Negative-Chirped EAM-SOA for Distance-Insensitive Optical OFDM Transmission in Long-Reach OFDMA PONs

Kuo-Chun Chang, Shin-Wei Shen, Mao-Chin Hsu, Yi-Jen Chiu, Chia-Chien Wei*, and Chao-Kuei Lee
Department of Photonics, National Sun Yat-sen University, Kaohsiung 804, Taiwan
*ccwei@mail.nsysu.edu.tw

Abstract: Enabled by negative-chirped EAM-SOA, we successfully demonstrate 23-Gbps OFDM transmission in the range of 60~100 km without adaptive bit- and/or power-loading. This distance-insensitive performance reveals the feasibility of simple and efficient OFDMA LR-PON.
OCIS codes: (060.4080) Modulation; (130.5990) Semiconductors; (230.4205) Multiple quantum well (MQW) modulators

1. Introduction

Due to the exponentially increasing of customer needs for broadband services, there have been growing interests in a new type of optical access networks, the so-called long-reach passive optical networks (LR-PONs) [1-5]. By integrating access networks with metro networks within the target range of 60~100 km, LR-PON claims to considerably reduce the capital and operational expenditures by increasing the coverage of the central office (CO) and consolidating the O/E/O conversion interfaces. Besides, the intensity modulation and direct detection (IMDD) scheme is still a promising candidate in LR-PONs to meet the requirement of low cost, and the technically matured 10-GHz-class electronics and optoelectronics are especially preferred. Accordingly, to achieve high capacity in a 10-GHz-class IMDD system, many recent reports have demonstrated spectrally efficient optical transmission based on orthogonal frequency division multiplexing (OFDM) modulation based on directly modulated DFB lasers (DMLs) or electro-absorption modulated lasers (EMLs) [4,5]. In addition to spectral efficiency, orthogonal frequency division multiple access (OFDMA) is an efficient multiple-access scheme, and it enables dynamic bandwidth granularity in optical access networks [6].

Moreover, the key transmission impairments of IMDD-based OFDM signals would be dispersion-relevant power fading and nonlinear distortion [5]. Although a few schemes have been proposed to eliminate the nonlinear distortion [7,8], the issue of power fading is still left by only applying bit- and power-loading to optimize bandwidth utilization. Actually, power fading still reduces available bandwidth and spectral efficiency [5]. Furthermore, the transmission performance will vary with the transmission distance, and both the modulation format and power allocation of subcarriers need to be adaptively controlled according to the transmission distance. For instance, the frequency of the first 3-dB power fading of a chirp-free IMDD signal will change from 5.7 to 4.4 GHz, as the fiber distance increases from 60 to 100 km [5]. In fact, the frequency of fading will further decrease as employing DMLs or EMLs of positive frequency chirp. Then, due to different distances from a CO to various optical network users (ONUs) in a LR-PON, different performances of ONUs will lead to more complex network management, and OFDMA is difficult to be effectively implemented.

In this work, an integrated modulator composed of an electro-absorption modulator (EAM) and a semiconductor optical amplifier (SOA) is proposed to realize an optical OFDM signal of negative frequency chirp. The negative chirp would not only provide power gain after fiber transmission but also extend the available modulation bandwidth. The measured chirp parameter is as low as −1.4, and the 3-dB bandwidth after 100-km transmission reaches ~6.7 GHz. As a result, the 23-Gbps OFDM signal with 6-GHz bandwidth and the fixed 16-QAM format is successfully demonstrated to achieve the FEC limit in the range of 60~100-km fiber transmission without the requirement of adaptive bit- and power-loading. Such distance-insensitive performance ensures simple network management and the feasibility of efficient OFDMA LR-PON.

2. Integrated EAM-SOA

A schematic diagram of the integration between SOA and EAM is plotted in Fig. 1(a). The material of active region used for modulation and amplification is a MOCVD-grown InGaAsP multiple quantum well (MQWs), which is sandwiched by a top p-InP and a bottom n-InP cladding layers for optical waveguide. Due to the quantum confined Stark effect (QCSE) in MQW, the modulated signal can be controlled as positive or negative chirped, depending on the bias of EAM [9]. Although the negative chirp can be obtained by large bias, the optical absorption inevitably lowers microwave link in transmission system. By integrating SOA with EAM, not only the signal can be amplified, but also the controllability in modulation efficiency and chirp can has more freedom. The output optical power with EAM bias is plotted in Fig. 1(b). Through current injection of SOA, the large modulation slope efficiency can be maintained in high level, while the negative chirp is still kept high level.

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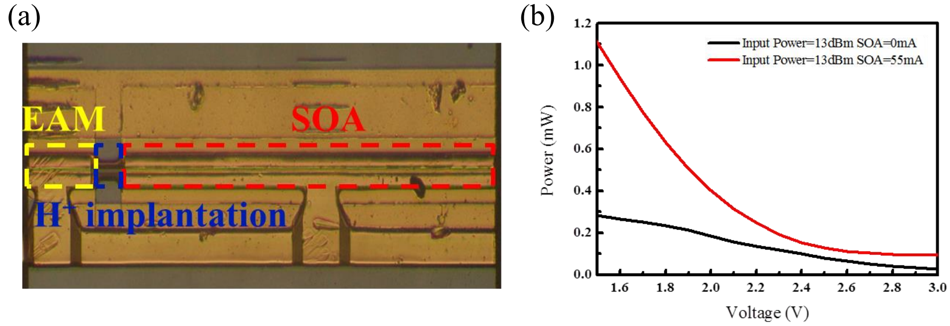

Fig. 1: (a) The schematic plot of the integration between EAM and SOA, and (b) the output optical power against with EAM bias at various SOA current levels.

3. Experimental Setup and Results

Fig. 2 shows the experimental setup. The electrical OFDM signal is generated by an arbitrary waveform generator (AWG) with using an off-line Matlab® program. The sampling rate and the DAC resolution of the AWG are 24 GS/s and 8 bit, respectively. The fast-Fourier transform size is set as 512 resulting in the subcarrier spacing of 46.88 MHz. The CP is 1/64, and the modulation format is fixed 16-QAM in the experiment. The bias voltage of the EAM is set either 1.6 V or 2.4 V to represent the case of the normally low chirp and the desired negative chirp, respectively, and the current of the SOA is set 55 mA. The peak-to-peak driving voltage is set 1.2 V after optimization. After optical intensity modulation based on the integrated EAM-SOA and 60~100-km standard single-mode fiber transmission, the optical signal of −6 dBm is detected by a single 10-GHz-class PIN, and the received electrical signal is recorded by a digital oscilloscope with 50-GS/s sampling rate, 8-bits ADC resolution and 3-dB bandwidth of 12 GHz. An off-line Matlab® DSP program is then applied to demodulate the OFDM signal, and the program includes the 2^{nd}-order nonlinear compensation to suppress both the dispersion-induced transmission distortion and the modulator nonlinearity [7]. After demodulation, the signal performance is evaluated by signal-to-noise ratio (SNR) and BER, which is measured by error counting.

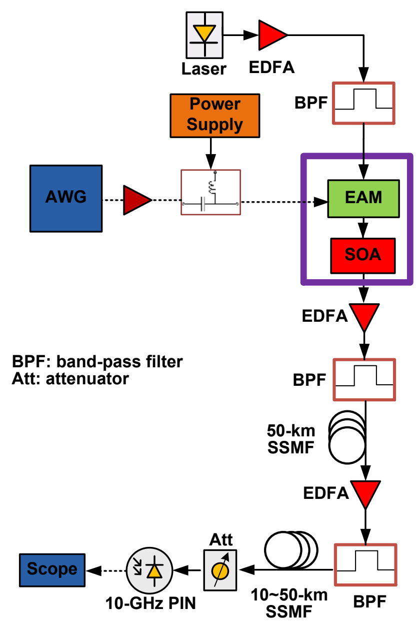

Fig. 2: Experimental setup

Instead of using a network analyzer to measure the small-signal transmission response, we directly apply the OFDM signal to test the large-signal transmission response, and the OFDM signal contains 224 subcarriers to occupy 10.5-GHz bandwidth. The measured responses are plotted in Fig. 3. After 60-km and 100-km transmission, the 3-dB bandwidths are only ~5.4 GHz and ~4.3 GHz in Fig. 3(a), respectively, but they are extended to ~8.5 GHz and ~6.7 GHz in Fig. 3(b), respectively. Moreover, compared with the small-signal model [5], Figs. 3(a) and (b) imply that the chirp parameters at the bias of 1.6 V and 2.4 V are about 0 and −1.4, i.e. the low-chirp and the negative-chirp cases, respectively. In fact, compared with Fig. 3(a), the negative chirp in Fig. 3(b) can provide not

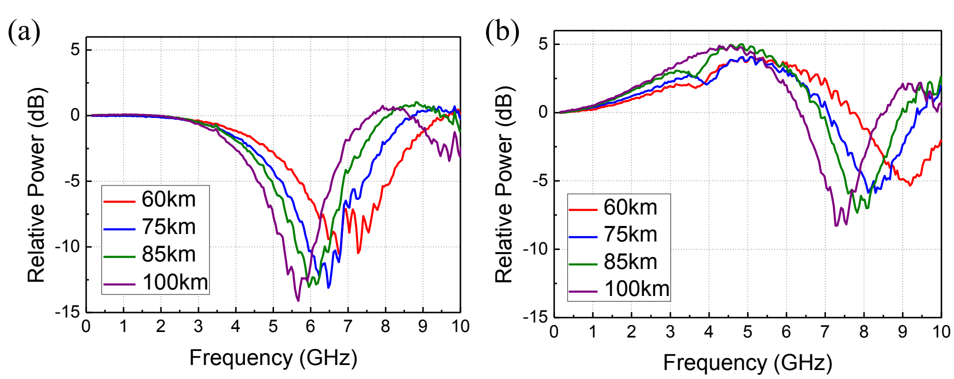

Fig. 3: Transmission frequency responses of the OFDM signal at the bias of (a) 1.6 V and (b) 2.4 V

only wider transmission bandwidth but also power gain. When the bias is 2.4 V, the subcarriers at the frequency of 0~6.3 GHz will enjoy the power gain even after 100-km transmission. Consequently, to achieve distance-insensitive transmission in a LR-PON of 60~100-km coverage, the ~6-GHz OFDM signal is adopted by setting 125 subcarriers, and the total capacity is 23 Gbps excluding CP. The measured SNR is exhibited in Fig. 4. At optical back-to-back (BtB), the SNR at the bias of 1.6 V is higher than that at 2.4 V owing to better modulation linearity. Nonetheless, in the transmission range of 60~100 km, the SNR at 2.4 V is improved thanks to the power gain provided by the negative chirp, but the power fading causes SNR degradation at 1.6 V. Furthermore, without adaptively controlling the subcarrier powers, the SNR is getting worse after longer transmission in Fig. 4(a), but the SNR is kept about the same to achieve distance-insensitivity in Fig. 4(b). Fig. 5 shows the measured BER of the 23-GHz OFDM signal at optical BtB and after 60~100-km fiber transmission, and the selective constellation diagrams are also plotted. Although the BER cannot reach the FEC limit (BER of 3.8×10^{-3}) at optical BtB, the case at the bias of 2.4 V can maintain the BER lower than the FEC limit in the target range of 60~100 km. In contrast, the BER at the bias of 1.6 V will increase with transmission distance, and it cannot attain the FEC limit after ~80-km transmission.

4. Conclusion

This work proposes to employ the integrated EAM-SOA to realize an optical OFDM signal of negative frequency chirp. When the bias is set 2.4 V, the chirp parameter is as low as 1.4, which not only extends the 3-dB bandwidth to ~6.7 GHz but also provide power gain at 0~6.3 GHz after 100-km fiber transmission. As a result, the 22-Gbps OFDM signal with 6-GHz bandwidth and the fixed 16-QAM format is experimentally demonstrated to achieve the FEC limit in the range of 60~100-km fiber transmission, and neither adaptive bit- nor power-loading is required. For comparison, the 6-GHz OFDM signal of low chirp will suffer from capacity penalty and require bit- and/or power-loading after ~80-km transmission. As a result, assisted by the negative chirp of the integrated EAM-SOA, we successfully carry out the distance-insensitive performance to ensure simple network management and the feasibility of efficient OFDMA LR-PON.

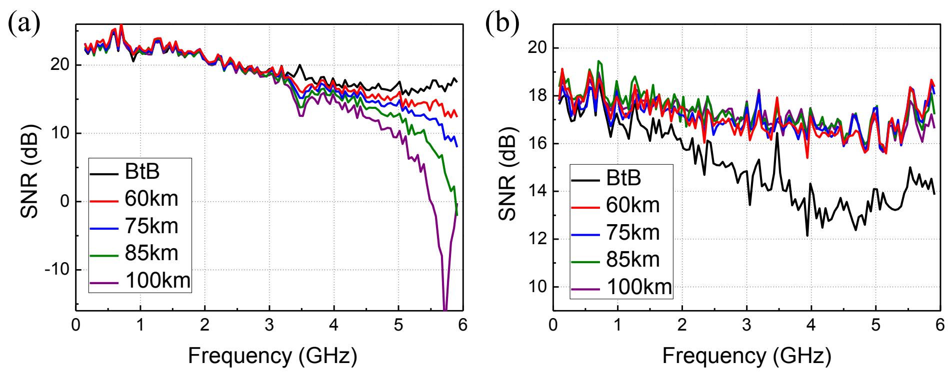

Fig. 4: The measured SNR of the OFDM signal at the bias of (a) 1.6 V and (b) 2.4 V

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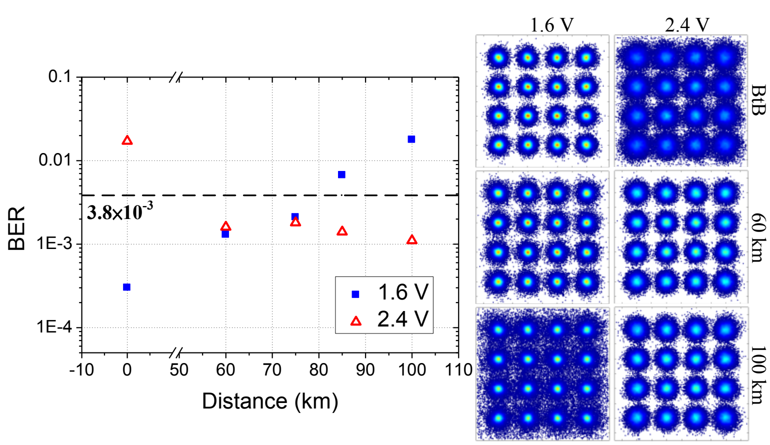

Fig. 5: BER and constellations