Long distance transmission of SC-FDMA signals by directly-modulated OIL-VCSEL

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We demonstrate the long distance transmission of single-carrier frequency division multiple address signals by directly-modulated optically injection-locked vertical-cavity surface-emitting laser. Transmission distance as long as 50 km is achieved at 5 Gb/s (2.5 Gb/s for each user) through data pattern inversion and higher frequency response gain under optical injection locking.

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Directly modulated vertical-cavity surface-emitting lasers (DM-VCSELs) are widely used as optical transmitters for local area networks (LANs) and storage area networks (SANs)[1]. DM-VCSELs have increasingly gained the interest of researchers due to their low cost, low power consumption, and high speed properties. However, DM-VCSEL cannot manage long-distance transmission in baseband transmission systems because of frequency chirp[2]. Optical-injection-locking (OIL) of semiconductor lasers has been studied to improve the frequency response performance of lasers. Resonance frequency and 3-dB bandwidth can reach 100 and 80 GHz, respectively[3,4]. For high-frequency response application, directly modulated 60-GHz narrow band signal on OIL-VCSEL is demonstrated in the radio-over-fiber (RoF) system[5]. A bidirectional RoF system based on two-carrier injection locked semiconductor lasers has also been proposed and experimentally demonstrated[6]. Compared with directly modulated electrical signals, the optical output data pattern of DM-OIL-VCSEL in long-distance transmission systems can be inverted. Therefore, negative chirp can be obtained by inverting the modulation signal pattern without changing carrier modulation. This novel phenomenon improves the transmission distance in single mode (SM) and multimode (MM) DM-OIL-VCSELs[7,8]. However, previous reports reveal that the modulation formats are both on-off keying (OOK)[7,8].

Recently, we experimentally demonstrated a single-carrier frequency division multiple address-based passive optical network (SCFDMA-PON)[9]. Here, we used laser diodes (LDs) and external modulators for up and down streams. A DM-OIL-VCSEL is considered in the experiment to replace the LD and the modulator.

In this letter, we demonstrates that OIL-VCSEL can improve transmission performance in high-order modulation formats SCFDM quadrature phase shift keying (QPSK) signals. The Q factor improvements in different intermediate frequency SCFDM-QPSK signals differ by OIL. The difference is compared in our experiment.

The SCFDMA-PON principle has been discussed in detail in Ref. [9]. Figure 1 shows the experimental setup. The baseband SC-FDMA signal was generated and up-converted to 2.5 GHz by digital in-phase and quadrature-phase (I-Q) modulation using MATLAB. The generated waveform was uploaded onto an arbitrary waveform generator (Tektronix AWG7122B), 2.5 Gb/s for each optical network unit (ONU). The SM-VCSEL was then directly modulated by the arbitrary waveform generator (AWG) 7122B. As a high power tunable semiconductor laser (Santec TSL210), the master laser locked the SM-VCSEL. The optical output data pattern was inverted after optimizing the following OIL parameters: injection ratio ($R_{\text{inj}} = P_{\text{Master}}/P_{\text{Slave}}$) and wavelength detuning ($\Delta\lambda = \lambda_{\text{Master}}—\lambda_{\text{Slave}}$). The optical output data pattern was detected and converted to an electrical signal by a photon detector (PD). After amplification, the signal was sampled by a real-time digital storage oscilloscope (Tektronix DPO72004B) at a sampling rate of 25 GS/s. The sampled data was finally decoded through an offline process.

Figures 2(a) and (b) exhibit the bit pattern waveform of a free-running SM-VCSEL with a threshold of 0.6 mA and maximum output power of 1 mW biased at 10 mA.

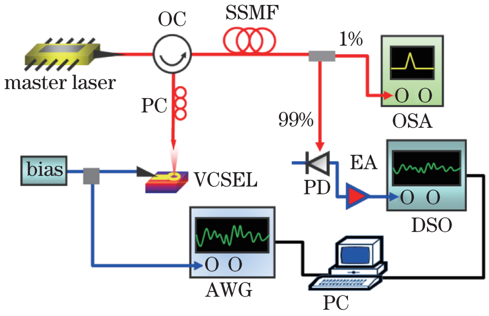

Fig. 1. Experimental setup for the DM-OIL-VCSEL long distance transmission. OC: optical circulator; PC: polarization controller; EA: electrical amplifier; OSA: optical spectrum analyzer; DSO: digital storage oscilloscope 72004B.

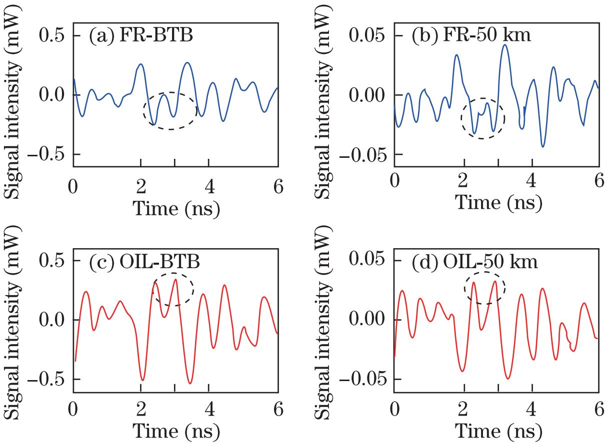

Fig. 2. Measured intensity waveforms under different conditions. (a) (b) VCSEL is free-running; (c) (d) VCSEL is optical injection locked.

The DC bias of VCSEL in this experiment is 9 mA, and the output power is about 0.8 mW. Figures 2(a) and (b) are waveforms for the back-to-back (BTB) case and after the 50-km transmission, respectively. Chromatic dispersion (CD) or more precise group-velocity dispersion causes the waveform to broaden and distort. The VCSEL underwent injection locking using a high-power tunable laser with a maximum output power of 18 dBm. This process was conducted to improve performance. The VCSEL was injection locked so that the injection parameters can be optimized. Trade-off between the large absolute value of extinction ratio and stable locking condition were also considered. Figures 2(c) and (d) show that the data pattern is inverted at 7.0 dB injection ratio (P_{Master}= 4 mW, P_{Slave}= 0.8 mW), and 1.14-nm wavelength detuning (λ_{Master}= 1 540.46 nm, λ_{Slave}= 1 539.32 nm). The data pattern inversion in our experiment is not very sensitive to injection parameters. Thus, a large region with different injection parameters can be utilized for system performance improvement. Drive modulation makes the transient chirp negative[7,8]. Moreover, under injection locking, the peak-to-peak power in Fig. 2(c) is higher by 2 dB compared with the free-running case in Fig. 2(a). This ratio frequency (RF) gain from OIL has been explained in Ref. [10].

Two ONU signals were combined in this experiment to modulate VCSEL. Frequency bands of 2.6 to 4 GHz and 1 to 2.4 GHz were assigned to ONU-1 and ONU-2, respectively. Details of this modulated signal have been described in Ref. [9]. Meanwhile, measured constellations and Q factors of two ONUs before and after standard single mode fiber (SSMF) transmission are shown in Figs. 3 and 4, respectively. Transmission performance under the free running condition quickly degrades with increased transmission distance, because the DM-VCSEL has a large positive chirp. Once the VCSEL is injection locked, the transmission performance improves after long-distance transmission compared with free running. This benefit comes from the negative chirp of OIL-VCSEL[7,8]. The direct current (DC) component of the master light has lower signal extinction ratio under OIL condition compared with the free-running condition. This explains why the Q factors could not be improved in short transmission distance ($<$ 10 km) under OIL. The experiment also reveals that the improvements of ONU-1 are better than those of ONU-2. Moreover, the intermediate frequency of ONU-1 is 3.3 GHz, which is higher than that of the ONU-2. The frequency responses were measured under different conditions to further analyze the varying performance improvements between the two ONUs (Fig. 5). This figure shows that OIL improves more effectively in the OUN-1 band range (2.6 to 4.0 GHz) than in ONU-2 (1.0 to 2.4 GHz), especially after the 50 km transmission. These results agree with the findings that the Q value improvements of ONU-1 are better than those of ONU-2. The response amplitude swings after long-distance transmission (Fig. 5 (b)). This phenomenon is caused by the interfering modulation sideband due to their relative phase variations resulting from fiber CD.

In conclusion, we extend the transmission distance of

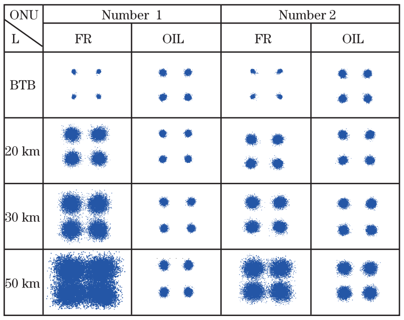

Fig. 3. Measured constellations of two ONUs before and after long-distance transmission.

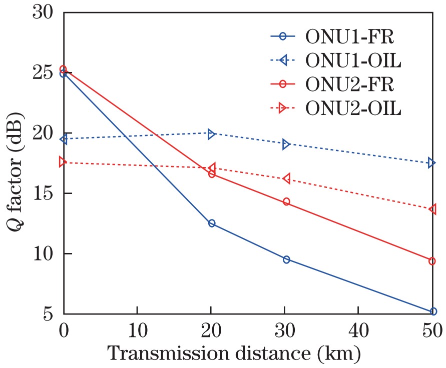

Fig. 4. Measured Q factors of two ONUs before and after long-distance transmission.

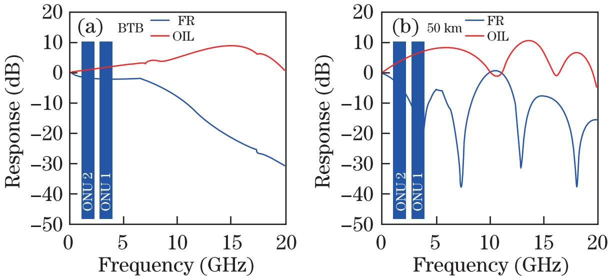

Fig. 5. (Color online) Measured frequency responses of DM-VCSELs under free running (blue curves) and injection locking conditions (red curves). (a) BTB transmission; (b) 50-km transmission.

5-Gb/s SC-FDMA signals by DM-OIL-VCSEL to 50 km. A maximum Q factor enhancement of 12.5 dB is achieved under the OIL condition, compared with the free running case. This benefit is due to the data pattern inversion and higher frequency response by OIL. The deployment of high-order modulation formats is also led to the spectral efficiency of optical fiber networks. These networks are important for the development of an optically injection-locked VCSEL, which is a strong candidate for future high-speed long-distance optical communications.

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