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High-capacity Dynamic Indoor Network Employing Optical-wireless and 60-GHz Radio Techniques

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Abstract—We demonstrate a hybrid radio-optical wireless communication system using a photonic integrated all-optical-cross-connect (OXC) chip to realize a highly reconfigurable and reliable bidirectional indoor wireless network which provides the ultimate capacity per user. By remote wavelength-tuning, narrow optical beams are directed to the users employing a passive 2D beam steering module fixed at the ceiling in each room. Robustness regarding line-of-sight issues is achieved by implementing 60-GHz radio protection channels generated optically using a shared amplitude modulator via the OXC chip. The use of a 35 GHz reflective electroabsorption modulator (REAM) monolithically integrated with a semiconductor optical amplifier (SOA) chip is proposed for upstream wideband analog applications. The REAM-SOA provides similar performances as a REAM, but over a wide range of input optical powers and wavelengths. This mitigates the need for accurate control of the input signal, especially at remote sites where simplicity is strictly required. System experiments showed downstream optical-wireless transmission capacities of up to 35 Gb/s per user and 60-GHz protection channels with a capacity of 20 Gb/s. Upstream RoF transmission rates of more than 35 Gb/s have also been achieved.

Index Terms—Free-space communication, beam steering, diffraction gratings, millimeter-wave radio-over fiber, reflective electroabsorption modulator, optical-cross-connect.

I. INTRODUCTION

DRIVEN by the ever increasing number of wireless devices and the growing demand for bandwidth-intensive services such as uncompressed 4K/8K UHD TV, a booming volume of wireless data has to be carried by indoor networks, where most of the internet traffic originates/terminates [1]. The interference among these devices is also severely impacting the throughput. This introduces immense pressure on current indoor networks. The available large bandwidths in 60-GHz and higher radio frequency (RF) bands have gained significant interest to tackle this problem. Using radio beam-forming techniques high-speed wireless links can be provided to the individual users with reduced interference between them [2]. Dynamically routed

radio-over-fiber (RoF) systems play an important role in transporting these broadband services to/from radio access points (RAPs) fixed in every room. These RAPs form energy-efficient pico-cells [3]. Remotely controlled wavelength-agnostic reflective upstream transmitters such as reflective electroabsorption modulators (REAMs) are preferred to implement simpler and more cost-efficient RAPs [4].

Another highly promising alternative is optical-wireless communication (OWC) with narrow directional beams which can provide even higher and non-shared capacities per user as well as longer reach [5][6]. OWC systems bring a huge unlicensed optical bandwidth, physical security, and immunity from electromagnetic interference to the wireless arena. A beam steering mechanism is needed at the access points to direct each beam to the individual users. Several approaches have been proposed for this purpose including micro-electromechanical mirrors [7], acousto-optic deflectors [8], on-chip grating modules [9][10], and liquid crystals [11][12]. However, these devices have drawbacks such as the need for local powering, slow steering speed, small steering angles and the need for separate control channels. To avoid these drawbacks, we designed a beam steering module using a crossed pair of diffraction gratings and investigated it in detail [13–14]. The wavelength of the incoming signal determines the 2-dimensional (2D) direction the beam is diffracted to. Hence, no separate (additional) control channel is required for the steering. A large number of users can be supported by using multiple beams, each at a different wavelength.

So far, the majority of the research on ultrahigh-capacity indoor wireless communication focused on static single-direction communication without considering major network functionalities such as reconfigurability, bidirectionality, mobility and reliability. Such functions are key for ensuring capacity-on-demand which is needed to meet changes in traffic patterns, to minimize power consumption, and to cope with indoor mobility and link failures.

Hence, in this paper, we use photonic integrated circuits (PICs) to realize dynamicity and reliability for bidirectional

Fig. 1 Indoor network architecture.

ultra-high capacity indoor wireless communication. This novel concept consists of pencil beam based OWC with millimeter-wave (mm-wave) radio fall-back system for downstream, and 60-GHz radio-over-fiber (RoF) for upstream transmissions aided with a very fast 4×4 space-, and wavelength-domain OXC chip for routing the signal to the appropriate rooms. Downstream optical beam steering is realized by cascading two crossed diffraction gratings where the steering is remotely controlled by only tuning the wavelength of the optical signal [13]. The downstream mm-wave radio system is operational only in case of failures in the optical-wireless link (incl. line-of-sight (LOS) blocking) in order to significantly increase the network's reliability [16]. A REAM integrated with a semiconductor optical amplifier (REAM-SOA) chip is used as a transmitter for the upstream RoF system. A REAM-SOA has great potential as a wavelength-agnostic, low-loss and high-speed transmitter for indoor applications, especially, at RAPs where cost-efficiency and simplicity are of paramount importance [17]. Downstream and upstream transmission rates of 35 Gb/s and 20 Gb/s per user, respectively are demonstrated using discrete multitone (DMT) modulation [18]. Experiments also show that a transmission capacity of 20 Gb/s can be achieved on the mm-wave fall-back channel.

In comparison to 60-GHz radio communication system, we believe that, in addition to the significantly higher unlicensed bandwidth (10 – 100 GHz) that it provides, our OWC system is

more cost efficient and scalable, especially when there are a high number of RAPs in the system. The radio beam-steering necessary to provide the available capacity in the 60-GHz region to individual users increases power consumption and complicates the RAPs and user terminals. Our beam steering module does not need local powering and allows us to control the steering remotely by changing the wavelength. Moreover, optical beams can have a smaller footprint than (60GHz) radio beams, thus enabling a denser cell network architecture and hence higher network capacity. The on-demand adaptable steering of these beams yields a high energy efficiency. Our IR beam-steered system deploys optical components which are readily available from the fiber-optic communication industry at low costs.

II. HETEROGENEOUS INDOOR NETWORK ARCHITECTURE

Figure 1 depicts the proposed hybrid indoor network architecture. Dynamic routing of downstream signals to the individual rooms via an optical fiber backbone network is performed using an OXC in the residential gateway (RG). Each room is equipped with one or more access points (called pencil radiating antennas (PRAs)) to direct wireless signals to/from the individual users. The wireless channel in the downstream is realized by implementing LOS infrared optical pencil beams with wavelengths beyond $1.4 \mu\text{m}$, where eye safety regulations allow higher beam powers than in the visible range; up to 10mW is allowed according to ANZI Z-136 and IEC 60825 standards.

We implemented a crossed pair of diffraction gratings (in cooperation with remote wavelength-tuned source) for downstream 2D optical beam steering. The design aspects and experimental validation of this beam steering module are explained in great detail in [6] and [14]. The system can be scaled to multiple users by adding wavelengths using tunable lasers (TLs) at the RG. The OXC plays a very important role in sharing the TLs among multiple users to reduce the overall cost of the system. Time-slotting may be applied to share the TLs between multiple users at the same time for further reduction of the number of TLs, and thus reducing costs, as demonstrated in [19]. In this mechanism, a TL serves a user at a specific wavelength during a specific time slot and another user at a

Fig. 2 Hybrid and reliable dynamic indoor network using an optical cross-connect and shared external amplitude modulator.

different wavelength during a different time slot.

Users must be localized (and tracked when they move) in order to adequately direct the optical beam and set up (and keep) the connection. The use of the already matured radio localization techniques [20–22] is foreseen for this purpose. As this topic is not within the scope of this paper, it will not be further discussed here. The RG also hosts the central communication controller (CCC) to carry out the indoor network management and control functions including user localization and tracking, and protection. A single optical fiber can be used for both upstream and downstream communications using optical circulators. Hence, installation becomes much simpler for home/building owners.

Implemented with spectrally-efficient modulation formats, the 7-GHz unlicensed bandwidth in the 60-GHz region (57 – 64 GHz) is well-suitable for high-capacity upstream per user (using beam forming techniques) [23] as well as accurate user localization [20]. A multi-beam phased-array antenna (PAA) providing distinctive tunable nulls in the radiation pattern can be employed at the PRAs to receive radio signals from multiple users distinctively. The subcarrier multiplexing (SCM) module (see the inset in Fig. 2) then combines these users together, after putting them on different subcarriers using arrays of local oscillators and mixers. To this end, we are developing an integrated 60-GHz system at the PRA, in which the PAA, power amplifiers, low-noise amplifiers, and phase shifters are integrated together to realize a compact solution [24][25]. The composite signal is modulated on to an optical carrier, sent from the RG and separated from the downstream optical-wireless signals at the PRA using a fiber Bragg grating (FBG), for upstream transmission. Using a multicast capable OXC, one laser source multicasting its output to the PRAs can be used to transport upstream radio signals from multiple PRAs. A REAM-SOA is used for upstream optical modulation of the radio signals on a robust SCM-RoF system. This device has various benefits, in addition to all the benefits that a REAM provides.

It is well known that the dynamic range (DR) of an RoF link is affected, mainly by the non-linearity of the optical modulator used [26]. This, in addition to the bandwidth of the REAM-SOA, limits the number of users that can be multiplexed. The DR of the REAM-SOA (whose transfer function is exponential with respect to voltage) can be improved by operating it at a higher bias current and higher input optical power as demonstrated in section II.D. We have successfully combined two users together each at 20 Gb/s wireless capacity using the REAM-SOA. Multiple users can be supported using more than one REAM-SOA (integrated together on the same chip) at the PRAs (in cooperation with multiple light sources located at the RG and shared between the PRAs). Detailed study of the REAM-SOA transmitter for use in analog systems, especially at RAPs, is given in section II.D.

To tackle outages in the downstream optical-wireless links, due to LOS blocking, a 60-GHz radio protection scheme is implemented. This allows us to support communication at lower speeds until the optical link is reestablished and normal operation resumes. An optical up-conversion technique using a

Fig. 3 OXC design for dynamic routing of optical wireless signals steered to the individual users using 2D grating.

Mach-Zehnder modulator (MZM) is implemented to generate the 60 GHz-radio signals from the baseband signals [27]. By using the OXC a single MZM can be shared to tackle link outages for multiple downstream wireless channels at the same time as shown in Fig. 2 and explained in section II.C.

A. OXC Design

Network functionalities such as reconfigurability and reliability are essential in any network. The OXC is a key component in our system to ensure capacity-on-demand and to handle user mobility. Each PRA, which serves multiple users, is connected to a port of the OXC using a single-mode optical fiber cable. Optionally, we may share a port of the OXC among PRAs by implementing waveband-multiplexing at the RG and demultiplexing the wavelengths near the PRAs [28]. Using the OXC, the relatively expensive components, notably the TLs, can be shared between the indoor users at the same time or different times, thereby reducing the overall energy consumption and cost.

Hence, the design of the OXC is important. To cope with traffic dynamicity and user mobility, the OXC should be transparent to wavelength, bitrate and protocol. This is because in our system, where a crossed pair of diffraction gratings is used to steer beams, each location in a room corresponds to a unique wavelength. The OXC should also allow routing from any input port to any output port independently of how other input signals are routed. Based on these requirements a design for the OXC for use in our system is shown in Fig. 3. An $m \times n$ OXC can be constructed from m $1 \times n$ optical switches and m $n \times 1$ optical couplers. Each switch acts only on a single input optical signal at a time and are controlled by the CCC.

Various switching fabrics exist currently that can be considered for the OXC design in our system. These include micro-electro-mechanical system (MEMS) mirrors [29][30], liquid crystals [31], thermo-optics [32], and SOA gates [33]. The suitability of these switching fabrics is determined by factors such as insertion loss, optical bandwidth, crosstalk, switching speed, power consumption, size/scalability and cost [34][35]. SOA gate based switches are highly attractive because of the possibility of integration with other components such as lasers and modulators resulting in a compact device. The presence of active components (SOAs) also help to overcome insertion losses. Additionally, they tend to be fast, energy-

efficient, and multicast capable. Hence, the experiments in this paper are performed using an SOA gating-switch based OXC.

B. Crossed Pair of Diffraction Gratings for Downstream Infrared Pencil Beam-steering

Using optical pencil beams for wireless communications allows us to provide ultrahigh non-shared capacities for individual users. However, a beam steering mechanism is needed at the PRAs to direct each beam to the users. Using remotely controlled passive dispersive components for this purpose was proven to be beneficial since local powering is not needed and control complexity is reduced [36][37]. Here we implement the 2D beam steering module (by cascading two diffraction gratings perpendicularly) that we studied previously [6][13]. The first grating has multiple times larger free-spectral range (FSR) than the second grating. Steering in one dimension is achieved by tuning the wavelength over less than the FSR of the first grating, whereas it is swept multiple times in the orthogonal dimension when it traverses multiple FSRs of the second grating. The location of the diffracted beams of the 2D gratings can be calculated by writing the grating equation in the x- and y-axes [38].

$$\theta_{x,m} = \sin^{-1}(\sin \theta_{x,i} - \frac{m_1 \lambda}{d_1})$$

$$\psi_{y,m} = \sin^{-1}(\sin \psi_{y,i} - \frac{m_2 \lambda}{d_2})$$

where d_1 and d_2 are the periods, m_1 and m_2 are the diffraction orders, $\theta_{x,i}$ and $\psi_{y,i}$ are the incident angles, $\theta_{x,m}$ and $\psi_{y,m}$ are the diffraction angles of grating 1 and grating 2, respectively.

We designed our 2D beam steering module by cascading a reflective blazed grating of FSR ~ 16 nm with a fused silica transmission grating of FSR ~ 125 nm perpendicularly [38]. With this arrangement we have achieved a coverage angle of $5.6^\circ \times 12.2^\circ$ corresponding to a $30 \text{ cm} \times 65 \text{ cm}$ area at a free-space distance of 3 m without angular magnification. The steering module has an optical loss of approximately 6 dB and a 3-dB pass bandwidth of approximately 10 GHz. The loss is inclusive of any end-to-end loss, including alignment and reflection losses. The spectral width is limited by the dispersion of the two gratings and the small aperture of the receiver collimator implemented to focus the narrow optical beam onto the fiber-pigtailed photoreceiver. Although the collimator has excellent efficiency, its reception angle is very limited (field-of-view $< 0.034^\circ$), thus requiring careful alignment at the receiving end. In practical bidirectional communication systems, the position of the receiver is determined by radio or optical localization techniques [20, 39, 40]. The details of the beam characterization and the optics involved are given in [38].

C. Downstream 60-GHz Radio Protection System Using an OXC and an Amplitude Modulator

Under normal operation conditions, the communication link is established by first obtaining the location of the users. This is done by implementing radio based localization techniques. The position of the user tells us the wavelength needed for the downstream optical-wireless, and the angle required for the PAA based upstream radio-wireless communications. PAAs with high overall antenna gain are implemented for the 60-GHz

upstream communication so that narrow radio beams are used to maximize the data rate per user.

Optical-wireless links are prone to link outages due to LOS blocking. To tackle this, a downstream 60-GHz radio system is implemented (employing the PAA system at the PRAs) to provide the user a lower speed alternative. When the user detects a link failure in its downstream optical-wireless path it reduces the gain of its PAA system (for example, by turning off one or more of its phased arrays) to reduce the effect of the LOS blocking in the radio domain. Compared to optical-wireless signals, because of their large footprint (especially, when the antenna gains are lower), 60-GHz signals are less susceptible to LOS issues due to reflections from walls and other materials [41]. This allows communication at lower speeds even under LOS blocking. Thus, when a LOS failure is detected, the user can notify the CCC about it via its 60-GHz upstream.

When the CCC receives a link-failure message from the user via the upstream 60-GHz radio system, it activates the downstream 60-GHz radio fallback channel. This involves tuning the wavelength so that, at the PRA, it can be reflected by the FBG and directed to the high-speed photodiode. Please note that, to avoid any tunable component at the PRAs, a fixed range of wavelengths, determined by the bandwidth of the FBG, is implemented for the up/downstream RoF system. The downstream 60-GHz radio signals are generated optically at the RG using a MZM using optical carrier suppression technique. Compared to other modulation schemes to generate mm-wave radio signals, this scheme has a simple configuration and relaxed-frequency bandwidth requirements for electrical and optical components, and results in better receiver sensitivity [27]. The OXC allows us to share this modulator among multiple PRAs in the system and to route the individual signals to the appropriate PRAs (see Fig. 2), hence enhancing the reliability of the system in a dynamic, and energy and cost efficient manner. Since the MZM can up-convert multiple signals to mm-wave frequency by using different wavelengths, it allows us to provide multiple protection channels at a time, assuming that only one user may be blocked at a time from those served by the same PRA and that the OXC supports multicast capability. When the user detects an optical signal (i.e., when the shadowing is removed), it can tell the CCC about it and the downstream optical-wireless link can be re-established. This can be done by using a separate TL (which can be shared among all the users) tuned at the appropriate wavelength for the optical-wireless communication. The TL which is being used for the 60-GHz communication could also be utilized for this purpose, however that would mean frequent tuning of the TL and reduced overall link efficiency.

We use a single drive MZM, biased at its minimum transmission point to generate the 60-GHz radio signals, although a double drive modulator could give better optical carrier suppression [42]. Neglecting the insertion loss of the OXC and modulators, and assuming infinite extinction ratio for the modulators, the output electric field of the optical signal from the second MZM (see Fig. 2) can be expressed as [43]:

$$E_o(t) = \frac{E_i(t)}{4} \cos\left(\frac{m_1 + \phi_1(t)}{2}\right) \exp\left(j \frac{m_1 + \phi_1(t)}{2}\right) \times \left[1 + \exp(jm_2) \sum_{n=-\infty}^{\infty} j^n J_n(m_3) \exp(jn\omega_{RF}t)\right] \quad (1)$$

$$\text{Here, } V_1(t) = V_{b1} + S(t), \quad m_1 = \frac{\pi V_{b1}}{V_{\pi 1}}, \quad \phi_1(t) = \frac{\pi S(t)}{V_{\pi 1}},$$

$$V_2(t) = V_{b2} + V_{RF} \cos(\omega_{RF}t), \quad m_2 = \frac{\pi V_{b2}}{V_{\pi 2}}, \quad m_3 = \frac{\pi V_{RF}}{V_{\pi 2}}$$

where, $E_i(t) = E_i \exp(j\omega_c t)$ is the output of the laser source with amplitude E_i and angular frequency ω_c , $V_{\pi 1}$ is the half-wave voltage of the first MZM biased at V_{b1} , $S(t)$ is the electrical baseband data, J_n is the first kind Bessel function of order n , $V_{\pi 2}$ is the half-wave voltage of the second MZM, V_{b2} and V_{RF} are the bias and driving voltages of the second MZM, respectively, and ω_{RF} is the angular frequency of the driving voltage. When the first MZM is biased at its linear region and the second MZM is biased at its minimum transmission point to realize OCS modulation, and considering the first harmonics only, (1) can be written as:

$$E_o(t) = A(t) \exp(j(\psi(t) - \pi/2)) \times [\exp(j(\omega_c + \omega_{RF})t) + \exp(j(\omega_c - \omega_{RF})t)] \quad (2)$$

$$\text{where } A(t) = \frac{E_i J_1(m_3)}{4} \cos(\psi(t)) \text{ and } \psi(t) = \frac{m_1 + \phi_1(t)}{2}$$

$E_o(t)$ is then routed to the target PRA using the OXC at the RG. At the PRA, the FBG reflects the signal which then passes via the AWG and received by a high-speed photodetector of responsivity R (see Fig. 2). Wavelengths known by the PRAs are implemented for the downstream radio signals to avoid any tunable component at the PRAs. The generated RF photocurrent is given by:

Fig. 4 (a) Photograph of the fabricated and wire-bonded REAM-SOA chip; (b) The packaged REAM-SOA device.

Fig. 5 (a) REAM-SOA insertion gain measurements with respect to the wavelength of the input signal with increasing REAM reverse bias voltage. (b) REAM-SOA output optical power against input optical power for input optical signal of wavelength 1530 nm.

$$i(t) = RP_{in} = R \cdot A^2(t) [2 + \cos(2\omega_{RF}t)] \quad (3)$$

The baseband signal can be filtered out by using a high-pass filter or band-pass microwave components. A 60 GHz signal can be generated by using 30 GHz as the RF frequency driving the second MZM. This signal is then transmitted via the OXC through a fiber to the PRA and further down to the user using a PAA after power amplification.

D. A REAM-SOA for indoor mm-wave RoF communication

A REAM is well known to be a key component in short-range RF-photonic links because of its benefits such as small size, low driving voltage, large bandwidth and its potential for monolithic integration with other devices [4]. By monolithically integrating an SOA with the REAM (hence, named REAM-SOA), we can compensate for the insertion loss introduced by the REAM. It has great potential for indoor mm-wave RoF applications, especially at RAPs where cost-efficiency and simplicity are critical requirements. However, a transmitter should be characterized differently for RoF applications where link RF gain and dynamic range are critical parameters, in addition to low driving voltage, large bandwidth, and low insertion loss [44]. Unlike REAMs whose analog performances are known to be sensitive to the input optical power and wavelength, experimental results show that a high link RF gain and a wide operation range can be realized by carefully driving the SOA in the REAM-SOA structure [45].

Device Fabrication and Packaging

A photograph of the fabricated and wire-bonded device is shown in Fig. 4. The REAM-SOA was fabricated in III-V Lab, Alcatel-Thales. Fabrication details and characterization using digital baseband modulation format are published in [17]. The device consists of a 400 μm long SOA monolithically integrated with a 70 μm long REAM. The active structure is composed of AlGaInAs/InP based multiple-quantum-wells (MQWs) between two InGaAsP separate confinement heterostructure layers. The contact separation between the REAM and the SOA was realized by proton implantation resulting in an inter-section resistance of $10^6 \Omega$. The SOA gain spectrum maximum was positively detuned from the REAM absorption edge in order to obtain amplification in the REAM working spectral range. The gain spectrum shift gives rise to an enhanced performance allowing larger gain and spectral ranges, and fast modulation dynamics.

We then mounted the REAM-SOA chip on a high frequency

Fig. 6 (a) REAM-SOA normalized optical transmission curve at input optical signal power of 0 dBm and SOA bias current of 50 mA when the wavelength was varied; (b) Slope of the normalized optical transmission curve at input optical powers of -10 dBm and 0 dBm, and SOA bias currents of 50 mA and 120 mA with respect to wavelength.

submount and bonded it with an RF micro-strip for electrical connection of the REAM (50 ohm impedance matched). The other side of the RF micro-strip line is connected to an RF cable using a commercially available V-flange mount connector. The SOA is bonded and connected with electrical feed-throughs in the package. The optical connection is realized with a lensed fiber. Details about the packaging of the REAM-SOA can be found in [46].

Static characteristics

We first performed static characterization of the REAM-SOA using an experimental setup described in [45]. The device combines the amplification function of an SOA and high-speed operation capability of REAM in a single device. Fig. 6a depicts the insertion loss/gain of the device when the SOA was biased at 120 mA current and input optical power was 0 dBm for different wavelengths and REAM bias voltages. Lossless

operation over a wavelength range of >40 nm was observed. For wavelengths between 1540 nm and 1560 nm an insertion gain >7.5 dB was measured. A small gain ripple is caused because of residual cavity feedback. However, we didn't see a significant performance degradation because of this. Insertion gain in excess of 20 dB is possible for low input optical power levels as demonstrated in Fig. 5b. The bandwidth of the REAM-SOA was measured to be 35 GHz.

Link RF gain

The link RF gain, g_{RF} , is a measure of the electro-optic conversion efficiency of a modulator. It is defined as the ratio of the output RF power, P_{RF}^{out} , to the input RF power, P_{RF}^{in} .

$$g_{RF} = \frac{P_{RF}^{out}}{P_{RF}^{in}} \quad (4)$$

The term link RF gain is widely adopted in the community although in most cases an analog fiber-optic link experiences a power loss instead of a gain (a loss is represented by a negative gain.) [44]. The link RF gain is determined by the modulation efficiency of the transmitter and detection efficiency of the receiver. The output RF power of an optical modulator depends quadratically on its optical transfer curve $T(V)$, which is defined as the ratio of the output optical power P_{out} to the input optical power P_{in} , as a function of the applied voltage V . In practice, $T(V)$ is usually normalized to the maximum transmission bias point. This point is conveniently chosen to be the zero bias of the REAM in the REAM-SOA device. The optical loss at zero bias point is referred to as the insertion loss (IL). Partitioning the REAM-SOA in to its modulation and amplification sections, its optical transmission curve can be expressed as

$$T(V) = \frac{P_{out}}{P_{in}} = G \exp(-\alpha(V)\Gamma L) \quad (5)$$

where G is the optical gain provided by the SOA, $\alpha(V)$ is the REAM material absorption coefficient, Γ is the absorption confinement factor, and L is the length of the REAM. The normalized optical transmission curve can be expressed as:

Fig. 7 REAM-SOA link RF gain at input optical signal of wavelength 1530 nm: (a) at input optical power of 0 dBm, and varying REAM-SOA bias currents and bias voltages; (b) at different input optical power and REAM-SOA bias currents. (c) REAM-SOA normalized transmission for input optical signal of wavelength 1530 nm and varying power when the REAM-SOA was biased at 50 mA current.

$$T_{nom}(V) = \frac{G \exp(-\alpha(V)\Gamma L)}{\beta} \quad (6)$$

where we defined,

$$\beta = T(0) = 1/I_L.$$

The received photocurrent I_R by a PD with responsivity R is expressed as

$$I_R = R P_{in} \beta T_{nom}(V) \quad (7)$$

If the REAM in the REAM-SOA is biased at V_b and the RF input signal is $v_s \sin(\omega_{RF}t + \phi)$, where ω is the angular frequency of the input signal, $T_{nom}(V)$ can be expanded by Taylor series around V_b .

$$I_R = R P_{in} \beta \sum_{n=0}^{\infty} \frac{T_{nom}^n(V_b)}{n!} (V(\omega) - V_b)^n \quad (8)$$

Taking only the first two terms and ignoring the dc component,

$$I_{RF}^{out} = R P_{in} \beta \eta_{slope}(V_b) v_s \sin(\omega_{RF}t + \phi) \quad (9)$$

where $T'_{nom}(V_b)$ is the normalized slope efficiency at V_b . The normalized slope efficiency is defined as:

$$\eta_{slope}(V) = T'_{nom}(V) = \frac{dT_{nom}(V)}{dV} \quad (10)$$

Hence, the link RF gain can be expressed as:

$$g_{RF} = 4[R P_{in} \beta \eta_{slope}(V_b)]^2 R_S R_L \quad (11)$$

where R_S and R_L are the source and load resistances, respectively.

Equation (11) shows that the link RF gain is proportional to the square of the slope efficiency of the REAM-SOA. The slope efficiency is determined by taking the first derivative of the normalized optical transfer curve. Therefore, we measured the normalized fiber-to-fiber optical transfer curve with respect to

the REAM bias voltage and performed a 7th order polynomial fitting. Fig. 6 summarizes the normalized transfer curve and the slope efficiency of the REAM-SOA for varying wavelengths, input powers, and SOA bias currents. Generally, the slope is the highest at lower input optical powers and SOA bias currents. The maximum normalized slope was $1/V$ (obtained for input wavelength of 1530 nm).

We then measured the link RF gain provided by the REAM-SOA chip. A tunable laser (TL) source at 1530 nm wavelength and an RF carrier of 20 GHz with a power of -10 dBm were used for the measurements. The link RF gain was evaluated for varying amount of input optical signal power to the REAM-SOA. The output optical signal was received and analyzed using a PIN photodiode of responsivity 1 A/W and an electrical spectrum analyzer (ESA). Fig. 8a shows the link RF gain at different SOA bias currents and REAM bias voltages for input optical signal of wavelength 1530 nm and power 0 dBm. The gain increased by 3 dB when the SOA bias current was increased from 50 mA to 100 mA because the SOA gain increased with increasing bias current (see Fig. 7b). In all the cases the gain was the maximum when the REAM was biased at -1.25 V. At constant SOA bias current, however, the optical power that reaches the REAM is stabilized because of the non-linearity of the gain provided by the SOA (when the input optical power was above -10 dBm). Hence, as shown in Fig. 8b, the RF gain stayed within 1 dB from the maximum of -25 dB. This means that strict control and tracking of the optical input power is not necessary, unlike in REAMs whose performances are very sensitive to the input optical power due to carrier pileup and band-filling effects [47]. This behavior is also visible in the normalized transfer curves shown in Fig. 8c (which overlap with each other when the input optical power was above -5 dBm). The SOA gives us an additional parameter, namely, its bias current to optimize the operation of the REAM-SOA.

Spurious-free dynamic range (SFDR)

One of the important performance parameters for high-speed analog communication is the SFDR [44]. It is usually assessed by performing a two tone test where two RF signals of small frequency offset modulate the optical signal. The most important distortions are the third-order intermodulation (IM3) signals due to their proximity to the fundamental signals.

Fig. 8 (a) Third-order derivative of the normalized optical transfer curve of the REAM-SOA at varying input optical power; (b) Measured fundamental (fund.) and third-order intermodulation (IM3) signals at REAM bias voltages of -0.5 V and -1.25 V for RF input signal of 20 GHz frequency and -10 dBm power; (c) REAM-SOA output RF power vs input RF power for input RF signal of 20 GHz frequency; for input optical signal of wavelength 1530 nm.

Fig. 9 Experimental setup using a 4×4 OXC chip at the RG for dynamic routing, a 2D gratings module at the PRA for optical beam steering to users in the downstream, and a REAM-SOA chip at the PRA for upstream SCM-RoF transmission (inset: spectrum of upstream multiplexed radio signals).

Referring to (8), the output photocurrent is expressed by the Taylor series expansion around the REAM bias voltage V_b as:

$$I_R = R P_{in} \beta \left\{ T_{norm}(V_b) + \sum_{n=1}^{\infty} \frac{T_{norm}^{(n)}(V_b)}{n!} (V(\varpi) - V_b)^n \right\} \quad (12)$$

where $V(\varpi)$ is the voltage applied to the REAM. $V(\varpi) = V_b + v_s \sin(\varpi_1 t + \phi_1) + v_s \sin(\varpi_2 t + \phi_2)$ is applied to the REAM to determine the SFDR. Taking only the third order components to determine IM3 signals we get,

$$IM3_{2f_1-f_2} = R P_{in} \beta v_s^3 \frac{T_{norm}^{(3)}(V_b)}{24} \sin[(2\varpi_1 - \varpi_2)t + (2\phi_1 - \phi_2)] \quad (13)$$

The SFDR is defined as the output signal to noise ratio (SNR) as the IM3 starts to emerge above the noise floor. We can see from (13) that the IM3 can be minimized and a high SFDR can be achieved if the REAM-SOA is biased at the null point of the third-order derivative of the transfer curve [44]. Fig. 8a plots the third-order derivatives of the measured normalized transfer curves (shown in Fig. 9c) of the REAM-SOA at different input optical powers. The third-order null points of the REAM-SOA are almost independent of input optical power when the input power was above -6 dBm. Fig. 8b presents the SFDR of the REAM-SOA under two REAM bias conditions, -1.25 V and -0.5 V, corresponding to the maximum link RF gain and the zero of the third-order derivative of the transfer curve, respectively. By biasing the REAM at -0.5 V instead of -1.25 V a 15 dB improvement in the SFDR (from 88 dB.Hz^{2/3} to 103 dB.Hz^{4/5}) could be obtained, with about 4 dB reduction in the link RF gain. Additionally, a fifth-order dependence on the input RF power can be seen in the IM3 distortion at this biasing condition [48]. Increasing the SOA bias current also improved the dynamic range as shown in Fig. 7a. Hence, higher SFDR can be obtained by increasing the bias current of the SOA.

RF saturation phenomena are anticipated due to the nonlinear characteristic of the transfer curve of the REAM-SOA. Fig. 8c depicts the output RF power versus the input RF power under different REAM-SOA input optical powers. The 1-dB compression point was found to be -1 dBm.

Fig. 10 Optical spectrum of the mm-wave downstream fallback signal.

III. EXPERIMENTAL DEMONSTRATION AND RESULTS

A data transmission experiment was carried out using the proof-of-concept setup shown in Fig. 9. For downstream optical-wireless communication, at the RG, an optical carrier of wavelength 1540 nm from a TL source was modulated by a 10 GHz wide DMT data from an arbitrary waveform generator (AWG) using a MZM modulator. A 4×4×4λ OXC chip was used to route downstream signals to the intended PRAs. The OXC chip was a broadcast and select switch consisting of a 1:N splitter, a wavelength selective switch (WSS) and an N:1 combiner on each path. Each WSS comprises SOA-gate switches and arrayed waveguide gratings to select one or more wavelength channels and forward them to the output ports according to the control signals. The downstream wavelength was chosen taking the output spectra of the OXC chip into consideration. The details about the design, fabrication process and characterization of the OXC chip are explained in [49]. The OXC chip was controlled to achieve the desired switching of the downstream optical-wireless signal to the intended output port by activating the SOA-gate to this port. The signal was then launched into a 1 km single-mode optical fiber. The erbium doped fiber amplifier (EDFA) implemented at the output port of the OXC chip compensated the total transmission losses including the 10 dB loss by the OXC chip at the RG and the 6 dB loss in the wireless link (the 2D gratings at the PRA and all coupling and alignment optics involved). The 2D grating steered the optical-wireless signal to a PIN+TIA photoreceiver located at a free-space distance of 2.5 m. Although we performed the experiment for a free-space distance of 2.5 m, the

Fig. 11 Downstream experimental results: (a) Achievable optical-wireless data rates at different received optical powers when the optical-wireless data was routed through two output ports (corresponding to two PRAs); (b) SNR, bit-loading profile and BER of the downstream optical-wireless and mm-wave RoF transmissions (please note that the bandwidth of the optical and radio wireless signals were 10 GHz and 6 GHz, respectively).

performance variation is negligible within a typical indoor scenario (room size <10 m) since collimated narrow beams (beam waist about 3.3 mm) were implemented for the communication. Our technology is primarily meant for indoor line-of-sight applications. Losses may become significant for non-line-of-sight transmission, and for outdoor applications during adverse atmospheric conditions.

In the upstream, an optical carrier of 1529 nm wavelength sent from a distributed-feedback (DFB) laser source at the RG and reflected by an FBG (5 nm bandwidth at 1530 nm) at the PRA was modulated by the radio signals using a REAM-SOA chip and sent back to the RG. Because our REAM-SOA has a bandwidth of 35 GHz, we implemented SCM to combine several 7 GHz-wide bands into the REAM-SOA's bandwidth, which was done by down-converting the 60-GHz RF bands separately using local oscillators and mixers. As a proof-of-concept, at the PRA an arbitrary waveform generator was used to generate two radio data signals (of bandwidth 6 GHz) with DMT modulation. One of the radio data signals was up-converted to 13 GHz and combined with the other radio data signal to form a subcarrier multiplexed radio signal (see the inset of Fig. 9). Using the REAM-SOA, the multiplexed signal then modulated the optical carrier sent from the RG. The input optical power to the REAM-SOA was -5 dBm.

We also evaluated the performance of the 60-GHz radio protection channel. When there is a LoS blocking in the optical-wireless path, the TL serving the user will be tuned to a different

wavelength (known by the PRA, as described in section II.C) and the OXC chip will be configured to switch the signal to the output port to which the 60-GHz generator is connected by activating the appropriate gating SOAs using the FPGA. In this experiment, we tuned the wavelength of the TL source to 1532 nm so that it can be reflected by the FBG. We also reduced the bandwidth of the DMT wireless data to 6 GHz to be within the 7-GHz unlicensed bandwidth limit for 60-GHz radio signals. The signal was then modulated by a 30 GHz tone using a single-drive MZM modulator employing optical carrier suppression technique. The input port of the MZM modulator was connected to one of the output ports of the OXC chip while its output port was connected to one of the input ports of the OXC chip (see Fig. 9). This configuration allows us to share the MZM modulator among multiple users. Optical carrier suppression ratio of >18 dB was achieved as shown in Fig. 10.

At the PRA, the FBG separates the upstream optical carrier (which is sent from the RG) and the 60-GHz radio signals from the optical-wireless signals from was sent to the 2D gratings for beam steering to the user. The FBG reflects the upstream CW wavelength and the downstream 60-GHz radio signal, which are then separated from each other by an arrayed waveguide gratings. While the mm-wave signal was received by a 70-GHz photodiode and analyzed by a digital phosphor oscilloscope, the CW wavelength was sent to the REAM-SOA to carry the SCM upstream radio signal to the RG.

We first determined the optimum operation conditions for the OXC chip. To minimize the losses incurred the booster SOA in the OXC chip was biased at 100 mA while any gating SOA would be biased at 40 mA when it had to be active to achieve the desired switching. Under this condition, the optimum optical input power to the OXC chip was measured to be 0 dBm. This was because higher ASE noise for lower input optical powers and SOA gain saturation for higher input powers limit the dynamic range. The achievable data rates for the optical-wireless link are illustrated in Fig. 11a with respect to the received optical powers for an average bit-error-rate (BER) $<1 \times 10^{-3}$. The OXC chip introduced a 3 dB penalty at a data rate of 34 Gb/s. The optical fiber and free-space links resulted in a reduction of <1 Gb/s in the achievable data rate (or, correspondingly, a 2 dB power penalty) partly due to the noise

Fig. 12 SNR, bit-loading profile and BER of the upstream radio signals.

from the EDFA and other components in the path and partly due to imperfections from the free-space optics. Switching to a different output port of the OXC chip (corresponding to a different PRA) introduced negligible difference on the achievable data rate as shown in Fig. 11a.

In our experiment, we implemented a collimated beam with a diameter of approximately 3.3 mm. The collimator's field-of-view is $<0.0340^\circ$, thus requiring careful alignment at the receiving end using an automated beam alignment system. This resulted in a maximum received power of +4 dBm at the user terminal when an optical signal of power +10 dBm (which is the ANSI-Z136 recommended transmitted power limit for eye-safe infrared wireless transmission of wavelength above 1400 nm) is transmitted. In practical deployments of such a system, where user alignment is not perfect, receivers with a larger field-of-view are necessary, together with accurate user localization, to significantly reduce the optical losses that arise from imperfections in beam alignment. Moreover, an SOA-pre-amplified receiver or an avalanche photodiode receiver can be implemented to tackle excess power losses.

At an average BER of 1.24×10^{-3} , the maximum transmission rate achieved using the downstream mm-wave radio backup channel was 20 Gb/s. A 4 Gb/s reduction was observed in the maximum bit-rate compared to the back-to-back case which was 25 Gb/s because of the ASE noise of the SOAs in the OXC chip and penalties due to the 60-GHz radio conversion process. The signal-to-noise ratios (SNRs), bit-loading profiles and BERs for the downstream optical-wireless and RoF transmissions are shown in Fig. 11b. It should be noted that the bandwidth of the radio wireless signal was 6 GHz which is within the 7-GHz unlicensed bandwidth limit for 60-GHz radio communication.

Aggregated transmission capacity of 35 Gb/s was achieved for the SCM radio signal at an average BER of 7.2×10^{-4} . The achievable data rate for the radio signal at the baseband was 17 Gb/s while the radio signal at 13 GHz frequency achieved a transmission rate of 18 Gb/s. The slight difference in the performance was due to the bias-T included for biasing the REAM-SOA modulator which resulted in some subcarriers near the dc in the DMT data of the radio signal at the baseband to be turned off by the bit-loading algorithm as illustrated in the SNR, bit-loading profile and BER per subcarrier plot in Fig. 12.

IV. CONCLUSION

We presented a concept of indoor wireless network employing a low-power fast-switching optical chip that combines optical and 60-GHz radio wireless techniques to provide highly dynamic, reliable and ultimate capacities per user. We employed a 2D optical beam steering module by orthogonally cascading two diffraction gratings. The steering is remotely controlled by wavelength-tuning of the signal. This is the first time, to the best of our knowledge, that such a high-capacity indoor system, with various aspects, has been demonstrated. >35 Gb/s bidirectional transmission rates were achieved using our current infrastructure. Our solution is scalable to handle more users demanding more bandwidth, which is a subject of on-going work.

One CW laser source is used at the RG to remotely feed the PRAs for upstream SCM-RoF communication using a REAM-SOA, hence making the PRAs simpler. The REAM-SOA, combines high-speed capabilities of a REAM with the amplification functions of an SOA in a single device. Unlike REAMs, analog performance of the REAM-SOA stays largely unaffected by input optical signal power and wavelength variations as the SOA also acts as stabilizer for the REAM. This alleviates the need for accurate control of the input signal, especially at RAPs, where simplicity and cost-efficiency are critical requirements.

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