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Experimental demonstration of CW light injection effect in upstream traffic TDM-PON

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ABSTRACT

High capacity time-division-multiplexed passive optical network (TDM-PON) is an emerging fiber access network that deploys optical access lines between a carrier's central office (CO) and a customer sites. In this investigation, we demonstrate and analyze the continuous wave (CW) upstream effect in TDM-PONs. Besides, we also propose and design a protection apparatus in each optical network unit (ONU) to avoid a CW upstream traffic in TDM-PONs due to sudden external environment change or ONU failure. When an upstream CW injection occurs in TDM access network, the protection scheme can stop the CW effect within a few ms to maintain the entire data traffic.

1. Introduction

The benefits of fiber to the home (FTTH) networks are their enormous capacity and high flexibility over the other telecommunication networks in fiber access domain. It means that fiber access networks can provide the greatest bandwidth for both downstream and upstream traffics. Without doubt, FTTH networks can provide the future-proof infrastructure with respect to bandwidth and application demands for the next decades. Hence, time-division-multiplexed passive optical network (TDM-PON) is emerging as a viable choice for the next generation FTTH broadband access technology [1–7]. PON system is a point-to-multipoint fiber optical network with no active elements in the signal's path. Recently, the Broadband-PON (B-PON) standard already exists [1]. Moreover, the Ethernet-PON (E-PON) and Gigabit-PON (G-PON) are oncoming [2,3] for broadband access communications. Furthermore, the optical transmitter (Tx) in each optical networking unit (ONU) needs the burst-mode characteristic for TDM uplink connection. However, when the burst-mode (BM) signal becomes continuous wave (CW) mode due to failure in driver circuit of laser diode (LD) in ONU, the entire access traffic would be affected due to CW injection into the receiver (Rx) at CO. While a CW light emitted by an ONU owing to failure was injected into the OLT, the entire TDM-PON would be degraded due to CW effect. Hence, to overcome this problem, a protection apparatus in each ONU is required.

In this study, we first propose and investigate a protection scheme in order to prevent the CW upstream effect in the TDM-PON. The CW upstream effect can be temporary due to the sudden external environment change or permanent because of the failure in LD driver circuit. In addition, the CW upstream effect in PON has also been analyzed and discussed.

2. Experiments and results

Fig. 1a and b illustrates the conventional downstream and upstream traffics in a tree-topology TDM-PON respectively. Traffic from the optical line terminal (OLT) to ONUs is point-to-multipoint (downstream); while traffic from ONUs to the OLT is multipoint-to-point (upstream). Two wavelengths are used for the data connections in the TDM-PON: the 1310 nm (λ_{up}) wavelength (Fabry–Perot laser diode, FP-LD) for the upstream transmission and 1490 nm (λ_{down}) wavelength (distributed feedback laser diode, DFB-LD) for the downstream transmission. In the downstream direction (from OLT to ONU) packets are broadcasted by the OLT and extracted by their destination ONUs based on their media access control (MAC) address. In the upstream direction (from ONU to OLT), each ONU will use a time shared channel arbitrated by OLT. Hence, the upstream wavelength on each ONU needs the burst-mode control for the multipoint control protocol (MPCP) operation in TDM access networks. In Fig. 1b, when a burst-mode in ONU_2 becomes CW due to the environment change or ONU failure, the other upstream signals from other ONUs (ONU_1 and ONU_3) and the CW signal will be combined by the optical splitter (SP) and launched to the Rx at OLT. Thus, the entire data traffic in the

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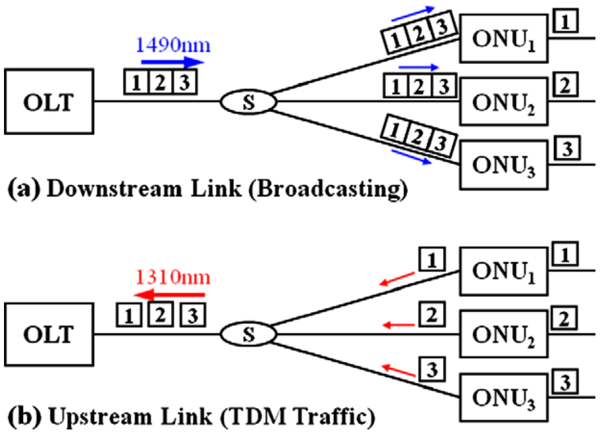

Fig. 1. (a) Downstream traffic operation with broadcasting transmission from and (b) upstream traffic with MPCP control in the PONs.

TDM-PON will be affected due to the CW injection. For example, at the ONU, the LD was directly modulated via a bias-tee using DC current and RF signal. There is occasion that when the RF driving circuit or the RF amplifier is out-of-order, then the LD was driven by a DC current only and produced CW signal.

To analyze and investigate the CW effect in upstream traffic for TDM-PON, an experimental setup for upstream traffic with CW injection effect is illustrated in Fig. 2. Two FP-LDs (FP-LD$_1$ and FP-LD$_2$) with similar output wavelengths are used to serve as the upstream data signal and CW injected wavelength, respectively. Two polarization controllers (PCs) in Fig. 2 are employed to align their polarization states to model the worst case of the beat noise. The two upstream signals are joined via a 3 dB optical coupler (CP) simultaneously and detected by the Rx (a PIN photodiode (PD) with electrical bandwidth of 2 GHz) in the OLT. In Fig. 2, FP-PD$_1$ is directly modulated by a 2.5 Gb/s non-return-to-zero (NRZ) pseudo random binary sequence (PRBS) at a pattern length of $2^{31}-1$ acting as the upstream signal. The FP-PD$_1$ is biased at 19 mA (two times of the threshold current). And the FP-LD$_2$ is used to simulate the CW injection light. Besides, two variable optical attenuators (VOAs) can be used to adjust the output power levels of two FP-LDs used. According to the PON standards [1–3], the split-ratio can be without splitting to 64 splits, hence the power loss difference is about 18–19 dB. The length of fiber can be 500 m to 20 km, hence the power loss difference is about 6 dB when the loss of fiber is ~0.3 dB/km. As the result, the total power difference can be 19 dB + 6 dB = 25 dB. Hence, in this analysis, we can adjust the CW injected powers to produce different upstream CW power ratios to realize the CW injection effect in upstream traffic for TDM access network.

We used two channels, one was under the measurement and the other one was failure, because the chance of having one of the channel failures is much higher than two or more channels failure. Besides, we would like to model the worse case of the beating and the two channels were in the same polarizations. First, we set the upstream power of FP-LD$_1$ at 0 dB with 2.5 Gb/s direct modulation, and the CW FP-LD$_2$ under different output powers of 0, −5, −10, −15, and −20 dB by adjusting a VOA for the experiment, as shown in Fig. 2. Here, Fig. 3 shows the bit error rate (BER) performance of the upstream traffic when the Rx of Fig. 2 is without and with different CW injections of 0, −5, −10, −15, and −20 dB, respectively. The inserts of Fig. 3 are the corresponding eye diagrams at BER of 10^{-9} without and with CW injections. Besides, Fig. 3 shows the power penalties of 3.2, 1.3, 0.6, 0.2 and <0.2 dB while the different CW injection powers of 0, −5, −10, −15, and −20 dB is used to interfere upstream data traffic, respectively. Therefore, when the powers of upstream signal and CW injection are equal in this measurement, the CW lightwave will cause the penalty of 3.2 dB at the BER of 10^{-9}, as illustrated in Fig. 3. Hence, Fig. 3 presents the penalty of <1.3 dB when the power variation between CW and data channels is around 10 dB. According to Fig. 3, with the decrease of CW injected power gradually, the power penalty would also decrease while the original upstream data channel is received at Rx with 0 dB power.

Moreover, when the distances between different ONUs and OLT vary, the incident power from ONUs which are far away could be small. Hence, in the section, to investigate the received performance under smaller upstream data signal after CW light injecting with different power. Thus, we decrease the upstream data power of the FP-LD$_1$ to −20 dB with 2.5 Gb/s NRZ direct modulation format, and the CW injection powers of FP-LD$_2$ are set to −17.5 and −20 dB, respectively. Here, Fig. 4 shows the BER of the upstream traffic without and with different CW injection powers of −17.5 and −20 dB, respectively. The inserts of Fig. 4 are the corresponding eye diagrams at BER of 10^{-9} without and with CW. Fig. 4 shows the power penalties of 6 and 5.6 dB under the different CW injection powers of −17.5 and −20 dB, respectively. Furthermore, when the CW injection power is above −17.5 dB, the BER cannot be error free due to higher error is generated by the CW injection. Therefore, in this measurement we can see that −20 dB upstream data signal would be affected easily under a smaller CW injection power level.

According to the measured results (as seen in Figs. 3 and 4), the larger upstream power (nearly 0 dB) in TDM-PON system can bear a larger CW injection level. In general, the received upstream powers in OLT are smaller than 0 dB due to the higher splitting ratio in

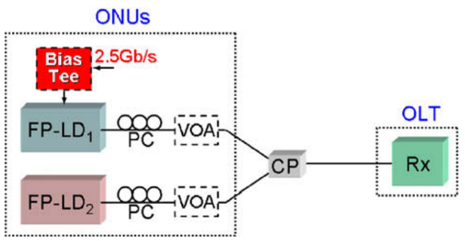

Fig. 2. Experimental setup for upstream traffic with CW injection effect in TDM-PON. FP-LD$_1$ acts as the upstream signal with 2.5 Gb/s and FP-LD$_2$ serves as the CW injected lightwave. FP-LD: Fabry–Perot laser diode; VOA: variable optical attenuator; PC: polarization controller; CP: 1 × 2 and 50/50 coupler; Rx: receiver.

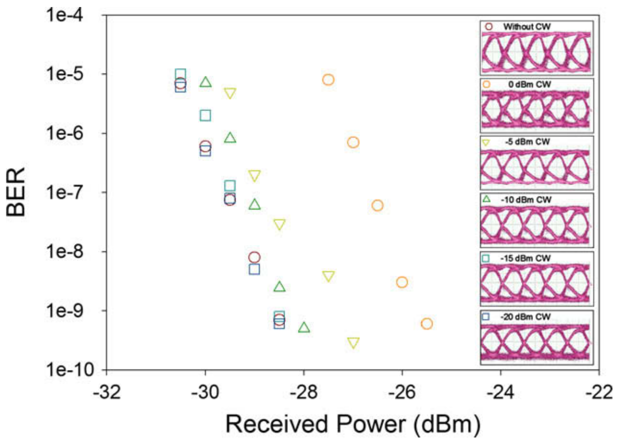

Fig. 3. BER of upstream traffic without and with different CW injection powers of 0, −5, −10, −15, and −20 dB, respectively. The inserts are the eye diagrams at BER of 10^{-9} without and with CW injections. The output power of FP-LD$_1$ is 0 dB with 2.5 Gb/s direct modulation.

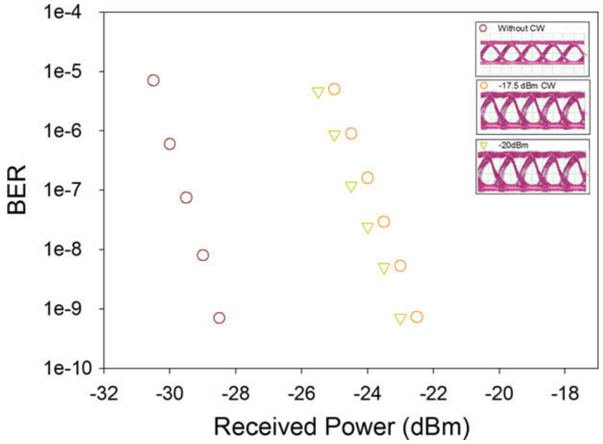

Fig. 4. BER of upstream traffic without and with different CW injection powers of −17.5 and −20 dB, respectively. The inserts are the eye diagrams at BER of 10^{-9} without and with CW injections. The output power of FP-LD_1 is −20 dB with 2.5 Gb/s direct modulation.

RN. However, the smaller upstream signal power could be easily affected by beating noise even under small CW injected power. In order to avoid the upstream CW signal effect in the PON system, a proposed protection apparatus is demonstrated and shown in Fig. 5. The proposed scheme can be integrated into each ONU to prevent the CW upstream effect. The module is consisted of a 1 × 1 optical switch (OS), a 1 × 2 and 95:5 CP, a PD and a control circuit (CC). In Fig. 5, the upstream signal will pass through the 1 × 2 CP and 1 × 1 OS, then the 95% output power will leave the ONU and transmit to the OLT. The remainder 5% signal power will enter the PD. The CC is used to judge the switching direction of OS to "on" or "off" depending on whether the upstream signal is CW light. Successful transmission of data in the upstream direction entails support of processes like clock recovery and start of burst delimitation [4]. According to the past report [5], the laser on–off time of each ONU is negotiable up to 512 ns in burst-mode operation. In the design, we only use a cheaper and low-speed PIN PD with 2 GHz bandwidth to detect the CW light. In normal status, the PD used in protection apparatus cannot detect the burst-mode upstream signal due to the lower response time. When a fault on LD driver produces CW status, then the PD would detect CW light. At this time, the CC will switch OS to "off" status to avoid upstream signal collision resulting in beat noise. Thus, the CS will judge the OS in "on" or "off" depending on whether the PD receives a CW light. The control circuit is used to detect the time of the upstream packet. For the maximum length of the upstream optical packet is 512 ns, even though all the data inside is logic "1", if the detected time is more than this time interval, then failure happens. And the control circuit will switch "off" the optical switch. Moreover, the switching time of the OS in this experiment can be measured within 10 ms, as shown in Fig. 6.

The control circuit is used to detect the time of the upstream packet. For the maximum length of the upstream optical packet is 512 ns, if the detected time is more than this time interval, then failure happens. And the control circuit will switch "off" the optical switch. Additional analysis using simulation (VPI TransmissionMakerV7.5) has been included. In the analysis, an optical packet (assuming all is logic "1") of packet length of 512 ns is detected by a PD with different receiver bandwidth (Bessel 3rd order). We can observe the detected packet lengths have nearly the same time interval when the receiver bandwidth is more than 50 MHz, as shown in Fig. 7.

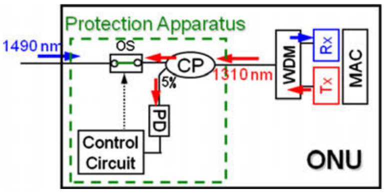

Fig. 5. The proposed self-protection module to prevent the CW upstream effect on each ONU in TDM-PON system.

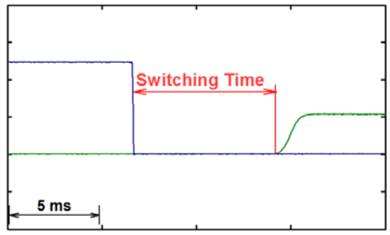

Fig. 6. Switching time measurement of the optical switch used in this experiment.

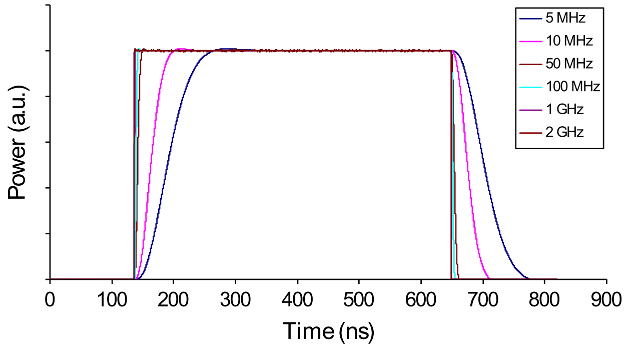

Fig. 7. An optical packet of packet length of 512 ns is detected by a PD under different receiver bandwidth of 5 MHz, 10 MHz, 50 MHz, 100 MHz, 1 GHz and 2 GHz, respectively.

As a result, the proposed protection apparatus can protect the transmission integrality of the TDM access network when the CW upstream lightwave is produced because of the ONU failure.

3. Conclusion

In summary, we have first analyzed and demonstrated the CW upstream effect in TDM-PONs. Besides, we also propose and design a protection apparatus in each ONU to avoid a CW upstream channel in TDM-PONs due to sudden external environment change or failure of ONU, resulting in the burst-mode traffic to CW status. In this measurement, an upstream signal with larger power is more tolerant to upstream CW effect. However, a smaller upstream power is more easily affected by beating noise under CW injection. In this demonstration, the upstream CW injected light can be blocked to the Rx at OLT by a simple protection scheme consists of OS and PD. Moreover, the proposed protection apparatus can stop the CW effect within a few ms while a CW light occurs in one ONU.

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