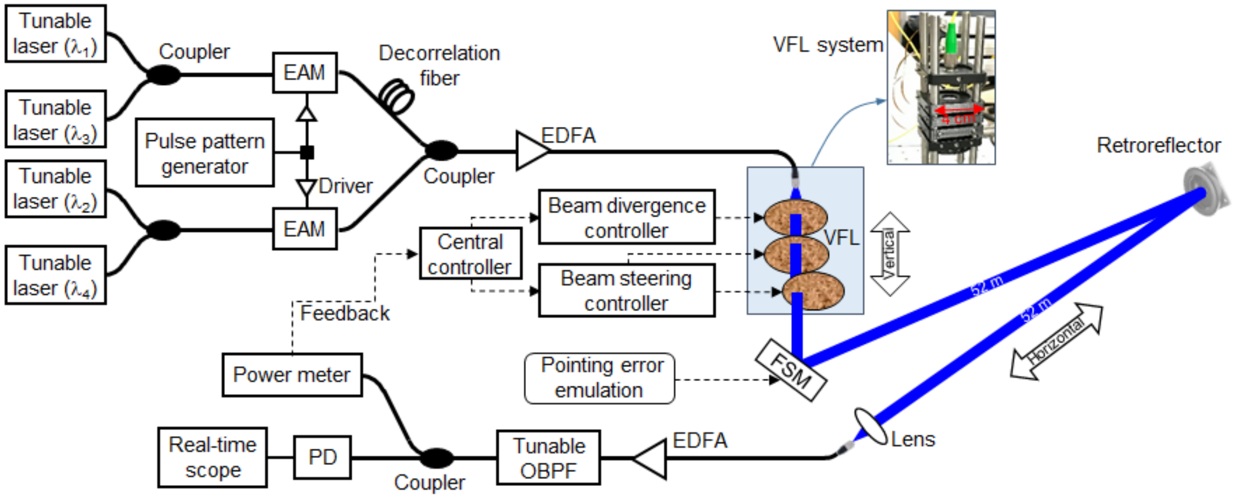

Fig. 1. Experimental setup.

lens (for the beam divergence control) with the input optical beam propagating along the optical axis of the lens. There are two off-axis lenses (for the beam steering) with the optical axis shifted by the offset distance to x- and y-directions. The offset distance is set to be 3 mm. These three VFLs are arranged vertically to minimize the adverse effects of gravity on the curvature of the lenses. The beam divergence controller and beam steering controller adjust the curvatures of the lenses through lens drivers. Each lens has a clear aperture of 10 mm. The optical power of the lens varies from +8.3 to +20 diopters when the current to the actuator ranges between 0 and 250 mA.

The optical beams emitted from the VFL system are first sent to an FSM (diameter of 25.5 mm). The reason for placing this mirror is twofold: one is to rotate the beam in the horizontal direction and the other is to emulate the pointing errors. The mirror has two piezoelectric inertia actuators (angular resolution of 0.5 μrad) attached to x- and y-axes of its mount. The optical signals propagate along the corridor of a building to a cube-corner retroreflector (clear aperture of 127 mm) placed 52 m away from the transmitter and comes back to the receiver. Thus, the transmission distance is 104 m. At the receiver, the optical beams are coupled into a standard single-mode fiber (SSMF) by a lens having a diameter of 35 mm and then amplified by an EDFA. A tunable optical bandpass filter (OBPF) is employed to select one of WDM signals. The bandwidth of this filter is 0.8 nm. The received optical signals are tapped and sent to an optical power meter. The information about the received signal power is sent back to the transmitter side for beam steering and divergence control. In a real scenario, this feedback channel can be realized by using an auxiliary RF link. The detected OOK signal is sampled and digitized by using a real-time oscilloscope. The bit-error ratio (BER) is measured offline.

We first measure the wavelength dependence of VFL-based beam steering and divergence control technique. For this purpose, we activate only one tunable laser and insert a charge-coupled device camera-based beam profiler between the FSM and the retroreflector. Then, we measure the beam steering angle as well as the beam divergence angle. Fig. 2(a) shows the deviation of beam steering angle with respect to the beam steering angle at λ_0=1546 nm. In the wavelength range from 1528 to 1565 nm, the VFL system is adjusted to direct the optical beam at three different beam angles. The results show that the offset of beam steering angle exhibits a linear relationship with the wavelength. The figure also shows that the offset of beam steering angle increases with the beam steering angle. For example, the wavelength dependency is measured to be -2.9 µrad/nm when the beam steering angle is set to be 0. However, this dependency is decreased to -6.4 µrad/nm for the beam steering angle of 23.8 mrad. This should be attributed to the chromatic aberration of the VFL. Fig. 2(b) shows the beam divergence angle versus the wavelength when the beam steering angle is set to be 23.8 mrad. The results show that the chromatic aberration also makes the divergence angle a function of wavelength. The slopes of the divergence angle are measured to be 0.5, 2, and 3.8 µrad for the beam divergence angles of 0.8, 1.5, and 2.1 mrad, respectively.

Next, we demonstrate a WDM transmission of 4×10-Gb/s OOK signals over the 104-m FSO link using the VFL system. There are four wavelengths with 0.8-nm channel spacing: λ_1 = 1549.2 nm, λ_2 = 1550 nm, λ_3 = 1550.8 nm, and λ_4 = 1551.6 nm. The received power at λ_1 is used as the feedback information for operations of beam steering and divergence control. Then, the BER performances of the other channels are measured sequentially without changing the beam steering and divergence controllers. This is to emulate the situation where all the channels are demodulated

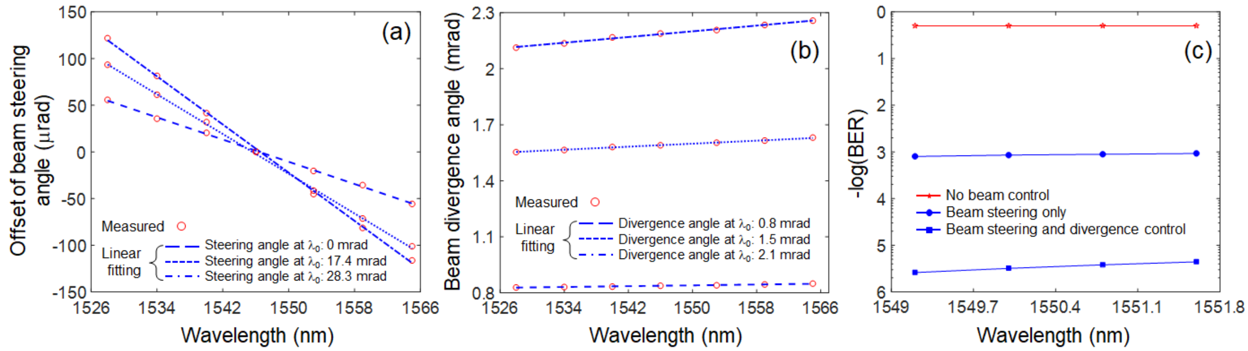

Fig. 2. (a) The offset of steering angle with respect to the steering angle at λ_0=1546 nm versus the wavelength. (b) The beam divergence angle as a function of the wavelength. The beam steering angle is set to be 28.3 mrad. (c) The measured BER performance of WDM transmission (4×10 Gb/s) in the presence of pointing error of 29.7 mrad.

simultaneously with the information about one of the channels being used for the feedback. Fig. 2(c) shows the measured BER values in the presence of a pointing error of 29.7 mrad. The results show that when the beam control is *not* activated, we have error floors at around 0.5. The received signal power is measured to be -50 dBm. When we activate only the beam steering control, we are able to achieve BERs at around 8.6×10^{-4}. Since the pointing error emulated in this demonstration exceeds the maximum steering range of 28.3 mrad, we observe a large links loss induced by pointing error. In this case, therefore, the BER performance can be improved considerably by adopting ABDC. Thus, when both the beam steering and divergence controls are activated, we achieve BERs at around 3.5×10^{-6}. Since the beam control is carried out using λ_1 channel, the BER performance deteriorates slightly as the wavelength increases. Nevertheless, we successfully transmit four 10-Gb/s WDM signals over the 104-m free-space link using the VFL-based beam steering and divergence control system in the presence of a large pointing error of 29.7 mrad.

3. Conclusions

We have explored the possibility of utilizing the variable focus lens-based optical beam steering and divergence control technique for WDM free-space optical communications. Although the beam steering and divergence characteristics exhibit wavelength dependency, we believe that the variable focus lens-based beam control technique could be used for short- and intermediate-haul WDM free-space optical communication systems.

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