Directly modulating a long weak-resonant-cavity laser diode at limited bandwidth of 5 GHz with pre-leveled 16-QAM OFDM transmission at 20 Gbit/s

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Abstract: Coherently injection-locked and directly modulated long weak-resonant-cavity FPLD for pre-leveled optical 16-QAM OFDM transmission in DWDM-PON at 20.25-Gbit/s over 25-km is demonstrated with receiving sensitivity of -8dBm at EVM of 8% and BER of 3.8×10^-3.
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1. Introduction
Optical orthogonal frequency division multiplexing (OFDM), a highly spectral usage and efficient modulation format, using versatile light sources has recently emerged for next-generation optical networks with transmitters possessing limited modulation bandwidth [1, 2]. Not long ago, the OFDM format has also been applied to the dense wavelength-division-multiplexed passive optical networks (DWDM-PONs). Numerous investigations were gradually focused on developing the directly modulated laser diode transmitters for carrying M-ary QAM and multi-subcarrier OFDM data [3, 4]. Among the potential DWDM-PON transmitters, a long weak-resonant-cavity laser diode (WRC-FPLD) designed with unique features of high mode density and low injection budget as compared to the conventional Fabry-Perot laser diode (FPLD) was considered to meet both the demands of colorless operation and OFDM transmission. Such a quasi-color-free light source has successfully demonstrated up to 2.5 Gbit/s DWDM-PON up-stream transmission with the injection-locking at different channels via a broadband amplified spontaneous emission source [5, 6]. However, the long-cavity WRC-FPLD packed by a cost-effective TO-56-can still possesses a gradually declined frequency response by injection-locking and a limited modulation bandwidth up to 4-5 GHz. This becomes a criterion on employing the OFDM modulation for the long-cavity WRC-FPLD. Recently, the fusion of OFDM with bit-loading or pre-scaling techniques have been considered to modify the QAM formats of the original data-stream carried by different OFDM subcarriers. In this work, we demonstrate an achievement on compensating the limited modulation bandwidth of the long-cavity WRC-FPLD to implement the 16-QAM OFDM transmission at total data bit-rate of 20.25 Gbit/s after 25-km transmission. The external injection-locking is applied to enhance the coherent and immune dispersion properties of the long-cavity WRC-FPLD at selected wavelength. The optimized operation parameters of such a long-cavity WRC-FPLD with improved error vector magnitude (EVM) and bit error rate (BER) of the carrier OFDM data are discussed. The declined modulation throughput is compensated by individually pre-leveling the power spectrum to significantly overcome the high-frequency unflattened modulation response of the directly modulated long-cavity WRC-FPLD.

2. Experimental Setup
Figure 1 shows the experimental setup of the directly modulated and coherently injection-locked long-cavity WRC-FPLD with a cavity length of 600-900 μm and a limited modulation bandwidth of 5 GHz for the subcarrier pre-leveled 16-QAM OFDM transmission at 20-Gbit/s over 25 km. The pseudo random binary sequence (PRBS) data was serial-to-parallel mapped into 16-QAM format and was packed into 108 OFDM subcarriers. In contrast to the traditional OFDM data without additional processing, the amplitude of the parallel 16-QAM data was pre-leveled by a rising exponential function to compensate the declined modulation frequency response set by the long-cavity WRC-FPLD. These 16-QAM and 108-subcarrier OFDM digitized data was converted into analog stream in time domain via the inverse fast Fourier transform (IFFT), which was then fed into an arbitrary waveform generator (Tektronix, AWG 7122B) with a sampling rate of 24 GS/s for up-shift its central carrier frequency to 2.5 GHz. The OFDM data-stream was employed to modulate the long-cavity WRC-FPLD biased at twice of its threshold current via a bias-tee. A tunable laser source with its power varying from -12 to 0 dBm simulates as a down-stream Tx to control the injection-locked wavelength of the directly modulated long-cavity WRC-FPLD after passing through a polarization controller. In the Rx, The optical OFDM data transmitted through 25-km long standard single mode fiber (SMF) is picked up by an optical receiver (Nortel, pp-10G). The amplified analog data-stream was sampled by
a real-time oscilloscope (Tektronix, DSO 71254) with a sampling rate 100 GS/s. The time-domain OFDM waveform was FFT back to the frequency domain and decoded with the MATLAB demodulation software after resampling, and the constellation plot, EVM and BER analyses of the 16-QAM OFDM data carried by the coherently injection-locked and directly modulated long-cavity WRC-FPLD were compared with the original one.


3. Results and Discussions

The coherently injection-locked spectrum of the WRC-FPLD is shown in Fig. 1. Without power spectrum pre-leveling, the constellation plots and BER response of the transmitted 16-QAM OFDM data carried by the free-running or injection-locking long-cavity WRC-FPLD at different injection-locking powers are depicted in Fig. 2(a). In contrast to the EVM of 11.5% observed at free-running case, the clearly separated constellation plots with an EVM of 8% under 0-dBm injection-locking is obtained. As the injection power enlarges from -9 to 0 dBm, the BER of the long-cavity WRC-FPLD gradually decreases and saturates at 10^-4 as a result of the reduction of relative intensity noise and the up-shift of relaxation oscillation peak within modulation bandwidth. Typically, the suppression of relative intensity is enhanced under injection-locking to promote the SNR of the transmitted 16-QAM OFDM data. However, the declined frequency response of the directly modulated long-cavity WRC-FPLD is detrimental to the BER performance of the 16-QAM data carried by the OFDM subcarrier at high frequency region. Nevertheless, the modulated RF spectra exhibit a significant decay on throughput power at higher injection powers, such a negative power-to-frequency slope is inevitably enlarged due to intense injection-locking, as shown in Fig. 2(b). To improve this drawback, a power spectrum pre-leveling technique is employed to compensate the imperfect direct modulation response inherently accompanied with the coherent injection-locking of long-cavity WRC-FPLD.

Fig. 2. (a) BER and constellation plots vs. injection power; (b) RF spectra of transmitted 16-QAM OFDM data. (c) Pre-leveled OFDM spectra with different power-to-frequency slopes.

The enlarged negative power-to-frequency slopes with a definition of R=dP/df in unit of dBm/GHz were measured from the RF OFDM spectra carried by the long-resonant-cavity colorless diode are shown in Fig. 2(c). Afterwards, the 16-QAM OFDM data was pre-leveled with several power-to-frequency slopes of R=1.3, 1.9, 2.5 and 3.2 preset to equivalently compensate with that induced by the directly modulated long-cavity WRC-FPLD. As a result, the power-to-frequency slope compensated RF spectra of the OFDM data received after 25-km SMF transmission are shown in Fig. 3(a), indicating the optimized spectral pre-leveling parameter for the directly modulated long-cavity WRC-FPLD. The pre-leveling effectively improves the OFDM transmission performance at optimized power-to-frequency slope of dP/df=1.9 dBm/GHz, leading to a BER improved from 1.3×10^-4 to 3×10^-5 under injection-locking at 0 dBm. In addition, the spectral slope of the pre-leveled 16-QAM OFDM data must be
properly controlled to avoid the less or over compensation induced BER degradation, as shown in Fig. 3(b). To compare, the 16-QAM constellation plots obtained with throughput pre-leveled slopes of 3.2 and 1.9 dBm/GHz are shown in Fig. 3(c), in which the pre-leveled slope of 1.9 shows a perfectly flattened data spectrum and a better constellation plot. In contrast, the over compensation on RF spectrum of the transmitted OFDM data results in a vague constellation plot with a degraded carrier to noise ratio (CNR) at high frequency region.

Fig. 3. (a) RF spectra of pre-leveled 16-QAM OFDM data after receiving; (b) BER vs. pre-leveled power-to-frequency slope; (c) Constellation plots of over (left) and properly (right) pre-leveled 16-QAM data; (d) BER of 16-QAM OFDM data carried by injection-locked and directly modulated WRC-FPLD vs. receiving power after back-to-back and 25-km transmissions with and without pre-leveling.

Concurrently, the less compensation leads to an insufficient compensation with lower CNR on the OFDM data amplitude at high frequency. With injection-locking and spectral pre-leveling, the directly modulated long-cavity WRC-FPLD greatly improves its transmission performance at a total bit rate of up to 20.25 Gbit/s, as shown in Fig. 3(c). After 25-km transmission, the directly modulated long-cavity WRC-FPLD can deliver a 16-QAM OFDM data with its BER fitting the criterion of forward error correction (FEC, 3.8×10^{-3}) at a receiving power sensitivity of -8 dBm. With pre-leveling, the receiving power penalty can further decrease by 1.5 dB at the same BER set by FEC limit. The lowest achievable BER of 1×10^{-3} is reached over 25 km transmission by increasing the receiving power to -7 dBm with pre-leveling and injection-locking. Moreover, the power penalty between back-to-back and 25-km transmission is only 2 dB under pre-leveling and injection-locking operations. These results elucidate that the fusion of spectral pre-leveling techniques into the wavelength injection-locking WRC-FPLD based DWDM-PON transmitter can essentially compensate the modulated power declination and improve the BER of the 16-QAM OFDM data transmitted by the directly modulated and coherently injection-locked long-cavity WRC-FPLD.

4. Conclusion
The 16-QAM OFDM transmission of up to 20Gbit/s with a coherently injection-locked and directly modulated long-cavity WRC-FPLD transmitter in DWDM-PON has been demonstrated by pre-leveling the power spectrum of the 16-QAM OFDM data-stream in frequency domain. The tradeoff between the pre-leveled power-to-frequency slope of OFDM subcarrier and the wavelength injection-locking power level for the long-cavity WRC-FPLD are elucidated. The BER and 16-QAM constellations of the injection-locked and directly modulated long-cavity WRC-FPLD transmitter without and with spectral pre-leveling are compared. The negative power-to-frequency slope of the data spectrum at wavelength injection-locking case is inevitably enlarged as compared to that at free-running case; however, the noise suppression by injection-locking essentially improves the EVM form 11.5% to 8% and reduces the BER to 10^{-3}. With the aid of OFDM spectral pre-leveling, the declined frequency response of the directly modulated long-cavity WRC-FPLD can be effectively compensated. This further provides a BER improvement by one order of magnitude from 1.3×10^{-4} to 3×10^{-5}. The receiving power sensitivity at FEC limit is -8 dBm after 25-km transmission. The fusion of pre-leveling and injection-locking promotes the receiving power sensitivity to -10 dBm, and reduces the power penalty between back-to-back and 25-km transmissions to only 2 dB.

5. References