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Citation for published version (APA):
https://doi.org/10.1109/JLT.2019.2917835

DOI:
10.1109/JLT.2019.2917835

Document status and date:
Published: 01/08/2019

Document Version:
Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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Download date: 31. Mar. 2022
Crosstalk-mitigated AWGR-based 2-D IR beam-steered indoor optical wireless communication system with a high spatial resolution

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Abstract—In this paper, a crosstalk-mitigated transmission scheme in AWGR-based two dimensional (2-D) infrared (IR) 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, PAM-4 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.

Index Terms—Infrared beam steering, optical wireless communications, AWG router, crosstalk mitigation.

I. INTRODUCTION

T

e 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 microelectro-mechanical 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 $\lambda$-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 $\lambda$-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 system architecture. The low-cost intensity modulation/direct detection (IM-DD) is widely used in access networks. The data including the frequency carrier is modulated onto an optical carrier provided by a tunable laser via a Mach-Zehnder modulator (MZM). After the power adjustment (by an EDFA), the output fibers of the AWGR are arranged in 2-D fiber array and this fiber array is located in the focal plane of a lens. The position of fiber in the focal plane determines the 2-D directions in which the corresponding beams are steered through the lens. In other words, each output port of the AWGR covers a certain area at a certain angle. Such $\lambda$-switched system has a simple architecture 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 and direct current (DC) crosstalk is deleted by an ac-coupled detector. This spectral overlap means higher spectral efficiency. The technique can also resist the wavelength mismatch between AWGRs and light source outputs. The constraint on high wavelength stability tunable lasers is also relieved. Moreover, in items of AWGR design, the higher port-count can be implemented simply by reducing the spatial gap between output waveguides on a chip, which allows a low-complexity high port-count AWGR design.

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 λ-split and then steered to different directions by a lens.
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). Then the received signal is detected by a photodiode and the photocurrent can be presented as (for a unity responsivity detector)

$$I_n = |E_{c,n,x} + E_{s,n,x} + \bar{E}_{c,n+1,y} + \bar{E}_{s,n+1,y}|^2 \quad (1)$$

where, $E_{c,n,x}$ and $E_{s,n,x}$ is the carrier and signal in $n^{th}$ (with x-polarization state) channel, respectively. $\bar{E}_{c,n+1,y}$ and $\bar{E}_{s,n+1,y}$, $E_{c,n-1,y}$ and $E_{s,n-1,y}$ 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

$$I_n = |E_{c,n,x} + E_{s,n,x}|^2$$

$$+ |E_{c,n+1,y} + E_{s,n+1,y} + E_{c,n-1,y} + E_{s,n-1,y}|^2$$

$$= |E_{c,n,x}|^2 + |E_{s,n,x}|^2 + 2\text{Re}(E_{s,n,x}E_{c,n,x}^*)$$

$$+ |\bar{E}_{c,n+1,y}|^2 + |\bar{E}_{s,n+1,y}|^2 + 2\text{Re}(\bar{E}_{s,n+1,y}\bar{E}_{c,n+1,y}^*)$$

$$+ |\bar{E}_{c,n-1,y}|^2 + |\bar{E}_{s,n-1,y}|^2 + 2\text{Re}(\bar{E}_{s,n-1,y}\bar{E}_{c,n-1,y}^*)$$

$$+ 2\text{Re}(\bar{E}_{s,n+1,y}\bar{E}_{s,n-1,y}) + 2\text{Re}(\bar{E}_{c,n+1,y}\bar{E}_{s,n-1,y})$$

$$+ 2\text{Re}(\bar{E}_{c,n+1,y}\bar{E}_{c,n-1,y}) + 2\text{Re}(\bar{E}_{c,n+1,y}\bar{E}_{s,n-1,y}) \quad (2)$$

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 $2\text{Re}(E_{s,n,x}E_{c,n,x}^*)$ 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 $|\bar{E}_{c,n+1,y}|^2$ and $|\bar{E}_{c,n-1,y}|^2$ are easy to be removed. Due to the filtering of the AWGR, the cross signal is smaller than the target signal ($E_{s,n,x} > E_{s,n+1,y}$, $E_{s,n,x} > E_{s,n+1,y}$). The cross SSBI items of $|E_{s,n+1,y}|^2$ and $|E_{s,n-1,y}|^2$ are also suppressed to a very low level that can be neglected. Similarly, $2\text{Re}(E_{s,n+1,y}E_{s,n-1,y}^*)$ can be ignored. $2\text{Re}(E_{c,n+1,y}E_{c,n-1,y}^*)$ 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 ($E_{c,n,x} \gg E_{c,n+1,y}$, $E_{c,n,x} \gg E_{c,n-1,y}$, normally $\gg 20$ dB). The left four beating crosstalk items, are at least 20-dB lower than the target signal component ($2\text{Re}(E_{s,n,x}E_{c,n,x}^*)$). 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.

Fig. 3 (a) The traditional AWGR response with large spectral guard band; (b) The Guard-band-reduced AWGR response for crosstalk-mitigated IR beamsteering system.

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
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 farther 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 wave-
guides, 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/25GHz, 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 am-
plitude modulation (PAM-4) signal is used. Three adjacent
AWGR channels (1549.92 nm, 1550.02 nm, and 1550.12nm)
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 cou-
pler (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 elec-
trical amplifiers (EA). The double-sideband main lobe band-
width 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 collimator followed by a commercial
avalanche photodiode (APD, DSC-R402). The variable optical

Fig. 4(a) The mask layout of a U-shaped AWG; (b) the connection between
the crosstalk and adjacent waveguide spacing. FPR: free propagation region.
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. Ch8 is the target channel and the channel-spacing is 12.5 GHz. The spectra of Ch8 after AWGR show the signal and crosstalk strength by switching the LD on and off. The strength of carrier leakage is -26.3 dB (Ch9) and -37.0 dB (Ch7), respectively, which is mainly caused by the AWGR response as shown in Fig. 6 (a).

V. 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 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 the 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

Fig. 6 (a) The AWGR response used in this experiment; (b) the measured BER versus received power curves with and without crosstalk mitigation; (c) the electrical spectra under each condition. BER: bit error rate; Tx signal: transmitted signal; Rx signal: received signal; pol.: polarization;
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 ($7 \times 10^{-2} ~ 2 \times 10^{-2}$). For the orthogonal state, the crosstalk is largely reduced and thus BER is improved to $\sim 5 \times 10^{-4}$, 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 $-6 \times 10^{-3}$ to $-3 \times 10^{-4}$ at -11-dBm power level. In contrast, the performance with crosstalk mitigation has a responsibility decrease of $-0.1$ dB, which is caused by the impact of slightly filtering. Fig. 8 (b) describes the optical spectra with and without the filter. $-9.7$-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 tradeoff 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.

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