Indoor Optical Wireless Communication System Using Beam-steering by Cascaded Diffractive Optical Elements

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While the radio spectrum continues to struggle with a soaring bandwidth demand, the optical spectrum promises virtually unlimited license-free bandwidth. We report the feasibility of high-capacity point-to-point links for indoor optical wireless communication with cascaded diffractive optical elements (DOEs) for free-space optical beam-steering. An investigation of such optical wireless transmission has been carried out in an experimental testbed. Error-free (bit error rate less than 10^{-9}) communication, with data rate of 10 Gbit/s over 2.5m, is demonstrated.

Introduction

In this era of hyper connectivity, communication has become part of human necessity. High-speed and on-the-spot communication has been a persistent demand ever since data over wireless technology was introduced. To date, data over wireless is supported by Wi-Fi technology which offers a maximum bit rate of up to 600 Mbit/s with the IEEE 802.11n standard. When we extrapolate the communication traffic demand further, as predicted by Edholm's Law, the exploitation of the finite bandwidth of the radio spectrum is approaching its limit. The increasing number of connected devices as well as high bandwidth demand applications, such as high definition video streaming and online gaming, will soon face bandwidth congestion and the devices will seriously interfere with each other. Consequently, this will result not only in the deterioration of quality-of-service but also requires costly network improvements by internet service providers.

Optical fiber technology facilitates an infrastructure that carries a huge bandwidth extending not only over intercontinental distances but also within our homes. In fact, this huge bandwidth can be harvested by tapping off the light signal propagating in the fiber, and redirecting it to free-space for infrared optical wireless communication (IOWC). The advantages of IOWC are that it is inherently immune to electromagnetic interference, physically secure and the transmission bandwidth is unregulated. The real challenge in implementing an IOWC system is in the "enabler" to provide large service coverage to multiple users. A broad diffused beam typically results in diffused power and hence, reduced received signal power and channel quality. On the other hand, a narrow, highly directional beam requires less transmission power while providing a dedicated bandwidth channel to a device. Therefore, several beam-steering initiatives for narrow beam IOWC for indoors have been proposed with mirrors and MEMs [1]. However, these solutions require local powering and mechanical intervention. In this paper, we conducted a feasibility study on an infrared-based line-of-sight indoor IOWC system propagating at 10 Gbit/s exploiting cascaded diffractive optical elements (DOEs) for free-space optical beam-steering and on-off-keying (OOK) modulation format. We employ two different echelle gratings arranged orthogonally to each other in order to facilitate a 2-dimensional spatial coverage.

Proposed Indoor Optical Wireless System

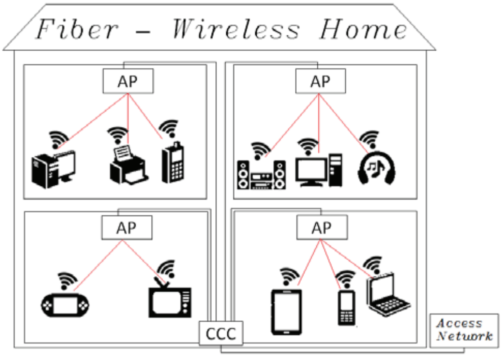

Fig. 1 Architecture of optical fiber – wireless indoor network.

The in-home fiber-wireless network architecture is proposed as in Fig. 1. In essence, the free-space communication links will be implemented with diffracted infrared optical beams for downlink and a 60 GHz radio wireless uplink is foreseen. The fiber backbone may be implemented using bend insensitive single- or multi-mode fibers (SMF or MMF). The central communication controller (CCC) hosts the intelligence of the system, such as protocols and routing logic and acts as the gateway between the in-home and access networks. The CCC will receive traffic from and to the access network and route it to the access points (APs) in every room; in our case, to beam-steering modules in different rooms or cells. For the radio upstream, a reflective-semiconductor optical amplifier (R-SOA) can be used to re-modulate the upstream data and carry it to the CCC. Radio or optical localization techniques [2] can be used to locate the position of the mobile user's device before establishing a connection.

Optical Beam Steering

The feasibility and reliability of an infrared optical beam, which acts as the carrier for data transmission, in providing a high quality communication link has been previously verified [3]. The key to practical implementation of such high bandwidth line-of-sight link is in the technique used to redirect these high capacity links to provide internet coverage to a group of users simultaneously and dynamically. Several free-space optical beam-steering devices, such as those composed of mirrors, acousto-optic deflectors, on-chip grating modules and liquid crystals, have been proposed in several studies. However, these devices require local-powering, separate communication channels and/or have small steering angles (i.e. small coverage). An ideal beam-steering device would require no or low power, while having a wide coverage, a simple distribution system and fast switching with reliable accuracy. In our work, we study the feasibility of employing two passive gratings, cascaded orthogonally, for 2-dimensional beam-steering for an in-home communication system. The primary use of diffraction gratings is to disperse light spatially by wavelength. In our system setup, the first grating has a lower free-spectral range (FSR) and the second grating has double the FSR of the first. By tuning the wavelength of the tunable laser, which is located at the CCC, the beams are then diffracted accordingly to the appropriate x- and y- direction, consequently providing an effective coverage area [4].

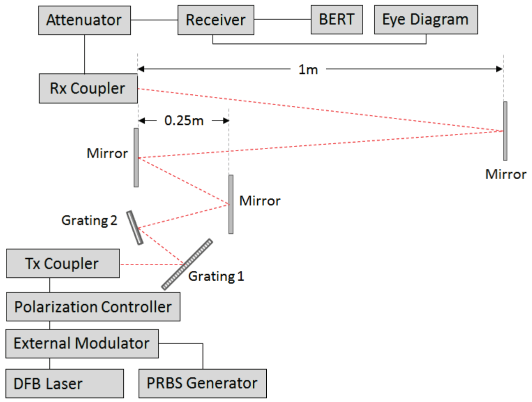

Fig. 2 Testbed setup for 2D beam-steered free-space transmission link of 2.5 m.

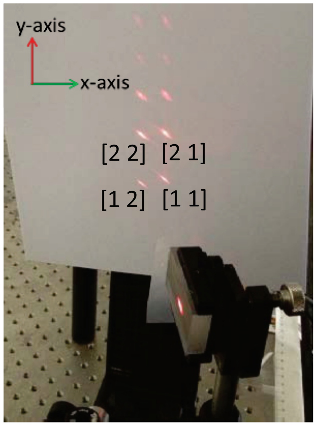

Fig. 3 2D tabulation for orthogonally cascaded echelle gratings.

Experimental Setup

Fig. 2 shows the experimental setup of a 2.5 m folded-path free-space optical transmission system with a pair of cascaded gratings. The free-space optical beam propagates from the transmitting (Tx) coupler toward the pair of gratings and 3 path-folding silver-coated mirrors before arriving at the receiving (Rx) coupler. The first grating is an echelle grating blazed at 63° (31.6 grooves/mm) and the second is an echelle grating blazed at 75° (79 grooves/mm). By means of wavelength tuning, the echelle grating blazed at 63° provides a tuning angle range of 5°. Similarly, the echelle grating blazed at 75° provides a tuning angle range of 17° [3]. This experiment is carried out for the wavelength of 1550 nm on the testbed. A 10 Gbit/s Mach-Zehnder modulator is used to modulate a pseudorandom binary sequence (PRBS) of 2^{31}- 1 with OOK format, onto the 1550 nm beam, which acts as the data carrier. A polarization controller is used to maintain the polarization of light that falls onto the polarization dependent gratings. The transmitted data signal is then captured at the Rx coupler and the signal power is attenuated accordingly in order to perform the bit error rate test (BERT) and eye-diagram measurement. The transmitted power measured at the output of the polarizer is $\leq$ 1.5 dBm. In accordance to the eye safety limit, the maximum optical power transmitted into free-space is about 10 dBm for 1550 nm wavelength, with a beam diameter of approximately 3.33 mm. As a benchmark, a back-to-back (BtB) measurement is carried out by connecting a 2 m long SMF between the polarizer controller and the attenuator.

Measurement Results and Discussion

The tabulation of the diffracted beams is illustrated in Fig. 3, which is obtained by transmitting a 657 nm laser (for visualization purposes) through the Tx coupler and captured after the second grating. With a similar tabulation for the 1550 nm laser, we measure the quality of four data modulated diffracted beams, labelled as shown in Fig. 3. The bit error rate (BER) performance is presented in Fig. 4. We observe that the measured performance curves of the diffracted data modulated beams overlap the performance curve of the BtB measurement. This signifies that the free-space

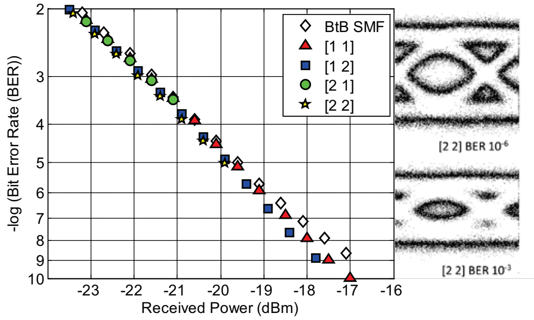

Fig. 4. Performance of 10 Gbit/s diffracted transmission links versus SMF BtB transmission. On the right is the captured eye-diagram for transmission at [2 2].

transmission quality is comparable to the quality of the transmission with an SMF. [1 1] and [1 2] links achieve BER $\leq 10^{-9}$ (error free). However, since there is insufficient power budget in the [2 1] and [2 2] links, the achieved BER can be measured only up to 10^{-6}. This is a consequence due to the loss from the diffraction gratings used. Approximate loss of 13 dB is observed for the [1 1] and [1 2] links while 19 dB is observed for the [2 1] and [2 2] links. This loss is mainly contributed by using the gratings at wavelengths far away from the blaze wavelength. It is important to note that these gratings are not selected for optimal power efficiency but they provide the FSRs needed for the proof-of-concept demonstration of steering with cascaded gratings. The eye diagrams of worst case beam diffracted at [2 2], at BER = 10^{-6} and BER = 10^{-3}, are recorded. The eye-diagrams do not show impairments except for a smaller eye opening due to reduced signal power. Lastly, at a receiving distance of 2.5 m, by calculation, the [1 1] and [1 2] beams are separated by an x-axis distance of 23 cm, which corresponds to angle difference of 5.3°. The y-axis distance between '[1 1] and [1 2]' and '[2 1] and [2 2]' beams is 60 cm, which corresponds to angle difference of 12.1°. This shows that a wider coverage can be achieved by using more diffraction orders.

Conclusion

We have presented the feasibility of using cascaded passive DOEs as the medium of beam-steering for indoor IOWC system. Error free links with BER < 10^{-9} has been achieved at a distance of 2.5 m with sufficient transmission power. This is a promising solution for the realization of IOWC systems in the future.

Acknowledgement

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