Crosstalk-mitigated AWGR-based two-dimensional IR beam-steered indoor optical wireless communication system with a high spatial resolution

Citation for published version (APA):

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain.
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.
Crosstalk-Mitigated AWGR-Based Two-Dimensional IR Beam-Steered Indoor Optical Wireless Communication System With a High Spatial Resolution

Xuebing Zhang, Student Member, IEEE, Chao Li, Yuqing Jiao, Member, IEEE, Eduward Tangdiongga, Member, IEEE, Yu Liu, Zizheng Cao, Member, IEEE, and Ton Koonen, Fellow, IEEE, Fellow, OSA

Abstract—In this paper, a crosstalk-mitigated transmission scheme in arrayed waveguide grating router (AWGR) based two dimensional infrared beam-steered optical wireless communication (OWC) system is proposed for indoor applications. By creating polarization orthogonality between the odd and even AWGR channels, high crosstalk tolerance between spectrally overlapping AWGR channels is realized experimentally. Because two signals with orthogonal polarization states will not beat with each other in a photodiode. The optical crosstalk on the orthogonal polarization state will not generate a beat note upon detection and thus crosstalk in the electrical domain can be largely reduced. Reduced crosstalk leads to a reduction in the required spectral guard band and/or an improved tolerance to spectral overlap, which allows higher spectral efficiency. Moreover, the port number of an AWGR can be increased by simply shortening the spatial gap between adjacent output waveguides on a chip. The higher port number can support the high spatial resolution of the steered OWC system. This technique can also tolerate the wavelength misalignment between AWGRs and lasers, which relaxes the design of low crosstalk AWGRs and high wavelength stable lasers. A 20 Gbit/s data rate, four-level pulse amplitude modulation OWC transmission has been experimentally demonstrated over 1.2-m free-space link. The experimental results show that the proposed scheme can maintain stable, low crosstalk impact with an apparent improvement of the responsivity.

I. INTRODUCTION

To satisfy the exponential bandwidth increase in indoor networks, beam-steered indoor infrared (IR) light optical wireless communication (OWC) employing narrow pencil beams is attracting increasing interest [1]–[4]. The IR spectrum is license-free and its wide frequency range offers a potentially large capacity. The steered free-space narrow IR beam brings the light only where and when needed, and offers non-shared connections [1]. So far many techniques have been reported to steer the free-space narrow IR beam, such as the microelectromechanical system (MEMS)-based mirrors [5], the miniaturized silicon integrated photonic circuit [6], or spatial light modulators (SLM-s) [7]–[9]. Each beam can carry 10 Gbit/s or more but requires a separate steering element. A. M. J. Koonen et al. propose the passive beam-steering modules which are based on two orthogonal gratings which enables 2-dimensional (2-D) beam steering by just tuning the wavelength of each beam [10]. Similarly, an easier assembling and less alignment passive-steering scheme: the λ-controlled 2-D IR beam steering system using a high port-count arrayed waveguide grating router (AWGR), has been proposed and experimentally demonstrated [2]. As the λ-routing component, the AWGR module determines the spatial resolution and spectral efficiency (the available optical bandwidth) in the beam steering system. Fig. 1(a) shows the regular MZM-based 2-D IR beam steering system. Each beam carry 10 Gbit/s or more but requires a separate steering element. A. M. J. Koonen et al. propose the passive beam-steering modules which are based on two orthogonal gratings which enables 2-dimensional (2-D) beam steering by just tuning the wavelength of each beam [10]. Similarly, an easier assembling and less alignment passive-steering scheme: the λ-controlled 2-D IR beam steering system using a high port-count arrayed waveguide grating router (AWGR), has been proposed and experimentally demonstrated [2]. As the λ-routing component, the AWGR module determines the spatial resolution and spectral efficiency (the available optical bandwidth) in the beam steering system. Fig. 1(a) shows the regular MZM-based 2-D IR beam steering system. Each beam carry 10 Gbit/s or more but requires a separate steering element. A. M. J. Koonen et al. propose the passive beam-steering modules which are based on two orthogonal gratings which enables 2-dimensional (2-D) beam steering by just tuning the wavelength of each beam [10]. Similarly, an easier assembling and less alignment passive-steering scheme: the λ-controlled 2-D IR beam steering system using a high port-count arrayed waveguide grating router (AWGR), has been proposed and experimentally demonstrated [2]. As the λ-routing component, the AWGR module determines the spatial resolution and spectral efficiency (the available optical bandwidth) in the beam steering system. Fig. 1(a) shows the regular MZM-based 2-D IR beam steering system. Each beam carry 10 Gbit/s or more but requires a separate steering element. A. M. J. Koonen et al. propose the passive beam-steering modules which are based on two orthogonal gratings which enables 2-dimensional (2-D) beam steering by just tuning the wavelength of each beam [10]. Similarly, an easier assembling and less alignment passive-steering scheme: the λ-controlled 2-D IR beam steering system using a high port-count arrayed waveguide grating router (AWGR), has been proposed and experimentally demonstrated [2]. As the λ-routing component, the AWGR module determines the spatial resolution and spectral efficiency (the available optical bandwidth) in the beam steering system. Fig. 1(a) shows the regular MZM-based 2-D IR beam steering system. Each beam carry 10 Gbit/s or more but requires a separate steering element. A. M. J. Koonen et al. propose the passive beam-steering modules which are based on two orthogonal gratings which enables 2-dimensional (2-D) beam steering by just tuning the wavelength of each beam [10]. Similarly, an easier assembling and less alignment passive-steering scheme: the λ-controlled 2-D IR beam steering system using a high port-count arrayed waveguide grating router (AWGR), has been proposed and experimentally demonstrated [2]. As the λ-routing component, the AWGR module determines the spatial resolution and spectral efficiency (the available optical bandwidth) in the beam steering system. Fig. 1(a) shows the regular MZM-based 2-D IR beam steering system. Each beam carry 10 Gbit/s or more but requires a separate steering element. A. M. J. Koonen et al. propose the passive beam-steering modules which are based on two orthogonal gratings which enables 2-dimensional (2-D) beam steering by just tuning the wavelength of each beam [10]. Similarly, an easier assembling and less alignment passive-steering scheme: the λ-controlled 2-D IR beam steering system using a high port-count arrayed waveguide grating router (AWGR), has been proposed and experimentally demonstrated [2]. As the λ-routing component, the AWGR module determines the spatial resolution and spectral efficiency (the available optical bandwidth) in the beam steering system. Fig. 1(a) shows the regular MZM-based 2-D IR beam steering system. Each beam carry 10 Gbit/s or more but requires a separate steering element. A. M. J. Koonen et al. propose the passive beam-steering modules which are based on two orthogonal gratings which enables 2-dimensional (2-D) beam steering by just tuning the wavelength of each beam [10]. Similarly, an easier assembling and less alignment passive-steering scheme: the λ-controlled 2-D IR beam steering system using a high port-count arrayed waveguide grating router (AWGR), has been proposed and experimentally demonstrated [2]. As the λ-routing component, the AWGR module determines the spatial resolution and spectral efficiency (the available optical bandwidth) in the beam steering system. Fig. 1(a) shows the regular MZM-based 2-D IR beam steering system. Each beam carry 10 Gbit/s or more but requires a separate steering element. A. M. J. Koonen et al. propose the passive beam-steering modules which are based on two orthogonal gratings which enables 2-dimensional (2-D) beam steering by just tuning the wavelength of each beam [10].
and most importantly it is remotely tuning scheme which benefits the centralized network management. Also, it well matches to the current wavelength division multiplexing system [1]. With the increase of spatial resolution and transport capacity, a higher port-count and larger channel bandwidth AWGR becomes the key element. Considering that the usable spectral range is limited (e.g., 35 nm for C band), the spatial resolution is compromised with channel bandwidth. Fig. 1(b) presents the normal AWGR response. It is clear that the most direct way of adding port-count is to reduce the channel spacing. But, to avoid the inter-channel crosstalk, a spectral guard band is inserted between adjacent AWGR channels, which inevitably causes a waste of spectral resources. Thus the channel bandwidth is also shrunk. Currently, the available solution is to reduce the AWGR channel grid (e.g., from a 50-GHz grid to 12.5-GHz grid) and at the same time, to shape the channel response from ‘Gaussian’ to ‘Flat-top’ to increase the available channel bandwidth as depicted in Fig. 1(c) [11]–[15]. The 1-dB bandwidth can be extended from 31% to >65% of channel spacing [11]. Nevertheless, this ‘Flat-top’ design leads to higher crosstalk which requires larger guard band between adjacent channels to mitigate, thus the improved spectral efficiency is weakened again.

In order to solve these problems, the following concept is proposed. By creating polarization orthogonality between the odd and even channels, a very high crosstalk tolerance between spectrally overlapping AWGR channels can be realized because two signals with orthogonal polarization states will not beat with each other upon the detection. The signal with the crosstalk on orthogonal polarization state will not generate a mixing product upon the detection. The signal with the crosstalk on orthogonal polarization state will not beat with each other upon the detection. The signal with the crosstalk on orthogonal polarization state will not generate a mixing product upon the detection. The signal with the crosstalk on orthogonal polarization state will not beat with each other upon the detection. The signal with the crosstalk on orthogonal polarization state will not generate a mixing product upon the detection. The signal with the crosstalk on orthogonal polarization state will not beat with each other upon the detection. The signal with the crosstalk on orthogonal polarization state will not generate a mixing product upon the detection. The signal with the crosstalk on orthogonal polarization state will not beat with each other upon the detection. The signal with the crosstalk on orthogonal polarization state will not generate a mixing product upon the detection. The signal with the crosstalk on orthogonal polarization state will not beat with each other upon the detection. The signal with the crosstalk on orthogonal polarization state will not generate a mixing product upon the detection. The signal with the crosstalk on orthogonal polarization state will not beat with each other upon the detection. The signal with the crosstalk on orthogonal polarization state will not generate a mixing product upon the detection.

II. OPERATING PRINCIPLES

In traditional IR beam-steered OWC systems, the signal that is fed into the AWGR module is not specially polarization-designed and non-spectrally-overlapped to avoid the inter-channel crosstalk of an AWGR. To improve the spectral efficiency and the high port-count of the AWGRs, the crosstalk mitigated method is presented. Fig. 2 shows the operating principle. Usually, the low-cost IM-DD method with one polarization state is utilized [2]. In the proposed scheme, the input signal is split into two groups: even and odd channels according to the spectral response of the AWGR as shown in Fig. 2(a) and (b). The adjacent channels are set to be spectrally overlapped to show the crosstalk. While the polarization states of even and odd groups are orthogonally enabled by a polarization beam combiner (PBC). Fig. 2(a)–(c) present the spectra before and after the PBC. Due to the filtering of the AWGR, the signal is \( \lambda \)-split and then steered to different directions by a lens. For the channels of \( \lambda_n \) and \( \lambda_{n+1} \), they contain the target signal and the so-called optical ‘crosstalk’ from adjacent channels with the orthogonal polarization state as shown in Fig. 2(d)–(e). The received signal is detected by a photodiode and the photocurrent can be presented as (for a unity responsivity detector)

\[
I_n = |E_{c,n,x} + E_{s,n,x} + \tilde{E}_{c,n+1,y} + \tilde{E}_{s,n+1,y} + \tilde{E}_{c,n-1,y} + \tilde{E}_{s,n-1,y}|^2
\]

where, \( E_{c,n,x} \) and \( E_{s,n,x} \) is the carrier and signal in \( nth \) (with x-polarization state) channel, respectively. \( \tilde{E}_{c,n+1,y} \) and \( \tilde{E}_{s,n+1,y} \), \( \tilde{E}_{c,n-1,y} \) and \( \tilde{E}_{s,n-1,y} \) are the crosstalk (including carriers and signals with y-polarization state) from \( (n+1)th \) and \( (n-1)th \) channels. Because two orthogonal polarization states do not affect each other upon detection, we have

\[
I_n = |E_{c,n,x} + E_{s,n,x}|^2 + |\tilde{E}_{c,n+1,y} + \tilde{E}_{s,n+1,y} + \tilde{E}_{c,n-1,y} + \tilde{E}_{s,n-1,y}|^2
\]
Fig. 2. The operating principle of the AWGR-based 2-D IR beam steering no-crosstalk transmission scheme: (a) the input optical spectrum of the PBC even channel; (b) the input optical spectrum of PBC odd channel; (c) the combined optical spectrum after PBC; (d)-(e) the optical spectrum of channel n and n + 1; (f)-(g) The electrical spectra of detected photocurrent. Tun. LD: tunable laser; PBC: polarization beam combiner; PD: photodiode.

\[
\begin{align*}
&= |E_{c,n,x}|^2 + |E_{s,n,x}|^2 + 2Re(E_{s,n,x}E_{c,n,x}^*) \\
&+ |\tilde{E}_{c,n+1,y}|^2 + |\tilde{E}_{s,n+1,y}|^2 + 2Re(\tilde{E}_{s,n+1,y}\tilde{E}_{c,n+1,y}^*) \\
&+ |\tilde{E}_{c,n-1,y}|^2 + |\tilde{E}_{s,n-1,y}|^2 + 2Re(\tilde{E}_{s,n-1,y}\tilde{E}_{c,n-1,y}^*) \\
&+ 2Re(\tilde{E}_{s,n+1,y}\tilde{E}_{c,n-1,y}^*) + 2Re(\tilde{E}_{s,n-1,y}\tilde{E}_{c,n+1,y}^*) \\
&+ 2Re(\tilde{E}_{c,n+1,y}\tilde{E}_{c,n-1,y}^*) + 2Re(\tilde{E}_{c,n-1,y}\tilde{E}_{c,n+1,y}^*) \\
&+ 2Re(\tilde{E}_{c,n+1,y}\tilde{E}_{c,n+1,y}^*) \\
&+ 2Re(\tilde{E}_{c,n-1,y}\tilde{E}_{c,n-1,y}^*) \\
&= |E_{c,n,x}|^2 + |E_{s,n,x}|^2 + 2Re(E_{s,n,x}E_{c,n,x}^*)
\end{align*}
\]

From the final expression of the photocurrent, the first item \(|E_{c,n,x}|^2\) is the DC generated by the target carrier, which does not affect the signal. The second item \(|E_{s,n,x}|^2\) is the inherent signal-to-signal beat interference (SSBI) generated by the target signal, and the third item \(2Re(E_{s,n,x}E_{c,n,x}^*)\) is the recovered signal. The SSBI item is noise that reduces the signal-to-noise ratio of the system. In a typical IM-DD system, the optical carrier is high-power-biased to suppress itself inherent SSBI [16], [17]. Thus \(E_{c,n,x} \gg E_{s,n,x}\). The other items are crosstalk, in which the DC components of \(|\tilde{E}_{c,n+1,y}|^2\) and \(|\tilde{E}_{c,n-1,y}|^2\) are easy to be removed. Due to the filtering of the AWGR, the cross signal is smaller than the target signal \((E_{c,n,x} > E_{s,n+1,y}; E_{c,n,x} > E_{s,n-1,y})\). The cross SSBI items of \(|\tilde{E}_{s,n+1,y}|^2\) and \(|\tilde{E}_{s,n-1,y}|^2\) are also suppressed to a very low level that can be neglected. Similarly, \(2Re(\tilde{E}_{s,n+1,y}\tilde{E}_{c,n-1,y}^*)\) can be ignored. \(2Re(\tilde{E}_{c,n+1,y}\tilde{E}_{c,n-1,y}^*)\) is located at the frequency of twice channel spacing, which will not impact the baseband signal. In addition, the cross carriers (the central wavelengths) are filtered to very low power compared to the target carrier \((E_{c,n,x} \gg E_{c,n+1,y}; E_{c,n,x} \gg E_{c,n-1,y})\). The left four beating crosstalk items, are at least 20-dB lower than the target signal component \(2Re(E_{s,n,x}E_{c,n,x}^*)\). Therefore, compared to the traditional IM-DD system, all electrical crosstalk items can be controlled at a very limited level. For \(\lambda_{n+1}\) channel, the similar results can be obtained.

III. ADVANTAGES AND DISCUSSIONS

By introducing the crosstalk-mitigated transmission method into the AWGR-based IR steered OWC system, many improvements and technical advantages can be obtained.

A. Spectral Efficiency Improvement

Fig. 3(a) presents the spectral response of a commercial AWG [18]. The crosstalk limit is −28 dB and the measured 3-dB bandwidth is 6 GHz. From 1549.85 nm to 1550.2 nm, there are three AWG channels with 12.5-GHz channel spacing. Usually, the energy of a signal is mainly in the passband (e.g., 3-dB bandwidth) but there is still spectrum leakage such as the sideband of the signal and the frequency offset of the signal in real communication systems. To reduce crosstalk (here is −28 dB), the spectral guard band should be large enough, which inevitably causes a waste of spectral resources. However, by creating polarization orthogonality between the odd and even channels, the so-called optical crosstalk can be mitigated in the electrical domain with largely reduced guard band as presented in Fig. 3(b). In order to suppress the crosstalk components, the adjacent cross carriers should be highly suppressed, here the −28-dB suppression ratio is maintained. With the decrease of the inter-channel spectral guard band, the optical crosstalk will increase. The crosstalk is reduced to −6 dB. For the traditional method, this optical crosstalk cannot be canceled but using a large guard band. However, for the proposed orthogonally-designed scheme, crosstalk can be neglected. It is clear that the available 3-dB bandwidth is not reduced when decreasing the channel spacing to 8.7 GHz, which means higher spectral efficiency (an increase from ~48% to ~69%). Meanwhile, the compact spectrum can support a higher port-count AWGR, which directly increases the spatial resolution of the IR steered OWC system. In Fig. 3(b), an extra port can be added within the same spectral region of 0.45 nm.
Fig. 3. (a) The traditional AWGR response with large spectral guard band; (b) The Guard-band-reduced AWGR response for crosstalk-mitigated IR beam-steering system. Besides, the 3-dB bandwidth can be further extended when the flat-top design is utilized, which potentially allows higher spectral efficiency.

B. A Low-Complexity Solution of the High Port-Number AWGR

Fig. 4(a) shows the mask layout of an AWG. The AWGR contains input and output waveguides, free propagation region (FPR) and the arrayed waveguides [10], [19], [20]. The tapered waveguides are utilized between typical narrow waveguides and FPR to obtain the proper input/output apertures. The input light is firstly fed into the FPR and the light will propagate in this slab waveguide and couples into the arrayed waveguides as shown in the left inset figure. Through a set of arrayed waveguides with constant length difference which determines the diffraction order of the grating, the light field distribution at the input aperture will be recovered in the image plane according to the wavelength as described in the right inset figure [10]. As presented in Fig. 4(b), the input mode profile will finally image on the image plane. And because the focus field has a certain width, the single-wavelength light may couple into adjacent output waveguides (or even father waveguides) when the gap is not large enough, which causes the spectral crosstalk. Thus the gap in current AWGRs is not too small to move closer.

Generally speaking, a higher port-count AWGR design has many requirements such as a larger FPR, more arrayed waveguides, a higher diffraction order, and so on [10]. So using the widely proved AWGR design (layout and parameters) can reduce complexity and improve reliability. In AWGR design, reducing the spatial distance between input/output waveguides on the image plane is the direct way to increase port-count. Fortunately, for the proposed method, higher optical crosstalk is not a problem anymore. Although the same AWGR layout is used, the port number can be further increased by reducing the gap between I/O waveguides. Thus the well-established AWGR design can be still used for adding more I/O ports, without causing extra designing and fabricating problems, which provides a low-complexity solution of the high port-count AWGR.

C. Wavelength Misalignment

The wavelength misalignment between the AWGR and the laser is an important factor that may affect system performance. It is caused by many reasons such as the laser wavelength shifting, AWGR’s thermal instability and the mismatch due to
fabrication error. The frequency mismatch can be up to several GHz [18] (e.g., Kylia AWG/25 GHz, the channel center offset 1.25 GHz and thermal offset ~6.25 GHz). For a large channel spacing (100 GHz or 200 GHz), the impact is very limited. But when the channel spacing becomes smaller (e.g., 25 GHz or 50 GHz), the performance will be sensitive to such wavelength mismatch. The proposed crosstalk-mitigated is a promising scheme that can solve this problem.

IV. EXPERIMENTAL SETUP AND PARAMETERS

Fig. 5(a) shows the schematic setup. For the experimental demonstration of the proposed scheme, the 4-level pulse amplitude modulation (PAM-4) signal is used. Three adjacent AWGR channels (1549.92 nm, 1550.02 nm, and 1550.12 nm) named Ch7 to Ch9 are utilized, in which Ch8 will be detailed discussed. For the two side channels, two individual tunable lasers (LD-1 and LD-2) are combined through an optical coupler (OC) and then are fed into the same MZM-1 driven by PAM-4 signal. The central channel utilizes a third LD (LD-3) and the second MZM (MZM-2) to de-correlate adjacent signals. The PAM-4 signal is generated by an arbitrary waveform generator (AWG) running at 10 GSa/s, and amplified by electrical amplifiers (EA). The double-sideband main lobe bandwidth and the data rate is 20 GHz and 20 Gbit/s, respectively. The modulated signal is λ-switched to two input ports of a PBC, which carry the odd and even channels of the AWGR. The combined signal is amplified by an EDFA. Then the specially designed signal is split into different channels and sent to a 1.2-m free-space link (~2.5-dB loss) via a collimator. The receiver consists of a combiner followed by a commercial avalanche photodiode (APD, DSC-R402). The variable optical attenuator (VOA) is only for measuring performance, which is removed in the real applications. The detected signal is sampled by a digital phosphor oscilloscope (DPO) at a sampling rate of 25 GSa/s. Fig. 5(b) shows the optical spectra before and after the AWGR. 

W. EXPERIMENTAL RESULTS AND DISCUSSIONS

A Gaussian-shaped commercial AWGR is used to evaluate the effectiveness of our crosstalk-mitigated transmission scheme as shown in Fig. 6(a). The AWGR has 12.5-GHz channel spacing with the 6.7-dB loss. Three channels are selected for the experiment, and the used optical carrier is set at the center of each channel. For the two adjacent carriers, the measured crosstalk into Ch8 is ~36.4 dB (Ch7) and ~27.3 dB (Ch9), respectively, which is well matched to the crosstalk in Fig. 5(b). Then we fix the wavelengths and 10-GBaud/s modulation baud rate in our measurement. By changing received optical power, the bit error rate (BER) versus received power curves are measured to evaluate system performance. To discuss the relationship between crosstalk and polarization state, an OC is employed as a combiner before AWGR. An extra PC is introduced to shift the relative polarization state to the same or orthogonal state. The results are shown in Fig. 6(b). It is clear that the crosstalk is rather high when adjacent channels have the same polarization state, which is much higher than that has an orthogonal state. There is an apparent error flow in the curve and BER is maintained at a high level (7 × 10⁻² ~ 2 × 10⁻²). For the orthogonal state, the crosstalk is largely reduced and thus BER is improved to ~ 5 × 10⁻⁴, which allows a 20-Gbit/s data transmission. This proves that the orthogonal polarization state can largely mitigate crosstalk. But, because OC is polarization sensitive to external interference, which cannot enable stable crosstalk mitigation. The PBC is used in our scheme, and its performance is measured as well. From the results, using PBC has a very close BER performance to the orthogonal case. Moreover, we also compare the crosstalk mitigation method with that with no crosstalk (turn off Ch7 and Ch9). A very limited BER decrease is obtained, which means the vast majority of crosstalk is mitigated. To further validate the effectiveness of this method, the more intuitive evidence (received electrical spectra) is presented in Fig. 6(c). The red one is our transmitted PAM-4 signal, and after the transmission, the received signal (cyan) is filtered mainly by the AWGR. When turning off Ch8, a very high crosstalk component (blue) can be obtained, which causes the performance drop.
However, after the crosstalk mitigation, the crosstalk component is a little bit higher than the no crosstalk case.

Different modulation rates are explored as shown in Fig. 7. 10 GBaud/s, 8 GBaud/s, and 6 GBaud/s is measured separately. The BER performance of the PBC system improves along the decrease of baud rate, obtaining 3-dB (from 10 GBaud/s to 8 GBaud/s) and 2.2-dB (from 8 GBaud/s to 6 GBaud/s) receiver responsivity improvement at the BER level of $1 \times 10^{-3}$, respectively. This improvement is mainly due to the weaker AWGR filtering, which allows less signal distortion. In contrast, the improvement without crosstalk mitigation is very limited. Actually, the performance improvement in cases with crosstalk mitigation is much faster than that without mitigation when signal bandwidth is reduced. Fig. 7(b) depicts the optical spectra under cases of Ch8-on/-off using different bandwidth. For 10-GBaud/s PAM-4 signal, the crosstalk comes from both the main lobe and the first side lobe of two adjacent PAM-4 signal bands. The crosstalk of the 8-GBaud/s signal is mainly caused by the two first side lobes. While the source of crosstalk in the 6-GBaud/s system is the first and second side lobes.

Two 4.4-GHz electrical filters are introduced before electrical amplifiers to analyze the influence of side lobes of the PAM-4 signal. As shown in Fig. 8(c), the insets are the transmitted electrical spectra with and without the filter. After filtering, the side lobes of the PAM-4 signal is reduced but the main lobe has little impact. For each condition, the same and orthogonal polarization state setting is measured, respectively as shown in Fig. 8(a). When the filter is applied, the BER versus received power performance without crosstalk mitigation is improved from $\sim 6 \times 10^{-3}$ to $\sim 3 \times 10^{-4}$ at $-11$-dBm power level. In contrast, the performance with crosstalk mitigation has a responsivity decrease of $\sim 0.1$ dB, which is caused by the impact of slightly filtering. Fig. 8(b) describes the optical spectra with and without the filter. $\sim 9.7$-dB crosstalk drop is achieved due to the filtering. The detailed electrical spectra are presented in Fig. 8(c). It is clear that the filter reduces some crosstalk. However, the residual crosstalk still apparently reduces the transmission performance compared with the proposed crosstalk mitigation method, especially in the high signal-to-noise region (high received power).
VI. CONCLUSION

The current AWGR-based OWC systems have a low spectral efficiency, which limits the user counts considerably. In this paper, we propose to create polarization orthogonality between adjacent AWGR channels, which in its turn produces a very high crosstalk tolerance. As two signals with orthogonal polarization states will not beat with each other in a photodiode. The optical crosstalk on the orthogonal polarization state will not generate a mixed beat note after detection and thus crosstalk in the electrical domain can be largely mitigated. By reducing the spectral guard band or even setting spectral overlap, such trade-off between higher port number and large channel bandwidth is broken. Moreover, the port number of an AWGR can be increased by simply shortening the spatial gap between adjacent output waveguides on a chip. The proposed method can also tolerate the wavelength misalignment between AWGRs and lasers, which relaxes the design of low crosstalk AWGRs and high wavelength stable lasers. The 20 Gbit/s data rate OWC capacity using PAM-4 format has been experimentally demonstrated over 1.2-m free-space link. The experimental results show that our proposed scheme can significantly reduce the inter-channel crosstalk. This method not only can be used in our AWG-based beam-steered OWC system but also can be applied in traditional WDM access networks.

REFERENCES

Xuebing Zhang (S’18) received the M.Eng. degree in optical engineering from Jinan University, Guangzhou, China, in 2015. He is currently working toward the Ph.D. degree with the electro-optical communications group, Eindhoven University of Technology, Eindhoven, The Netherlands. During master study, he has been working for one and half years with the State Key Laboratory of Optical Communication Technologies and Networks, Wuhan, China. Since 2015, he has been a Research Assistant working around one year with Hong Kong Polytechnic University. He is an Inventor of a US granted patent. His research interests include integrated photonics circuits, microwave photonics, and optical wireless communication.

Chao Li received the Ph.D. degree from the School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan, China, in 2015, focusing on ultra-high capacity fiber-optic communication. From 2015 to 2018, he was a postdoctoral with the Department of Electronic Engineering and Information Science, School of Information Science and Technology, University of Science and Technology of China, Hefei, China. Since August 2018, he has been doing postdoc research at Eindhoven University of Technology, Eindhoven, The Netherlands. His research interests include fiber and wireless optical communications.

Yuqing Jiao received the B.Eng. degree in 2008. He received the dual Ph.D. degree from Eindhoven University of Technology, Eindhoven, The Netherlands, and from Zhejiang University, Hangzhou, China, in 2013. He is currently an Assistant Professor with the Photonic Integration Group, Department of Electrical Engineering, Eindhoven University of Technology, where he is focused on an advanced InP membrane based photonic integration platform for wide applications including beam steering. His other research interests include novel semiconductor technology and materials, emerging photonic applications.

Edward Tangdiongga (S’01–M’10) received the M.Sc. and Ph.D. degrees from the Eindhoven University of Technology, Eindhoven, The Netherlands, in 1994 and 2001, respectively. In 2001, he joined the COBRA Research Institute working on the ultrafast optical signal processing using semiconductor devices. In 2016, he was an Associate Professor on advanced optical access and local area networks. His current research interests include the passive optical networks, a radio over (single mode, multimode, and plastic) fiber, and an optical wireless communication.

Yu Liu was born in Hunan, China, in 1976. He received the M.S. and Ph.D. degrees in microelectronics and solid-state electronics from the Institute of Semiconductors, Chinese Academy of Sciences (CAS), Beijing, China, in 2004 and 2008, respectively. He is currently a Full Professor with the Institute of Semiconductors, CAS. His research interests include high-frequency characteristics of microwave optoelectronic devices and design of high-speed optical transceiver modules.

Zizheng Cao (S’11–M’19) received the M.Eng. degree in telecom engineering from Hunan University (Outstanding Thesis in 2010), Changsha, and the Ph.D. degree (Cum Laude) from the Eindhoven University of Technology (TU/e), Eindhoven, The Netherlands, in 2015. In 2016, he was appointed as an Assistant Professor at TU/e. His research interests include modeling and design of integrated photonics circuits, microwave photonics, advanced DSP, and physical layer design of optical networks. His research activities produce a series of interesting scientific results on peer-reviewed journals (LSA, JLT, and JQE) and many invited talks in international conferences. He was a recipient of Graduate Student Fellowship of the IEEE Photonics Society 2014. He serves as an Active Reviewer for many top IEEE/OSA journals.

Ton Koonen (F’07) worked for more than 20 years in applied research in the industry, amongst others in the Bell Labs—Lucent Technologies, before 2001. Since 2001, he has been a Full Professor with the Eindhoven University of Technology (TU/e), Eindhoven, The Netherlands. Since 2004, he has been the Chairman with the Group of Electro-Optical Communication Systems, and since 2012, as a Vice-Dean with the Department of Electrical Engineering. Since 2016, he has been the Scientific Director with the Institute for Photonic Integration, TU/e. He was a Distinguished Guest Professor with the Hunan University, Changsha, China, in 2014. His current research interests include optical fiber-supported in-building networks (including the optical wireless communication techniques, the radio-over-fiber techniques, and the high-capacity plastic optical fiber techniques), the optical access networks, and the spatial division multiplexed systems. He was the recipient of an Advanced Investigator Grant of the European Research Council on an optical wireless communication in 2013. He is a Bell Labs Fellow (1998) and an OSA Fellow (2013).