Novel EA-DFB Mode-Switching Transmitter Supporting Continuous Phase Frequency Shift Keying and Intensity Modulation for All-Photonics Network

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Abstract *A novel transmitter that offers both short-reach IM-DD transmission and higher optical budget coherent transmission is proposed for cost-effective user terminals. 25 Gb/s signal detection experiments confirm enhanced optical budget of 13 dB with high sensitivity of -37.7 dBm by modulation format switching.*

Introduction

New attractive services that utilize distributed computing resources on networks have emerged; such as the autonomous operation of facilities, connected cars, telesurgery based on high definition video streaming and haptics-immersive communication, cloud data center and so on. Since these applications require ultra-low latency and sufficiently high bandwidth, conventional electrical-aggregation-based networks are unsuitable. Recently, the All-Photonics Network (APN) was proposed as a part of the Innovative Optical and Wireless Network (IOWN)[1]. The basic concept of APN is minimizing electrical switching and routing processing on the communication path by the aid of wavelength division multiplexing (WDM) based optical routing technology, which realizes end-to-end connections without any electrical aggregation. It realizes ultra-low latency application services in that it not only minimizes the packet queuing time but also eliminates the process of data encode and decode through the uncompressed high-capacity data transmission enabled by APN. In addition, APN can decrease the total energy consumption of the network, since the optical switching devices generally have lower energy consumption than electrical switching devices such as Layer 2 switch.

Fig. 1 overviews APN. APN consists of “Core full-mesh”, “Local full-mesh” and “Access area”, these correspond to conventional core, metro and access networks, respectively. At the entrance of this mesh-topology-based network, optical switching systems called photonic gateway (Ph-GW) are deployed to accommodate user terminals (UTs) distributed in the access area. The UTs communicate using arbitrary optical paths and wavelengths, allocated by an APN controller connected to Ph-GW that considers wavelength usage in APN. Ph-GWs control the optical path by changing connection ports of optical switches when starting communication between UTs, as directed by the APN controller. For example, when UTs are accommodated by the same Ph-GW, the Ph-GW uses a turn back port to directly connect the UTs (see Fig. 1)[2]. When the UTs are accommodated by different Ph-GWs located far from each other, optical signals are transmitted through multiple Ph-GWs and long fibers. For this usage case, Ph-GW must have not only optical repeaters but also 3R repeaters in order to compensate the increased optical path loss and signal to noise ratio (SNR) degradation created by chromatic dispersion. Although repeater devices are effective for reach extension, we have to consider repeater power consumption and cost because utilizing many repeater devices may degrade the APN benefits of low energy consumption and high cost-effectiveness.

One way of suppressing the number of relay and repeater devices is to improve the optical budget between the UT and the 3R repeater. Digital coherent reception assisted by optical preamplification can achieve high optical

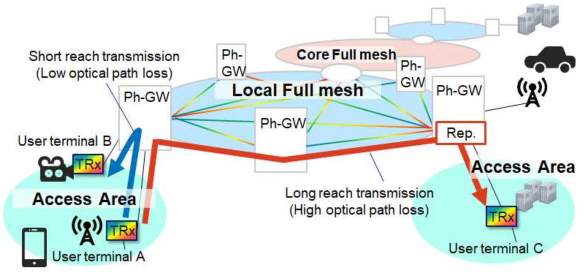

Fig. 1: Overview of All-Photonics Network (APN)

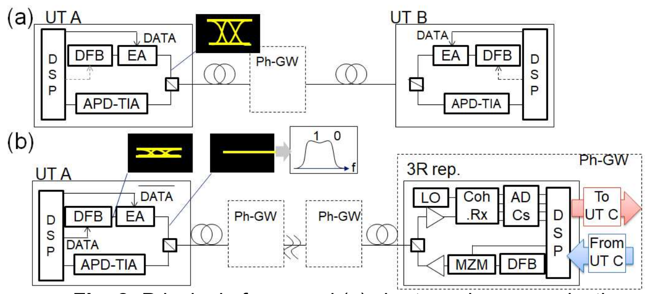

Fig. 2: Principal of proposal (a) short reach communication between UTs, and (b) long reach communication between a the UT and a 3R Repeater

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budgets [3]. However, the conventional coherent transceivers utilized in existing core networks will increase of cost and power consumption of the UT side because of the complex optical front-end and advanced digital signal processing (DSP) circuit needed. Therefore, conventional coherent transceivers should not be used for all UTs, mandating a new transmission method for the UT that realizes high optical budgets and cost-efficiency with lower power consumption.

We have already investigated the electro absorption modulator integrated distributed feedback laser (EA-DFB-LD) based continuous phase frequency shift keying (CPFSK) transmitter and detailed a digital coherent reception scheme for 10G-class passive optical network (PON) upstream transmission; it increases the optical budget in a cost-effective manner[4,5].

This paper extends our advances to APN by proposing a novel intensity modulation (IM) and CPFSK transmitter that uses same EA-DFB-LD to realize modulation format switching to suit the required optical-budget. Its feasibility is evaluated in 10 Gb/s and 25 Gb/s signal reception experiments. Notably, it is a first demonstration of high sensitivity reception for 25 Gb/s CPFSK signals generated by directly modulating of a DFB-LD.

Proposed configuration

Fig.2 shows that the proposed UT consists of an EA-DFB-LD as transmitter, an avalanche photo diode (APD) as a direct-detection (DD) receiver and a DSP. The UT switches modulation format between IM and CPFSK according to the transmission-mode-control signals informed by the Ph-GW using control channels such as the auxiliary management and control channel (AMCC). AMCC is also used for route and wavelength notification [2].

Fig. 2(a) shows short reach transmission between the UTs. The UT transmits IM signals modulated by EA modulator for reception by the APD of the other UT. Here, we assume the use of C- and/or L-band signal transmission. To compensate part of the waveform distortion caused by limited bandwidth of TRx and chromatic dispersion, the DSP offers simple time domain equalization.

Fig. 2(b) shows long reach transmission between the UT and 3R repeater. Here, we define the communication direction from the UT to the 3R repeater as upstream and the opposite direction as downstream. For upstream transmission, CPFSK signals are generated by direct modulation of the bias current of DFB-LD which causes frequency and phase shift of output signals. In this paper, we assume the use of binary non-return zero (NRZ) signals for CPFSK

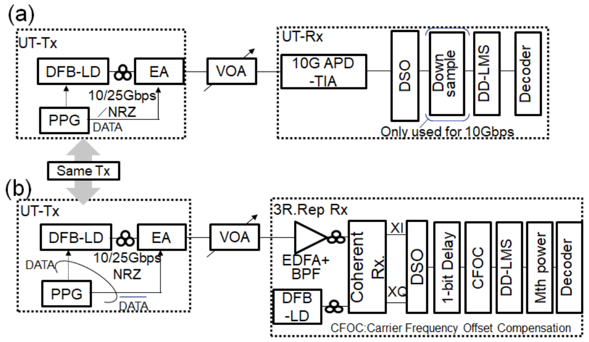

Fig. 3: Experimental setup; (a) IM-DD and (b) CPFSK detection

Tab. 1: Typical parameters for IM-DD detection

	10 Gb/s	25 Gb/s
Extinction ratio	6 dB	
Receiver bandwidth	10 GHz	
ADC sampling rate	20 GSa/s (downsampled)	25 GSa/s
Over sampling rate	2	1
FIR filter tap length	7	

Tab. 2: Typical parameters for CPFSK detection

	10 Gb/s	25 Gb/s
Modulation index:h	0.85	
Receiver bandwidth	23 GHz	
ADC sampling rate	50 GSa/s	100GSa/s
Over sampling rate	5	4
1 bit delay time	0.6 T	0.75 T
FIR filter tap length	15	
Output pow. of LO	+ 10 dBm	

modulation. Here, undesirable IM components that degrade the SNR in space '0' level of received signals are erased by the EA modulator realizing data inversion (see Fig.2 (b))[4].

At the receiver side, the DSP converts the FSK signals to phase modulated signals by the differential detection blocks and demodulates them. Combining coherent detection with optical preamplification significantly improves the optical budget compared to the IM-DD scheme shown in Fig.2 (a). For downstream transmission, IM signals are transmitted and directly detected by the APD in UT. An optical post-amplifier is utilized to increase the downstream optical budget to equal that of the upstream. However, it is difficult to remove the transmission penalty completely in the IM-DD scheme in spite of using the equalizer at the UT. Therefore, we assume that the 3R repeater utilizes a chirp-controlled Mach-Zehnder modulator to suppress the SNR degradation created by chromatic dispersion[6]. This asymmetrical transmission scheme offers high optical budget for communication between the UT and the 3R repeater equipped in the Ph-GW without complicated optical transceivers in the UT.

Experiments and results

To evaluate the optical budget of the proposal, we conducted bit error rate (BER) measurements for 10 Gb/s and 25 Gb/s signals. Notably, we utilized the same Tx to generate IM and CPFSK signals. Fig. 3(a) shows the experimental setup for IM-DD detection. The UT-Tx consists of a DFB-LD and an EA. The EA is operated by NRZ signals with pseudo random bit sequence pattern (PRBS) of 2^{15}-1. The Tx output power and center wavelength are set to 0 dBm and 1553.45 nm, respectively. A variable optical attenuator (VOA) emulates the optical path loss caused by fiber transmission and Ph-GW.

The receiver side is consisted of an APD and a digital storage oscilloscope (DSO). After analogue to digital conversion, an offline DSP, consisting of an adaptive filter based on decision directed least mean squared (DD-LMS) algorithm and a decoder, processes sampled data. Here, we used a 10G-class APD as the UT receiver since 25G-class APDs for C-band are not sufficiently mature. Although a dedicated receiver designed with proper electrical bandwidth against the baud rate would offer higher sensitivity, utilizing cost-effective and mature low-bandwidth devices combined with DSP technology is still attractive for the UT. Typical parameters used in IM-DD detection are summarized in Tab. 1. To prevent increasing UT cost, we assume the ADC's sampling rate is below 25 GSa/s. Thus 10 Gb/s received signals are first sampled at 50 GSa/s, then downsampled to 20 GSa/s.

Fig. 3(b) shows the experimental setup for CPFSK detection. The Tx used in IM-DD measurement is applied. Tab. 2 shows typical parameters used in CPFSK measurements. The Tx output power and center wavelength are also set to 0 dBm and 1553.5nm, respectively. Compared to the IM scheme, both DFB-LD and EA are operated by NRZ signals with PRBS of 2^{15}-1. Fig. 4 shows optical spectrums for 10 Gb/s (Fig. 4(a)) and 25 Gb/s modulated signals (Fig. 4(b)), with and without EA modulation. Modulation index h is 0.85 for both 10 Gb/s and 25 Gb/s modulation. As shown in the figure, the power difference between '1 ' and '0' is suppressed to 0 dB by the EA.

The receiver consists of an EDFA with noise figure of 5.1 dB, an optical band-pass filter (BPF), a DFB-LD as local oscillator (LO), a polarization and phase diversity coherent receiver, and a DSO. The received I-Q signals are sampled by the DSO, at sampling rate of 50 GSa/s for 10 Gb/s and 100 GSa/s for 25Gb/s signals. The sampled signals are processed by an offline DSP consisting of 1-bit delay differential detection, a carrier frequency offset compensation (CFOC)[5], a DD-LMS, an Mth power algorithm based phase rotation and decoder. In the experiments, state of polarization is manually controlled to the main axis for the coherent receiver by a polarization

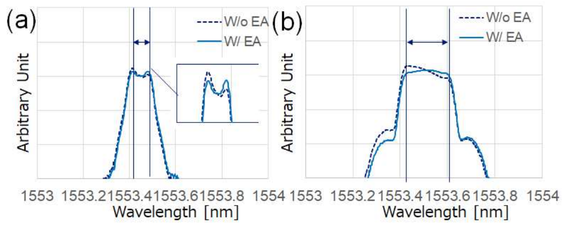

Fig. 4: Optical Spectrums of CPFSK signals; (a) 10 Gb/s and (b) 25 Gb/s modulated signals

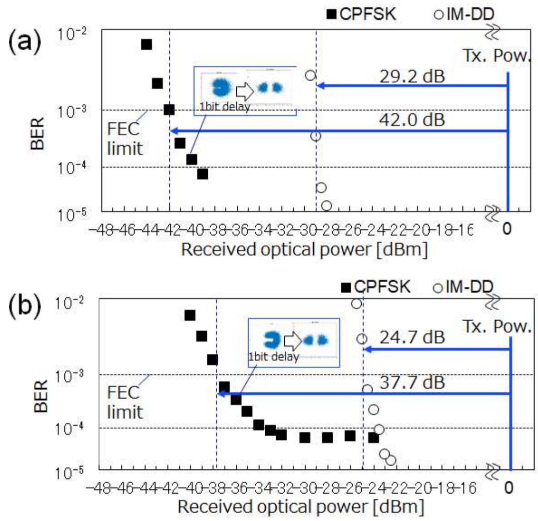

Fig. 5: BER characteristics; (a) 10 Gb/s and (b) 25 Gb/s signals detection

controller. The center wavelength differences between Tx output and LO output is 0 GHz.

Fig. 5 shows the measured results. The target forward error correction (FEC) limit to obtain error free operation is the BER of 10^{-3}. The receiver sensitivity for 10 Gb/s IM and CPFSK signals is -29.2 dBm and -42.0 dBm, respectively (see Fig. 5(a)). As a result, the enhanced optical budget of 12.8 dB is achieved by modulation format switching for the 10 Gb/s signals. Similarly, the receiver sensitivity for 25 Gb/s IM-DD and CPFSK signals is -24.7 dBm and -37.7 dBm, respectively (see Fig. 5(b)). The enhanced optical budget is 13.0 dB which equals 52 km reach extension assuming the fiber loss of 0.25 dB/km.

Conclusion

APN realizes ultra-low latency and high transmission capacity networks by minimizing electrical aggregation devices in the communication path. One key issue with APN is how to realize both short and long reach transmission with cost-effective UTs. We proposed a novel transmitter configuration that enables the same Tx to realize both IM and CPFSK modulation. Experiments confirmed the proposal achieved the high sensitivity of -37.7dBm and -24.7 dBm for 25 Gb/s CPFSK signals and IM-DD signals, respectively. The modulation format switching proposal achieved the large optical budget enhancement of 13 dB.

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