

Optics Letters

Asymmetrical bidirectional optical wireless communication system based on a transmissive 1D LC-SLM for NG-PON2

Hsi-Hsir Chou*  AND Wei-Ta Huang

Department of Electronic and Computer Engineering, National Taiwan University of Science and Technology, No. 43, Keelung Rd., Sec. 4, Da'an Dist., Taipei City 10607, Taiwan

*Corresponding author: hsi-hsir.chou@trinity.cantab.net

Received 23 June 2020; revised 14 July 2020; accepted 14 July 2020; posted 14 July 2020 (Doc. ID 400832); published 10 August 2020

An asymmetric bidirectional optical wireless communication (B-OWC) system using optical fibers as the transmitter and receiver and capable of wavelength switching is proposed for next generation passive optical network stage two (NG-PON2) extension to home area network (HAN), without optical/electrical (O/E) and electrical/optical (E/O) conversions, which is based on a transmissive “floating” pixel size one-dimensional (1D) liquid crystal spatial light modulator (LC-SLM) at the access node (AN) and a modulated retroreflector (MRR) at the terminal user (TU). The utilization of a reflective grating element and a low-cost LC-SLM in the AN offers a high flexibility of beam steering and wavelength selection in the scenario of B-OWC. Instead of a light source used at conventional TU, a MRR was employed at a TU in order to improve the problems of the power consumptions, alignment difficulties, wavelength contentions, and cost of the TUs. Downlink and uplink data transmissions at a link speed over 2.5 Gbits/s, using wavelengths between 1590 ~ 1603 nm and 1524 ~ 1544 nm, respectively, corresponding to the downlink and uplink wavelengths specified by the NG-PON2 standard, have been experimentally demonstrated successfully, with quality factors (Q-factors) beyond the forward error correction limit (Q-factor = 16.9 dB, bit error rate = 10^{-12}). © 2020 Optical Society of America

<https://doi.org/10.1364/OL.400832>

Symmetric bidirectional optical wireless communication (B-OWC) systems using optical fibers as the transmitter and receiver and capable of wavelength switching, for next generation passive optical network (PON) stage 2 (NG-PON2) [1] extension to home area network (HAN), without optical/electrical/optical (O/E/O) conversions has been reported [2]. In particular, that B-OWC with direct coupling from the optical fiber network allowing data rate beyond 10Gbit/s has recently demonstrated [3]. Nevertheless, problems from the terminal users (TUs) and access node (AN)-like alignment difficulties, high-power consumption, as well as wavelength contention have not well addressed.

In this Letter, an asymmetric B-OWC system, as illustrated in Fig. 1, is proposed for a NG-PON2 extension to HAN, which is based on a low-cost transmissive “floating” pixel size one-dimensional (1D) liquid crystal (LC) spatial light modulator (SLM) at the AN and a modulated retroreflector (MRR) at the TU. The SLM-based beam steering system allows AN to exchange data with multiple TUs in different positions. A compact MRR system is utilized to provide TUs with the solution to the challenges faced in the conventional symmetric B-OWC system as mentioned above. Since the proposed work was designed for the application of fiber-to-the-home (FTTH) networks realized by time-division multiplexed (TDM) PONs, the uplink and downlink wavelengths are located in the C-band (1524–1544 nm) and L-band (1590–1603 nm), respectively, corresponding to the wavelengths specified by the NG-PON2 standard [1]. It is distinguished from the conventional asymmetric optical wireless communication (OWC) system for indoor retroreflector-based Internet of Things (IoT) devices, which can only perform one-way data transmission (uplink), where both downlink and uplink data transmissions can be achieved simultaneously by the proposed system architecture.

In the proposed system architecture, as illustrated in Fig. 1, optical fibers were used as the transmitter and receiver within the AN, and therefore no O/E/O conversions were required. The AN transmitted a modulated and an unmodulated light into free space, in which the wavelengths are between 1590 ~ 1603 nm and 1524 ~ 1544 nm, respectively, corresponding to the downlink (from AN to TUs) and uplink (from TUs to AN) wavelengths specified by NG-PON2. While the modulated downlink wavelength will be steered to the photodetector (PD) of a targeted TU, the unmodulated uplink wavelength will be reflected parallel to the incident light path to the output fiber (OF) of the AN after being modulated by the MRR at the TU. The key advantage of using re-modulation at each TU is that wavelength and bandwidth can be directly assigned by AN to each TU, which will simultaneously raise the system performance and solve the wavelength contention problem since the uplink wavelength and bandwidth used in each TU will be fixed, given that a conventional transmitter was used. Moreover, compared with the conventional symmetric B-OWC system using a reflective LC-SLM that has been reported previously [2],

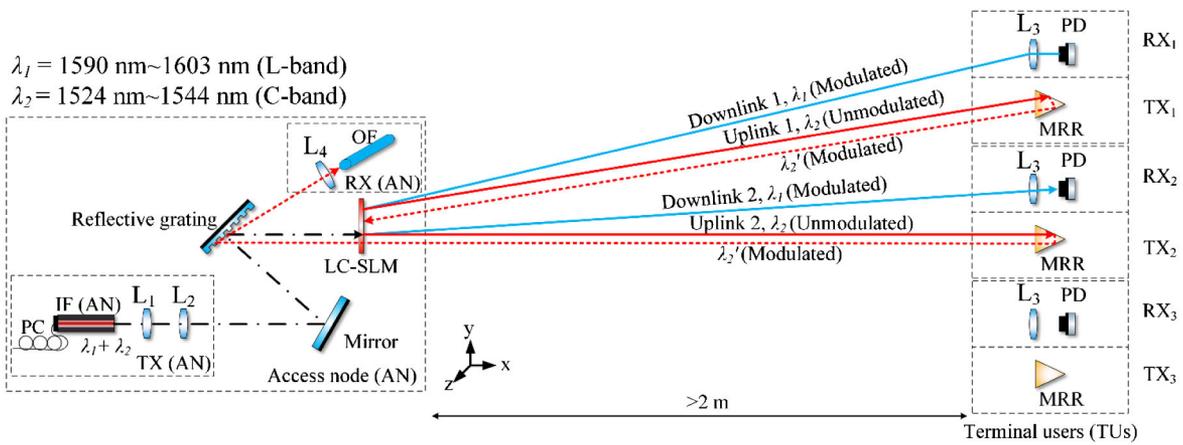


Fig. 1. Proposed asymmetric B-OWC system (PC/PL, polarization controller; IF, GRIN lens input fiber; $L_1 \sim L_4$, spherical lens; PD, detector).

the employment of a transmissive LC-SLM will provide a better diffraction efficiency.

One of the vital components of the proposed system, the LC-SLM and its mask are shown in Figs. 2(a) and 2(b), respectively, which is capable of displaying reconfigurable phase-only

holograms. In contrast to the regular arrangement of the pixel sizes, as illustrated in Fig. 2(c), that has been widely used in commercial LC-SLMs, the proposed LC-SLM is composed by an array of 1080 pixels \times 1 pixel with a “floating” pixel size, where the average pixel size is 10 μm , as illustrated in Fig. 2(d), which provides a smoother phase difference distribution, as shown in Fig. 2(e), and a better lens quality [4,5]. Moreover, the power consumption resulted from the zero order will also be reduced. In distinguish with commercial available transmissive LC-SLM, i.e., HOLOEYE Photonics AG, in which the pixel pitch is 30 μm , the average pixel size of 10 μm used in the proposed LC-SLM device will provide a wider diffraction angle for wavelength separation and beam steering application. The birefringence $\Delta n = 0.25$ at 633 nm. A computer program that comprises a universal serial bus (USB) control software and a user interface is used to control each pixel on the LC-SLM individually by applying 256 discrete voltage levels between 0 and 6.5 V. Thus, the device is capable of resolving 256 different phase levels with a maximum phase modulation of $1.21\lambda (2.42\pi)$ at 1550 nm, and the rise/fall time is 106 ms.

For the proof of concept, an experimental system was implemented and is shown in Fig. 3, where all of the lens and optical components used within the AN and TU were purchased from a commercial market (Thorlabs, Inc.). As illustrated in Fig. 3, the retroreflector is interrogated by uplink wavelengths, 1528–1544 nm, with a channel spacing of 2 nm, and the PD is interrogated by a downlink wavelength, 1590 nm. The multiplexed wavelengths, which include uplink (unmodulated) and

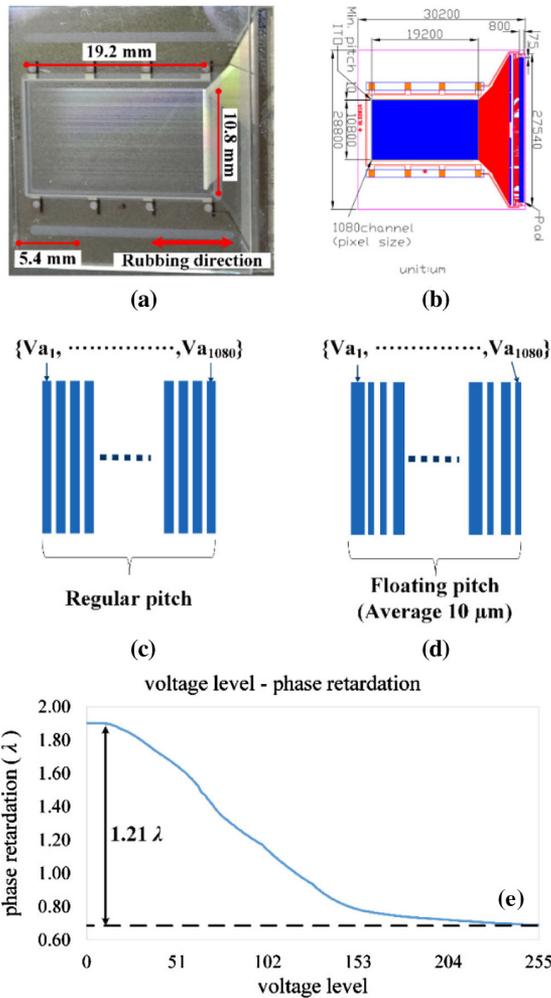


Fig. 2. Proposed 1-D LC-SLM: (a) physical layout, (b) mask, (c) regular pixel size, (d) floating pixel size, and (e) measured phase retardation.

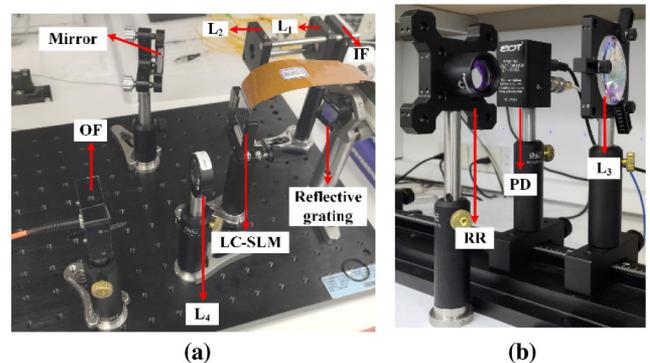


Fig. 3. Experimental setup of the proposed system: (a) AN and (b) TU.

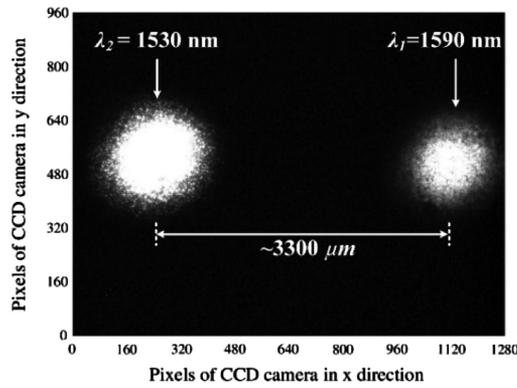


Fig. 4. Spot diagrams of uplink and downlink wavelengths on the LC-SLM plane (the pixel size of the CCD camera is $3.75 \mu\text{m} \times 3.75 \mu\text{m}$).

downlink (modulated) wavelengths, are transmitted through a gradient-index (GRIN) lens input fiber (IF) (50-1550 A-FC) in the AN. A beam expander, which is composed of lens L_1 (LB1092-C) and L_2 (LB1844-C), was used to collimate these multiplexed beam, before they are separated by a reflective grating (GR13-0616, 600 grooves/mm) and steered by the LC-SLM, which has a steering angles of $\pm 4.5^\circ$ to the TUs. These two wavelengths, which were destined for uplink and downlink transmissions, will be steered, respectively, to the MRR and a PD (EOT ET-3000 A) at a TU, which was focused through lens L_3 (LB1723-C). Figure 4 shows the spot diagrams of these two wavelengths separated by a reflective grating on the plane of the LC-SLM, which were captured by an IR CCD camera (Point Grey Chameleon CMLN-13S2M) through a focusing lens. From the measurement of the spot diameter of 1530 nm on the plane of the SLM and MRR by a vernier, which are 3.83 mm and 4.88 mm, respectively, we can calculate that the beam divergence angle of 1530 nm behind the SLM plane is approximately 0.015° . The wavelength for uplink transmission delivered to the MRR will be modulated and reflected back to the AN following the path parallel to the incident light path. The LC-SLM in combination with the reflective grating will steer this uplink wavelength into the OF (GIF625) of the node, through focusing lens L_4 (LB1901-C).

The total insertion loss of the AN was measured to be 3.45 dB, where the majority of light loss resulted from the fixed grating element and the LC-SLM, which are 1.29 dB and 1.28 dB, respectively. The insertion loss of the LC-SLM was

Table 1. Optical Power of Uplink Wavelengths at AN

Wavelength (nm)	IF (dBm)	Linear Position (dBm)	Maximum Position (dBm)	Minimum Position (dBm)
1528	8.41	-23.32	-28.05	-28.38
1530	7.93	-22.51	-28.21	-28.64
1532	8.10	-23.04	-28.88	-28.11
1534	7.69	-23.21	-29.30	-29.71
1536	7.65	-22.14	-28.70	-29.74
1538	7.84	-22.59	-28.05	-29.04
1540	8.30	-23.21	-28.89	-28.30
1542	8.04	-22.36	-28.87	-29.40
1544	8.43	-22.37	-29.89	-29.53

measured when no phase pattern was uploaded. However, since the diffraction efficiency of LC-SLM is 50% and 60%, respectively, when steering the interrogating beam to its maximum and minimum position, additional diffraction losses of 3.0 dB and 2.2 dB will be resulted, respectively. The losses resulted from other components within the AN, i.e., GRIN lens, beam expander, and mirror were measured to be 0.28 dB, 0.22 dB, and 0.38 dB respectively.

In the performance evaluation of data transmission tests, the uplink wavelength was amplified by an erbium-doped optical fiber amplifier (EDFA) with a gain of 10 dB and multiplexed with the downlink wavelength before being collimated by a GRIN lens and a beam expander (L_1 and L_2). Although the presence of an EDFA at the AN is not realistic in terms of cost, it can be replaced by using a high-power broadband light source [i.e., Fabry-Perot laser diode (FP-LD)] in combination with a tunable filter through an optical self-injection technique for uplink wavelength generation at the AN. The implementation of the proposed MRR at each TU can be achieved by using LCs, micro-electro-mechanical systems (MEMS), and electro-absorption modulator (EAM) optical shutters. Although the current modulation speeds of LC and MEMS devices are limited to a few kilobits per second (kbps) and megabits per second (Mbps), respectively [6], a high-speed data modulation rate up to 200 Mb/s with a bit error rate (BER) of 2×10^{-4} in lab conditions has been reported using multiple quantum wells (MQW)-based EAMs [6]. However, due to the shortage of the external modulator at the TU, the uplink wavelength was modulated at the AN, and a retroreflector (PS975M-C) was used at the TU to prove the concept of the proposed system. Both uplink and downlink wavelengths were modulated by on-off keying (OOK) signals with $2^7 - 1$ pseudo random sequence symbols at a link speed beyond 2.5 Gbits/s, generated by a pseudorandom binary sequence (PRBS) generator (Keysight N4970A), and analyzed by a 20 GHz digital communication analyzer (Agilent 83480A) during the experiments.

As shown in Table 1, the majority of light losses in the uplink transmission resulted from the fiber coupling at the AN, which is around 21 dB in all the cases. However, this poor fiber coupling efficiency can be improved when a core expanding fiber was used. Moreover, except for the insertion loss of each component used within the AN that has included, as mentioned previously, additional light losses resulted from the LC-SLM and reflective grating for the incident wavelength reflected by the TU located in linear, maximum, and minimum positions were also counted, which are 7.24 dB, 7.86 dB, and 8.99 dB, respectively. Besides, the light losses resulting from the TU's retroreflector located in the linear, maximum, and minimum

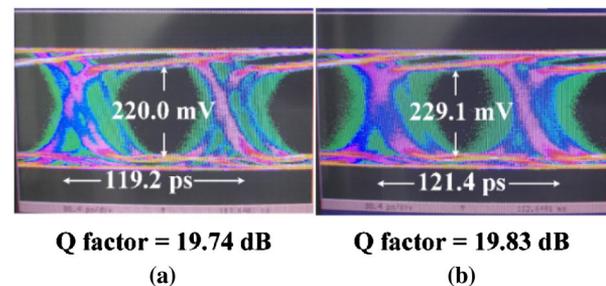


Fig. 5. Eye diagrams of downlink transmission (1590 nm) for TU [receiver (RX)] located at (a) linear and (b) maximum.

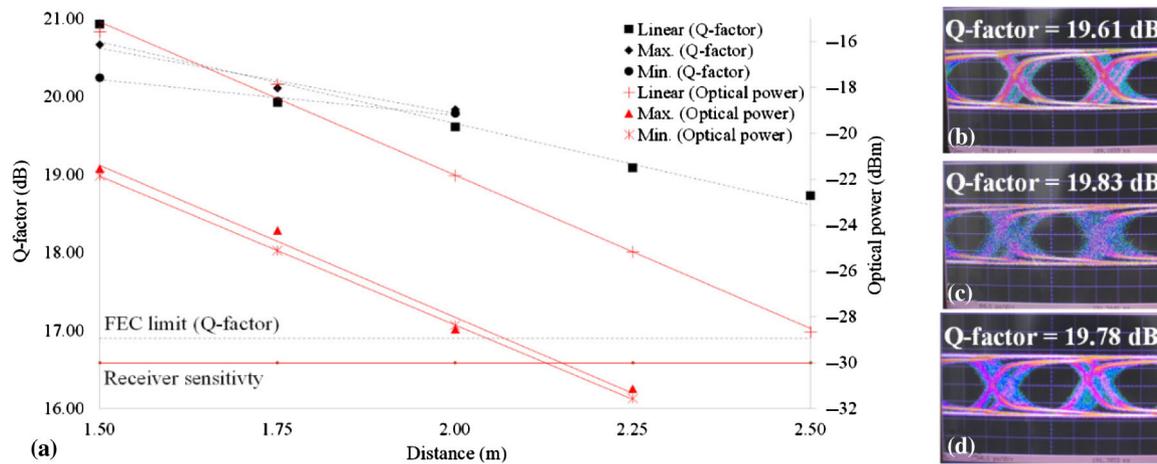


Fig. 6. (a) Q -factor (dotted line), optical power curve (solid line), and eye diagram of uplink transmission (1530 nm) when measured at the AN reflected from the TU located at the (b) linear position, (c) maximum position, and (d) minimum position with 2 m distance between the AN and TU.

positions are also significant, which are 0.74 dB, 2.3 dB, and 2.4 dB, respectively, due to its limited aperture. According to the measured eye diagrams, as shown in Figs. 5 and 6, the quality factor (Q -factor) for both uplink and down link transmissions are all larger than 18.42 dB, which are all beyond the forward error correction (FEC) limit [7]. Since the maximum communication distance of the proposed system is limited by the uplink transmission, as its transmission path is the double distance of the downlink transmission, the Q -factors of uplink transmission at different communication distances were also analyzed and are illustrated in Fig. 6. Due to the minimum receiver sensitivity of the receiver used in our experiments being limited to -30 dBm, a longer communication distance over 2 m was not well evaluated, as the received optical powers, which were reflected from TU located in different positions, were less than -30 dBm. From Fig. 6, it is clear that a communication distance longer than 2 m is only possible for a TU located in the linear position during the uplink transmission. Otherwise, the maximum communication distance of the proposed system will be limited to 2 m in order to meet the FEC requirement.

In summary, an experimental asymmetrical B-OWC system using optical fibers as the transmitter and receiver and capable of wavelength switching based on a transmissive 1D LC-SLM for NG-PON 2 extension to HAN without O/E/O conversions is proposed and experimentally demonstrated. In contrast to the conventional asymmetrical B-OWC, which can only perform one-way data transmission (uplink), both downlink and uplink data transmissions can be achieved simultaneously by the proposed system architecture. Moreover, using re-modulation at each TU also allows that wavelength and bandwidth to be directly assigned by AN to each TU, which will simultaneously raise the system performance and solve the wavelength contention problem since the uplink wavelength and bandwidth used in each TU will be fixed given a conventional transmitter was used. Although the proposed works in uplink transmission will result in a higher light transmission loss due to the poor fiber

coupling at the AN, the measured eye diagrams of both uplink and downlink transmissions demonstrated that the Q -factors are all beyond the FEC limit. Most importantly, the problems of power consumption, alignment difficulties, wavelength contentions, and cost of the TUs that are faced in conventional symmetric B-OWC systems will be significantly improved.

Funding. Ministry of Science and Technology, Taiwan (MOST 109-2622-E-011-006-CC3/107-2622-E-011-028-CC3).

Acknowledgment. The authors thank Liqxtal Technology Inc. and Cambridge University Engineering Department, U.K. for technical support and cooperation in the development of the 1D LC-SLM. We also thank Prof. D.C. O'Brien from Department of Engineering Science Oxford University, U.K for the fruitful discussions.

Disclosures. The authors declare no conflicts of interest.

REFERENCES

1. D. Nasset, *J. Lightwave Technol.* **33**, 1136 (2015).
2. H.-H. Chou and J.-H. Hsiao, in *Optical Fiber Communication Conference*, OSA Technical Digest (online) (Optical Society of America, 2018), paper M1F.7.
3. F. Feng, P. Sangwongngam, G. Faulkner, and D. O'Brien, *Opt. Lett.* **44**, 6009 (2019).
4. L. Li, D. Bryant, T. Van Heugten, and P. J. Bos, *Opt. Express* **21**, 8371 (2013).
5. H.-S. Chen and M.-S. Chen, "Electrically tunable optical phase modulation element," U.S. patent 10,168,586 (1 January 2019).
6. C. Quintana, Q. Wang, D. Jakonis, X. Piao, G. Erry, D. Platt, Y. Thueux, A. Gomez, G. Faulkner, H. Chun, M. Salter, and D. O'Brien, *IEEE Photon. Technol. Lett.* **29**, 707 (2017).
7. A. Alvarado, E. Agrell, D. Lavery, R. Maher, and P. Bayvel, *J. Lightwave Technol.* **33**, 4338 (2015).