42.8 Gbit/s Indoor Optical Wireless Communication with 2-Dimensional Optical Beam-steering

C. W. (Joanne) Oh, Eduward Tangdiongga and A. M. J. (Ton) Koonen
COBRA Research Institute, Eindhoven University of Technology, P.O. Box 513, 5600MB Eindhoven, The Netherlands.
C.W.Oh@tue.nl

Abstract: To combat the imminent radio frequency spectrum crunch, we propose an infrared optical wireless communication solution for in-home networks, with remotely controlled 2-dimensional passive optical beam-steering, which exhibited 42.8 Gbit/s over 2.5 m free-space transmission.

OCIS codes: (050.1950) Diffraction gratings; (060.2605) Free-space optical communication

1. Introduction

The rapid growth of wireless bandwidth demand has introduced immense pressure on the limited radio frequency spectrum. Indoor wireless networks have to support more and more devices ('Internet of things') and already today, more traffic is generated from devices indoor than outdoor [1]. Alternative solutions, such as utilizing the 60 GHz band, multilevel modulation formats, complex digital signal processing and multiple-input-multiple-output (MIMO) techniques, are on the rise, but are still struggling with the limited radio spectrum resources. Ultimately, optical wireless communication (OWC) is viewed as a promising alternative or complementary solution to high speed radio wireless communication systems. The benefits of optical wireless technique are in its fundamentally wide bandwidth, inherent immunity against electromagnetic interference, physically secure and unregulated bandwidth.

In this paper, we introduce an infrared optical wireless communication (IOWC) system which, with respect to radio communication and visual light communication, offers not only the benefit of a gigantic bandwidth but also of lower component costs by reusing fiber communication devices that are already available commercially, easy (potentially seamless) interfacing with the fiber-to-the-home access network, higher link budget due to relaxed eye safety regulation, insensitivity to ambient light, better photodetector sensitivity, and physically secure channels. Despite these attractive benefits, a major challenge is to realize a system that provides a wide coverage of high-capacity service to multiple devices simultaneously. For this, we propose a pair of cascaded passive diffractive optical elements (DOEs) for steering optical data beams for 2D area coverage. The communication link quality of beams diffracted by cascaded gratings over 2.5 m has been evaluated experimentally.

2. Indoor Optical Wireless System Architecture

A schematic of our proposed system is shown in Figure 1. The solution combines novel free-space line-of-sight optical beam techniques for downlink and radio communication for uplink. Data signals will be routed from the central communication controller (CCC) to the rooms through the fiber backbone, which can be implemented using bend-insensitive single-mode fibers (SMF) or multi-mode fibers. The CCC hosts the intelligence of the system, such as protocols and routing logics, and acts as the gateway between in-home and access networks. Radio and optical localization techniques may be implemented to locate the position of the mobile user's device before establishing a connection. At the access points (APs), beam-steering modules will be implemented to direct downstream data signals from the fiber network to the respective wireless devices. The key to practical implementation of such high bandwidth optical beam links is in the technique used to direct these high capacity links to provide network coverage to many users individually, simultaneously and dynamically. Several free-space optical beam-steering solutions, such as those composed of mirrors, acousto-optic deflectors, on-chip grating modules and liquid crystals, have been proposed by several studies [2]. However, these devices require local powering, need separate beam control channels, have relatively slow beam-steering and/or have small steering angles (i.e. small coverage). In this regard, we propose the use of two crossed cascaded diffractive optical elements for an instantaneous, passive and effective 2D beam-steering technique. The idea is that the first grating has a lower

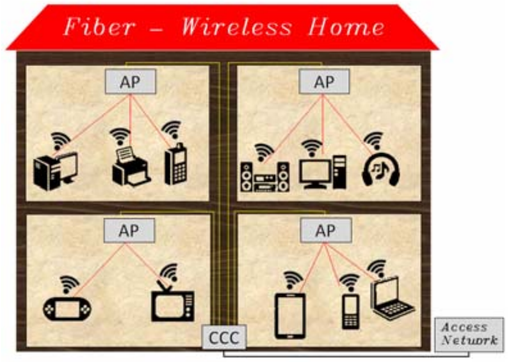

Fig. 1. Architecture of in-home network with optical wireless with beam-steering for downlink and radio wireless for uplink.

free-spectral range (FSR) and the second grating has multiple times the FSR of the first grating. By tuning the wavelength of a tunable laser, which is located at the CCC, the beams are then diffracted accordingly to the appropriate x- and y-direction, consequently providing a 2D coverage [3]. For the proof of principle, we use an echelle grating blazed at 63° with 31.6 grooves-per-mm and with FSR = 41 nm, and an echelle grating blazed at 75° with 79 grooves-per-mm) and FSR = 96 nm. Their mentioned FSRs can be calculated using:

$$Free\ spectral\ range\ (FSR) = \frac{\lambda_m}{m+1} \qquad (1)$$

where λ_m refers to the wavelength operating in the order m. By operating the laser between 1529 nm and 1611 nm, a 2D distribution as shown in Figure 2 can be obtained. Likewise, by using a first grating with a much smaller FSR, a different distribution with more scanning rows can be obtained.

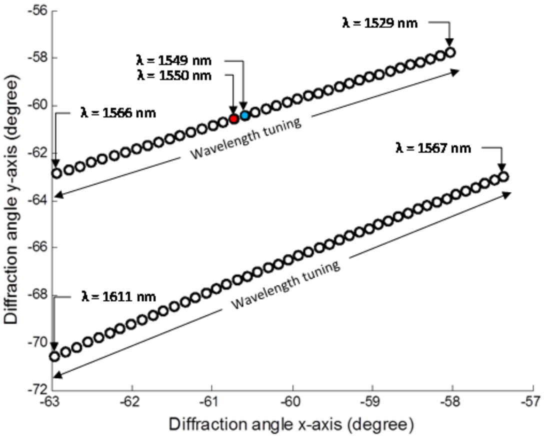

Fig. 2. Distribution of diffracted beams over a wavelength range of 1529 nm to 1611 nm.

3. Experimental Setup and Procedure

Figure 3 presents the testbed setup that is used to measure the transmission link quality of the diffracted beams. First, the system has been evaluated using a non-return-to-zero (NRZ) on-off-keying (OOK) signal with a pseudorandom binary sequence (PRBS) of length 2^{31}-1 (constructed with components in the grey-shaded boxes to the right of Fig. 3). The data is modulated onto a 1550 nm laser beam. The signal passes through a polarization controller [4] and then, is emitted to free-space through a transmitting coupler (Tx) at a beam diameter of 3.33 mm. The transmitted power of the laser used is measured to be ≤ 9.3 dBm (thus, below the eye safety limit of 10 dBm at $\lambda > 1.4$ µm). The beam is then diffracted by a crossed pair of cascaded echelle gratings, as described in the section above. To build a compact testbed, a 2.5 m folded path free-space transmission distance is constructed using silver-coated mirrors. At the receiver side, a receiving fiber-pigtailed lens coupler (Rx) receives the beam and sends it to the receiver. The OOK signal quality is evaluated with the bit error rate tester (BERT) and the eye diagram is viewed on an oscilloscope. The experiment is repeated for a carrier wavelength of 1549 nm. The testbed is subsequently reshaped to allow measurements with discrete multitone (DMT) modulated signals in order to maximize link capacity. The components in the grey-shaded boxes to the right of Fig. 3 are now replaced with the components in the grey-shaded box on the left. The DMT signal is evaluated using offline processing with Matlab. Back-to-back (BtB) measurements are done for both OOK and DMT signals by connecting a 2 m long SMF from the output of the polarizer controller (for OOK) or the output of the DFB laser (for DMT) to the input of the attenuator.

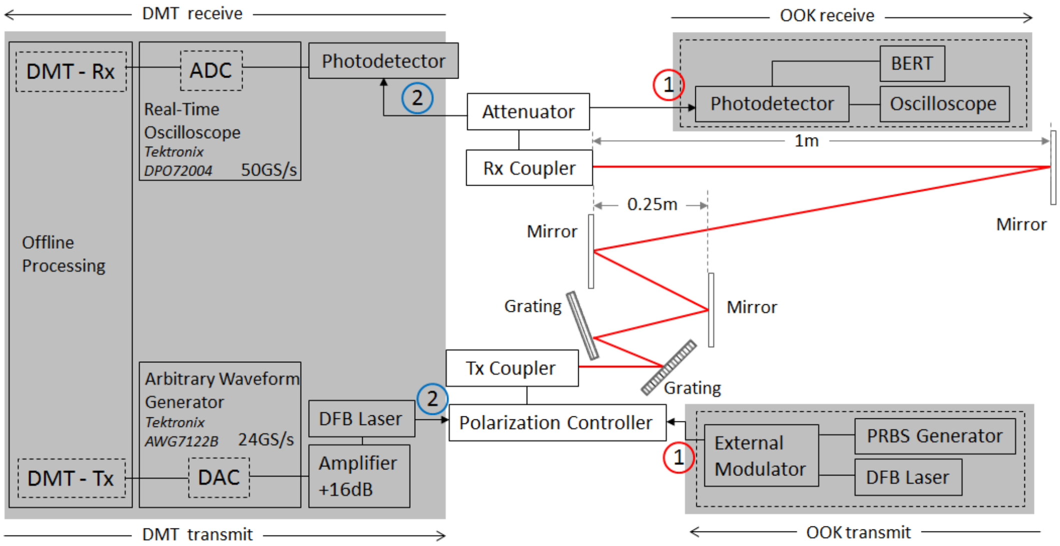

Fig. 3. Testbed setup for infrared optical wireless transmission covering a distance of over 2.5 m with cascaded diffraction gratings for 2-dimensional beam-steering. Left greyed-block: Setup for DMT transmission. Two right greyed-blocks: Setup for NRZ-OOK transmission. Discrete Multitone (DMT), Digital-to-Analog Converter (DAC) , Distributed Feedback (DFB), Transmitter (Tx), Receiver (Rx), Pseudorandom Binary Sequence (PRBS), Bit Error Rate Tester (BERT).

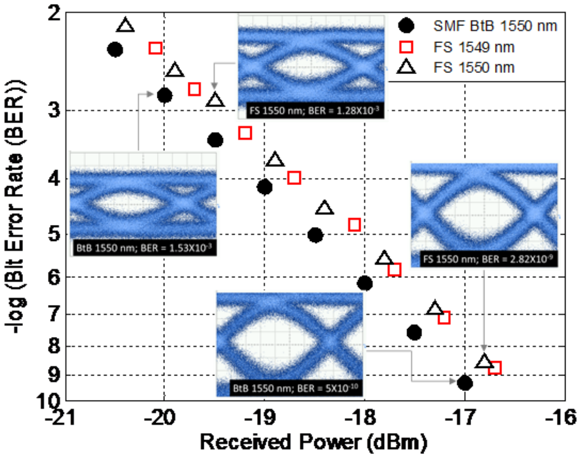

Fig. 4. BER performance of NRZ-OOK transmission for diffracted beams at 1549 nm, 1550 nm and SMF BtB; Eye-diagrams for BtB and 2.5m free-space (FS) 1550 nm link.

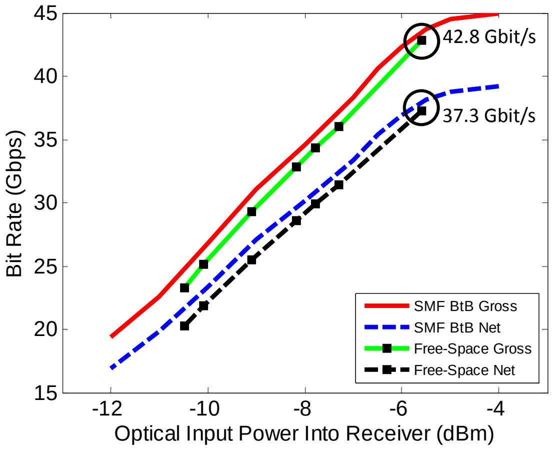

Fig. 5.Performance of DMT transmission for SMF BtB and diffracted beam at 1550 nm.

4. Results and discussion

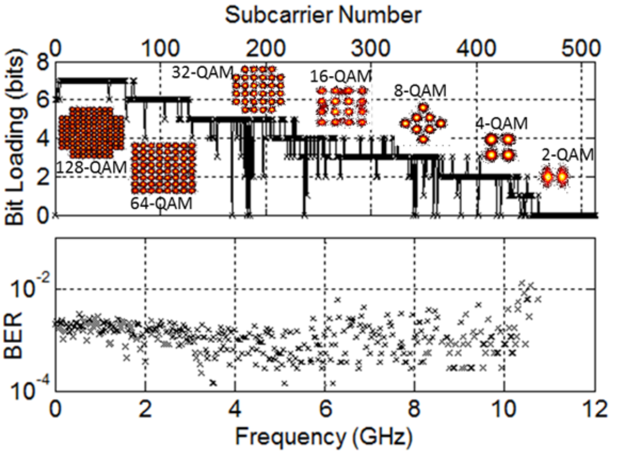

Fig. 6. Bit-loading and BER for each subcarrier together with the corresponding QAM constellations.

The performance of the free-space diffracted OOK signals is plotted in Figure 4. Consistent overlapping of the 2.5 m link curves with the BtB curves shows that the free-space beam can achieve error-free transmission (BER ≤ 10^{-9}) similar to transmission through SMF. Free-space optical power loss is measured up to 14.6dB. This loss is mainly contributed by using the gratings at wavelengths far away from the blaze wavelengths (57 µm and 25 µm for the first and second grating, respectively). It is important to note that these gratings are not selected for optimal power efficiency but they provide the FSRs needed for our proof-of-concept demonstration and for conducting the initial feasibility study. In the link optimization for capacity, the DMT signal has achieved a gross bitrate of 42.8 Gbit/s and a net bitrate of 37.3Gbit/s. The corresponding bit loading, BER and constellations are plotted in Figure 6. It can be observed that not all subcarriers achieved a BER ≤ 3.8 X10^{-3} but the overall BER is still within the FEC limit for error-free transmission (note that in DMT transmission, the signal is not demodulated per subcarrier but as an entire frame). The constellation diagrams are clearly distinguishable, as shown in Fig. 6, signifying good performance.

5. Conclusion & Acknowledgement

We have successfully demonstrated an IOWC system with 2-dimensional optical beam-steering, by cascading two crossed DOEs. This beam-steering solution does not require local powering while providing instantaneous remotely controlled steering. Error-free transmission at BER ≤ 10^{-9} is achieved for 10 Gbit/s OOK signals and FEC correctable transmission is achieved for the 42.8 Gbit/s DMT signal, over a free-space transmission distance of 2.5 m. These results are promising for the realization of future high-capacity narrow-beam IOWC systems.

This work is part of the Advanced Grant project Beam-steered Reconfigurable Optical-Wireless System for Energy-efficient communication (BROWSE), funded by the European Research Council within the FP7 program.

7. References

[1] A. M. J. Koonen, "Optical Techniques for Gbit/s Wireless Indoor Access" in Proceedings of the MWP/APMP, (Sapporo, 2014), Keynote paper.

[2] P. F. McManamon, P. J. Bos, M. J. Escuti, J. Heikenfeld, S. Serati, H. Xie, and E. A. Watson, "A review of phased array steering for narrow-band electrooptical systems," in Proceedings of the IEEE, (New York, 2009), **97**(6), pp. 1078-1096.

[3] A. M. J. Koonen, C. W. Oh and E. Tangdiongga, "Reconfigurable free-space optical indoor network using multiple pencil beam steering," in Proceedings of the OECC/ACOFT 2014, (Melbourne, 2014), Paper Tu3F-1.

[4] C. W. Oh, E. Tangdiongga and A. M. J. Koonen, "Steerable pencil beams for multi-Gbps indoor optical wireless communication," OSA Optics Letters, **39**(18). pp. 5427-5430 (2014).