Low-Cost 100G Coherent PON Enabled by TFDM Digital Subchannels and Optical Injection Locking

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Abstract: We demonstrate a novel 100G TFDM coherent PON architecture featuring low-cost ECL-free ONU enabled by remote optical carrier delivery through injection locking. System performance shows no degradation compared to a regular ECL based system.

1. Introduction

Driven by the ever-growing demands for higher bandwidth, today's optical access network is rapidly evolving towards higher capacity, better coverage, and greater penetration. Among the various access technologies, passive optical network (PON) benefits from a passive point-to-multipoint topology that enables efficient resource sharing and has been widely deployed around the world over the last two decades [1, 2]. Although existing PON solutions extensively employ intensity-modulation direct-detection (IM-DD) technology, this path is gaining more and more challenges for the emerging 100G PON due to limited link budget and severe transmission impairments. To address the challenges, coherent PON is considered a future-proof solution thanks to its high sensitivity, advanced modulation formats, and powerful digital signal processing (DSP) capabilities. Several coherent PON technologies have been developed in the past, including coherent time-division-multiplexing (TDM) PON [2, 3], coherent wavelength-division-multiplexing (WDM) PON [4], and coherent time-and-frequency-division multiplexing (TFDM) PON [5, 6]. TDM coherent PON, while offering a practical solution by sharing bandwidth in the time domain, may need new scheduling algorithm for reduced latency in the big covering group. WDM coherent PON can provide more flexible bandwidth allocation, but requires multiple wavelengths and colored optics, which introduce additional cost and operational complexity. TFDM coherent PON uses digital subcarrier multiplexing and provides flexible bandwidth sharing in both the time domain and frequency domain while only requiring a single wavelength, making it a promising candidate for future access networks [5].

Although extensive efforts have been made to simplify coherent optics for short-haul applications, the high cost associated with the products that exist today is still the main obstacle to enabling large-scale adoption for access networks. High quality optical sources, typically external cavity lasers (ECLs) as transmitter sources and local oscillators (LOs), contribute a significant portion of the cost in a coherent module. Optical injection locking (OIL), in which a laser subjected to external light injection, is frequency and phase locked to the external optical tone [7], offers a viable route to low-cost coherent optics for PON applications, particularly for customer premise devices.

In this work, we propose and experimentally demonstrate a novel TFDM coherent PON architecture that features remote delivery of two optical tones to the optical network units (ONUs). By power-amplifying the remotely delivered optical tones through OIL [7] to provide optical carrier and LO at the ONU, significant cost reduction in optical hardware can be achieved by replacing high-cost lasers such as ECLs with inexpensive Fabry-Perot laser diodes (FP-LDs). We experimentally studied the proposed architecture and no significant performance penalties were observed when compared to a regular ECL-based system. Additionally, the proposed architecture benefits from the frequency synchronization of the ONU light sources with the optical line terminal (OLT) lasers and can mitigate random frequency drifts on ONUs introduced by independently operated lasers.

2. Operating Principles

Fig. 1(a) shows the conceptual scheme of the proposed TFDM coherent PON architecture with remote laser source delivery. Leveraging the highly flexible bandwidth allocation capability of TFDM coherent PON [6], different subcarrier configurations can be used for a variety of capacities and link budgets. As an example, in the downstream (DS) direction two subcarriers are generated on a single wavelength in the OLT. Two optical tones centered at frequencies f_1 and f_2 for remote delivery, are combined with the TFDM signal for DS transmission. One of the tones at f_1, which is identical to the optical carrier frequency of the DS TFDM signal, is used to generate the LO for DS signal detection at the ONU through OIL. The other optical tone at f_2 is used to generate an optical carrier through OIL at the ONU for upstream (US) signal transmission. Note that the optical power of both tones is amplified by the OIL process, eliminating the need for an additional optical amplifier. In the US direction, four TFDM subcarriers are generated at the ONU with a carrier frequency of f_2. The layout of the TFDM subchannels is shown in Fig. 1(b). The two subchannels for DS transmission are placed in two 15 GHz frequency windows centered at -15 and +15 GHz with respect to f_1. Each DS subchannel is modulated with a 50 Gb/s dual polarization (DP)-quadrature phase shift keying (QPSK) signal at 12.5 GBd, for an aggregate DS data rate of 100 Gb/s. In the US direction, the four subchannels each occupy a 10 GHz frequency window, with center frequencies at -15, -5, +5 and +15 GHz with respect to f_2. Each US subchannel modulating with a 25 Gb/s DP-QPSK signal at 6.25 GBd, for an aggregated US data rate of 100 Gb/s. Frequency spacing between f_1 and f_2 is set to be, e.g., 100 GHz to match the ITU DWDM frequency grid.

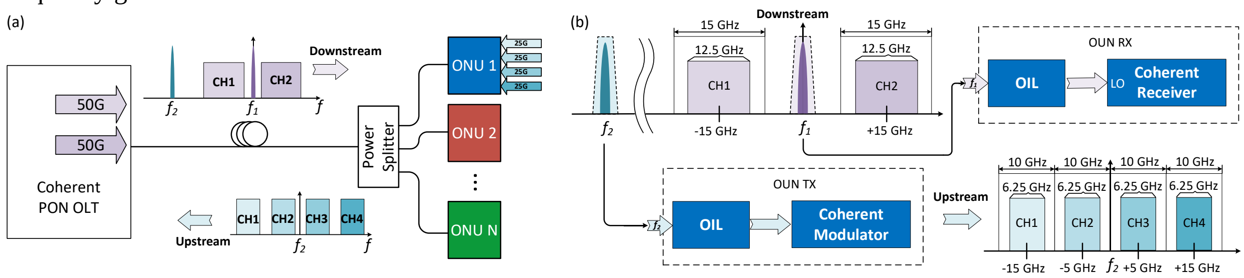

Fig. 1. (a) Proposed TFDM coherent PON scheme; (b) subchannel design for DS and US transmission.

3. Experimental Setup and Results

The experimental setup of the proposed TFDM coherent PON is shown in Fig. 2(a). On the OLT side, the output from one of the ECLs with a center frequency at f_1 (191.7 THz) is split into two parts. One is sent into a coherent driver modulator (CDM) to generate DS TFDM signals with two subcarriers, where the other is sent downlink. The output of the second ECL centered at f_2 (191.6 THz) is also split into two components, one is used as the LO of the OLT receiver for US signal detection, the other is also sent downlink. A homodyne coherent receiver is used to receive the US signal and an offline DSP is applied to demodulate the data. To emulate a bidirectional point-to-multi-point transmission, the optical network consists of a 50 km fiber link and a 1×32 passive optical splitter. On the ONU side, a multiport tunable optical filter (TOF) separates the DS TFDM signals and the two optical tones. One of the optical tones centered at f_1 is fed into an OIL setup, consisting of a polarization controller (PC), a three-port optical circulator, and a FP-LD, to produce an LO that is coupled to a homodyne coherent receiver with offline DSP for DS signal detection. The other optical tone centered at f_2 is used to generate an optical carrier for US transmission through another OIL setup. The output of the OIL is sent into a CDM to produce four-subcarrier US TFDM signals. Note that for demonstration although we only use discrete components for the experimental setup, for potential commercial products the OIL setup and TOF can be integrated, leveraging cutting-edge photonic integration technology to reduce the ONU cost. Fig. 2(b) shows the optical spectrum of the two-channel TFDM signal with the two optical tones in the DS direction. Fig. 2(c) shows the optical spectrum of the US TFDM signal with four subchannels. Fig. 2(d) shows an optical spectrum of the FP-LD before injection locking, where Fig. 2(e) shows the injection locking FP-LD spectrums with locking frequencies at f_1 and f_2 respectively.

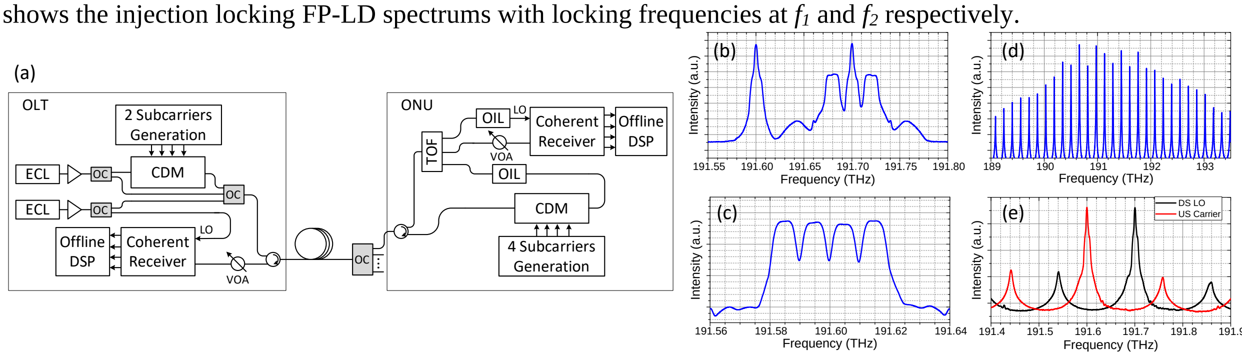

Fig. 2. (a) Experimental setup; (b) spectrum of TFDM DS channels and two optical tones; (c) spectrum of TFDM US channels; (d) free-running FP-LD spectrum; (d) injection locked FP-LD spectrums.

Several experimental verifications aimed at demonstrating the performance of the proposed TFDM coherent PON architecture with remote optical carrier transmission for ONU transmitters and LO have been performed. For DS transmission using an OIL laser as ONU LO, the bit-error-rate (BER) performance is plotted against the received optical power (ROP) per channel for both TFDM subchannels over a 50 km fiber transmission and a 32-way split in Fig. 3(a) and (b). Back-to-back (B2B) BER vs. ROP results for both subchannels using the OIL LO are also measured. Additionally, fiber transmission and B2B BER performance using regular ECL as LO are included in each chart, along with staircase hard-decision (HD) forward error correction (FEC) threshold (BER=4.5E-3) and concatenated soft decision (SD) FEC threshold (BER=1.2E-2) for references. The system functionality of the proposed architecture was demonstrated in DS transmission, no significant performance degradation was observed when using a remotely delivered optical tone in combination with OIL for ONU LO compared to regular ECL LO.

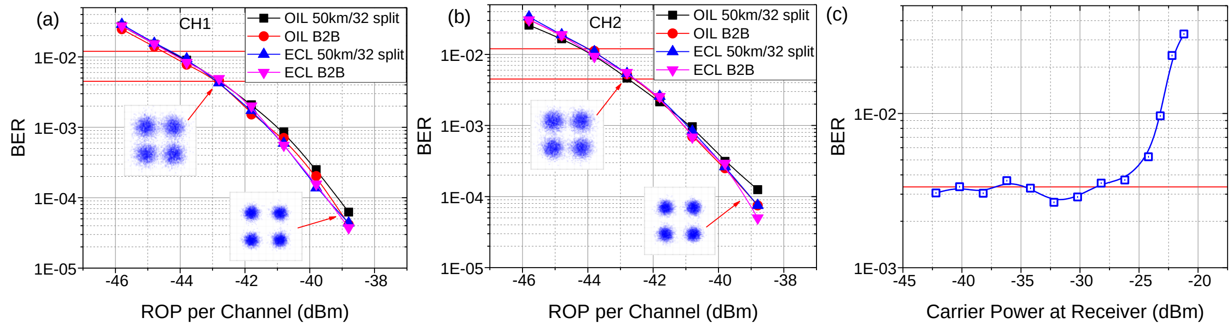

Fig. 3. Experimental results for DS transmission: (a) BER versus ROP in TFDM CH1; (b) BER versus ROP in TFDM CH2; (c) impact of received optical carrier power on TFDM signal.

Since the optical carrier is centered between the TFDM subchannels, it is important to understand its impact to the adjacent subchannels. Fig. 3(c) shows the BER performance of a TFDM subchannel at different optical carrier power values. The optical power of the carrier and the TFDM subchannel is measured separately at the receiver, the carrier power is adjusted by a variable optical attenuator, with the TFDM subchannel power fixed at -40.2 dBm. The red line in Fig. 3(c) represents the BER value of 3.34E-3 as a reference when no optical carrier is present. From the results in Fig. 3(c), it can be seen that, thanks to the effective digital filtering capability of the TFDM DSP [5], the optical carrier does not have a significant impact on the TFDM subchannel until its power is much higher than the TFDM signal (i.e., >-25 dBm carrier vs. -40 dBm TFDM signal). In the experiment with the TOF, we keep the received carrier power below -30 dBm, to avoid affecting the TFDM signals. By keeping the received carrier power below -25 dBm, the system can be further simplified by removing the receiver-side TOF.

Fig. 4(a)-(d) show the system performance for US transmission, each of the four TFDM subchannels is measured and plotted separately. The BER vs. ROP per channel performance and constellation diagrams for each TFDM subchannel using an OIL transmitter laser for a 50 km fiber transmission and a 32-way split are plotted in each sub-figure. For reference, B2B BER vs. ROP results using OIL laser are included in each chart, along with fiber transmission BER vs. ROP performance and B2B results using an ECL for comparison. At both the staircase HD FEC threshold (BER=4.5E-3) and the concatenated SD FEC threshold (BER=1.2E-2), the system performance in each subchannel indicates that when used of OIL as a transmitter light source there is no performance penalty compared to ECL light source. Note that the power budget difference between subchannels is minimal, thanks to the previously reported pre-equalization and power rebalancing algorithms [6].

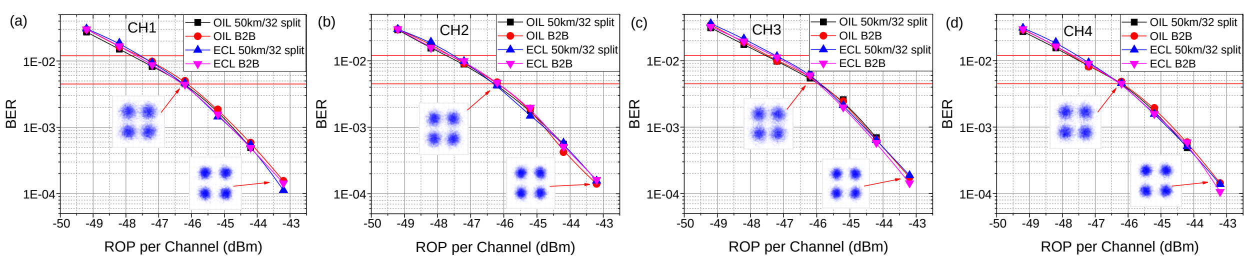

Fig. 4. Experimental results for US transmission: (a) BER versus ROP in TFDM CH1; (b) BER versus ROP in TFDM CH2; (c) BER versus ROP in TFDM CH3; (d) BER versus ROP in TFDM CH4.

4. Conclusion

We propose and demonstrate a novel TFDM coherent PON architecture that provides remote optical carrier delivery to the ONU to enable low-cost laser sources at customer premises, which is one of the key challenges in coherent PON implementations. The downstream and upstream transmission of the proposed scheme are investigated experimentally and show negligible performance degradation compared to a regular ECL-based system. Additionally, benefiting from the frequency locking of the ONU light sources to the OLT lasers, the proposed architecture can mitigate random frequency drifts on ONUs introduced by independently operated lasers.

Reference

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