Wavelength Tunable Asymmetric B-OWC System Based on Self-Injection Locking for TDM-PONs

Hsi-Hsir Chou and Wei-Ta Huang

***Abstract*—The challenge of asymmetric bidirectional optical wireless communication is majority resulted from the power shortage of uplink transmission, since it is double the downlink transmission distance. In this research, a wavelength tunable self-injection locking (SIL) system based on free-space configuration for uplink transmission in a modulated retroreflector based asymmetric bidirectional optical wireless communication system is proposed and experimentally evaluated. The proposed works were investigated from access node (AN) to terminal user(TU) respectively. A power gain of 34.51 dB, and uplink data transmission test over 2 Gbits/s, with Q-factors beyond FEC limit, are reported.**

***Index Terms*—Asymmetric free-space optical communication, wavelength tunable, self-injection locking.**

I. Introduction

AN ASYMMETRIC bidirectional optical wireless communication (B-OWC) system using optical fibers as the transceiver and capable of wavelength steering for next generation passive optical network stage 2 (NG-PON2) extension to Home Area Network (HAN), without optical/electrical (O/E) and E/O conversions has recently proposed and reported [1]. The major advantages of asymmetric B-OWC are that instead of a light source used at conventional terminal user (TU), a modulated retroreflector (MRR) is employed at TU, which will reduce the power consumptions, alignment difficulties, and cost of the TUs. In particularly, the wavelength for uplink transmission and the modulation bandwidth used in each TU can be dynamically assigned by access node (AN), which will simultaneously solve the problem of wavelength contentions and raise the efficiency of bandwidth utilization. However, the major problem of such asymmetric B-OWC is that the system coverage area will be limited by the uplink transmission distance, since it is twice the downlink transmission distance and the transmission loss is also proportional to $1/R^4$ [2], where R is the distance between AN and TUs. To address this issue, the utilization of an erbium-doped optical fiber amplifier (EDFA) or a semiconductor optical amplifier

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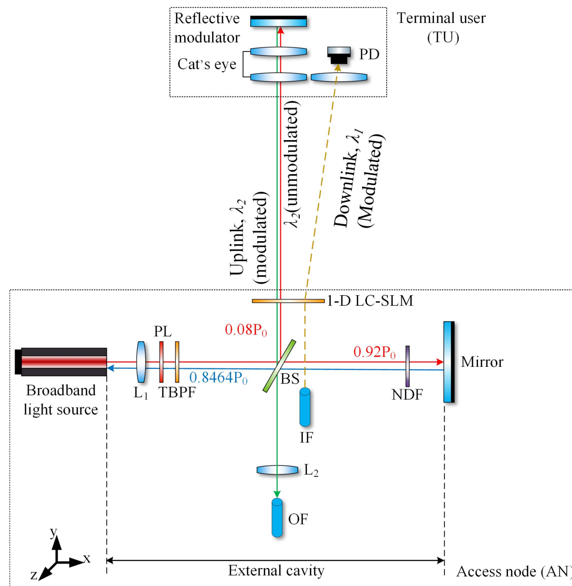

Fig. 1. System configuration of asymmetrical SIL-based B-OWC system.

(SOA) at AN have been a common solution to compensate the power shortage of uplink wavelengths. Nevertheless, using EDFA or SOA at AN seems unrealistic not only because of the cost and the extra power consumption, but they also amplified the noise, and has limited gain bandwidth. Therefore, the demand for new low-cost power amplified approach has increased. One of the low-cost approaches promising to solve the problem mentioned above is the utilization of optical injection locking (OIL) technique [3]. Although this technique has been well studied in recent years, the advantages of increasing frequency response, modulation bandwidth, as well as reducing linewidth, relative intensity noise(RIN), nonlinear distortion and gain improvement have made it still an attractive approach that can be used to enhance the optical performance in a variety of applications. In contrast to the conventional external injection locking (EIL) technique which requires a high quality master laser to inject the optical power into a slave laser, self-injection locking (SIL) technique only requires one laser source, and a Fiber Bragg Grating (FBG) or fiber mirror, which will be used to re-inject the optical power back to the active region of the original laser, thus the optical performance can be enhanced.

In this research, a novel design based on the utilization of SIL technique [3] for uplink transmission in an asymmetric

B-OWC system as illustrated in Fig.1 is proposed and investigated for the potential application of fiber-to-the-home (FTTH) networks realized by time-division multiplexed (TDM) PONs. To the best of our research, this is the first work that a SIL based on free-space configuration is proposed and investigated experimentally for an B-OWC system. The proposed works were evaluated from AN to TU respectively. The AN which is expected to provide a higher optical power gain, higher side mode suppression ratio, higher modulation bandwidth as well as a lower noise, in contrast to the configuration without SIL is majority composed of a broadband light source and a tunable bandpass filter (TBPF) for uplink transmission and an input fiber (IF) for downlink transmission. A 1-D LC-SLM was also used for wavelength separation and beam steering during bidirectional communications [1]. In the AN, multiple wavelengths emitted from the broadband light source can be selected arbitrary for uplink transmission through the utilization of a collimator (L_1) and the TBPF. The light beam of the selected wavelength will interrogate a pellicle beam splitter (BS, i.e. 92:8), where 92% of the optical power will be delivered towards a high reflectivity mirror, which forms one end of the ∼0.45 m long external cavity. A neutral density filter (NDF) is added between the mirror and the beam splitter to adjust the injection ratio of the feedback optical power, thus enabling the SIL characterization.

The other 8% of the optical power from the beam splitter will be transmitted to a TU through the 1D LC-SLM. Downlink transmission of the AN was achieved through the utilization of an input fiber which was placed behind the beam splitter and connecting directly to the external fiber network. The TU is composed of a receiver module which includes a collimating lens and a photodetector (PD) to receive downlink transmission. Moreover, a cat's eye lens system, and a reflective high speed modulator were also designed for uplink transmission. At TU, the interrogating beam will be modulated and reflected parallel to the incident beam by a MRR, and back to the AN. The advantage of the proposed work is the wavelength flexibility. By utilizing a tunable bandpass filter and a broadband light source in combination with the SIL technique, the wavelength as well as the modulation bandwidth can be dynamically adjusted for uplink transmission in a low noise and high power configurations, thus enabling a longer transmission distance.

II. Experimental System Implementation

For the proof of concept, an B-OWC system based on SIL technique was implemented, where all the lens and optical components used within the AN and TU were purchased from commercial market (i.e. THORLABS). A transmission distance of around 1∼2.5 m between AN and TU was initially used. Instead of using a broadband light source and a tunable bandpass filter, a TO-can laser diode (ML725B8F) mounted within an integrated temperature and current controller mount (LDM9T/M) was used as the light source to generate a single spatial mode wavelength for SIL, before delivered to TU for uplink transmission. For the proof of concept research, a 1310 nm single spatial mode coherent beam was generated

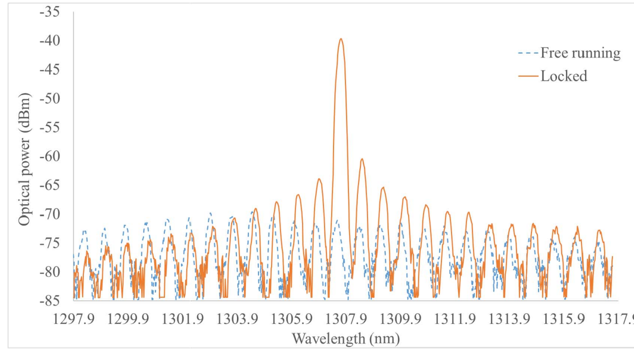

Fig. 2. Optical spectrum under free running and SIL. (at TU).

from the TO-can laser diode (LD) and collimated by an aspheric lens L_1 (C660TME-C), which has a focal length of 2.97 mm. The standard optical power output of this LD is around 5 mW. A 92:8 pellicle BS (BP108) was used to enable SIL and measurement in the same time. 92% of the optical power was transmitted toward a high reflectivity silver mirror (PF10-03-P01), which formed one end of the external cavity, then reflected back into the laser diode. By utilizing a NDF (Newport 50FS04DV.4) which was placed between the mirror and the BS, we can adjust the optical power injection ratio that injected back to the LD, thus enabling SIL characterization. The other 8% of the optical power from BS was transmitted to TU through a cat's eye lens system (LB1723-C & LB1607-C) and reflected by a retroreflector (PS975M-C) following the path parallel to the incident light path back to AN, then focusing by a spherical bi-convex lens L_2 (AC254-60-C) before received by an output fiber (OF, GIF625).

III. Performance Evaluations

The performance of the proposed AN based on the utilization of SIL technique was evaluated and analyzed. The spectrums of the TO-can LD under free running and SIL conditions which were based on an external cavity of 0.45 m in length, were compared and analyzed by an optical spectrum analyzer (OSA, HP 70950B). The measurement results as illustrate in Fig. 2 shown that the maximum power gain of approximately 34.51 dB was occurred in the center wavelength of 1307.7 nm when the injection current was approximately 6 mA. Moreover, a side mode suppression ratio (SMSR) of approximately 20.73 dB was also observed. Another important sign of a successful SIL is the decrease of the LD threshold current, and according to the measurement results as illustrated in Fig. 3, the threshold current has reduced significantly from 5.90 mA (free running) to 4.49 mA (SIL), which has indicated that the LD has been successfully locked.

The characteristics of LD linewidth relative to injection current under free running and SIL conditions were also compared and the results shown that the linewidth in SIL case decreased compared to free running case with a maximum reduction of 0.08 nm. The modulation bandwidth and injection current under free running and SIL conditions were explored and the measurement results shown that the modulation bandwidth

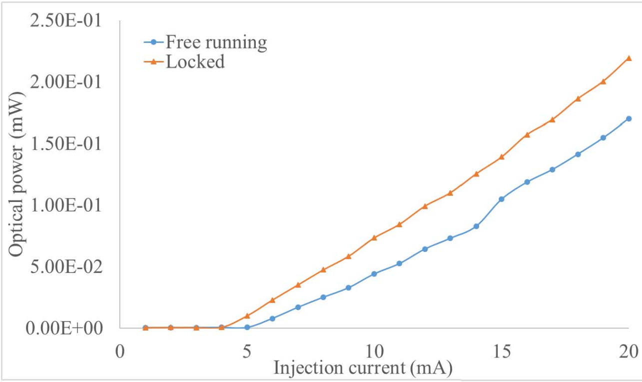

Fig. 3. Optical power & injection current under free running and SIL.

increased from 21.05 GHz (free running) to 29.82 GHz (SIL). The modulation bandwidth increased approximately 8.77 GHz. This modulation bandwidth, which was the 3 dB bandwidth of its center wavelength, was measured by the OSA and then transformed from wavelengths to frequencies [4]. The linewidth and injection ratio under free running and SIL conditions were also investigated when both of the injection currents were fixed at 20 mA. By utilizing the adjustable NDF during the experiments, the injection ratio of the injected optical power can be adjusted and the measurement results shown that the linewidth of the SIL case decreased comparing to the case of free running regardless of the injection ratio. Moreover, the modulation bandwidth of the SIL case also increased comparing to the case of free running regardless of the injection ratio.

The performance of uplink data transmission was also investigated, in which an external modulator should be used at a TU. This can be implemented through the utilization of an external modulators, such as liquid crystal (LC), micro-electro-mechanical systems (MEMs), and electro-absorption modulator (EAMs) optical shutters, where the fastest modulation speed up to 200 Mbit/s with a BER of 2×10^{-4} has been demonstrated in laboratory and reported [5]. However, in order to explore the robust modulation bandwidth of the used light source with SIL in this research, the uplink wavelength from TU was modulated in advance at AN by OOK signals at a faster modulation speed over 2 Gbit/s during our experiments. Comparing with the ideal case, in which the uplink wavelength was modulated at TU in a modulation speed close to 200 Mbit/s, the conditions for verification from our experiments used were much higher than an ideal case since the wavelength for uplink transmission was modulated at AN at a modulation speed over 2 Gbit/s and measured at AN again after it has delivered to TU and reflected back to the AN. In order to make the proposed work appropriate for indoor application, a transmission distance of 2.5 m between AN and TU was setup for performance evaluation. However, this will simultaneously require a higher driving current and injection ratio for the light source.

During the data transmission experiments, a 2^7-1 pseudo random sequence symbols at a link transmission rate between 2∼3 Gbits/s were generated by a PRBS generator (Keysight

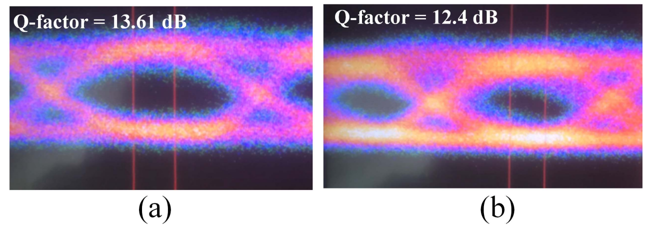

Fig. 4. Eye diagrams of uplink (a) 2 Gbits/s, (b) 2.5 Gbit/s. (at AN).

N4970A) and a 20 GHz digital communication analyzer (Agilent 83480A) was used to analyze the data transmission measurements. The recorded eye diagrams of the received uplink wavelength as illustrated in Fig. 4 (a) & (b) shown that the Q-factors were 13.61 dB, and 12.4 dB at a link speed of 2.0 and 2.5 Gbits/s, respectively. These results were all beyond the forward error correction (FEC) limit for FSO system which is approximately 9.80 dB (BER $= 3.8 \times 10^{-3}$) [6]. Given the SIL was not applied, for the same conditions i.e. the same driving current, uplink data transmission will not be able to be performed since the power shortage due to the long transmission distance and fiber coupling loss will result a lower signal to noise ratio (SNR).

IV. Conclusion

In summary, a wavelength tunable SIL system for uplink transmission in a MRR-based B-OWC system that was proposed and experimentally implemented has evaluated. The key advantage of using re-modulation at each TU is that wavelength and bandwidth can be arbitrary controlled by AN to each TU, which will simultaneously raise the system performance and solve the wavelength contention problem since the uplink wavelength and its bandwidth used in each TU will be fixed given a conventional transmitter was used. The measurement results have demonstrated a successful evaluation compared with the state of the art and will provide an alternative low-cost amplified solution for a MRR-based B-OWC system.

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