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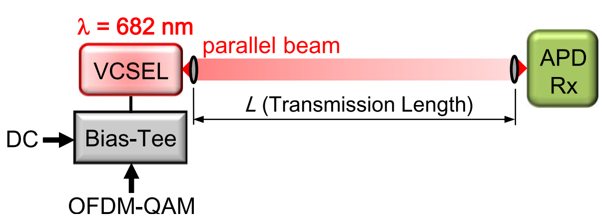

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Utilization of 1-GHz VCSEL for 11.1-Gbps OFDM VLC Wireless Communication

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Abstract: In this paper, we propose using an energy-efficient and low-cost 682-nm vertical-cavity surface-emitting laser (VCSEL) with 1-GHz modulation bandwidth for high-speed wireless visible light communication (VLC). Moreover, by using spectral-efficient orthogonal frequency division multiplexing (OFDM) modulation with bit-and-power-loading algorithm, we successfully demonstrate VCSEL-based transmission at 11.1 Gbps (10.2 Gbps in a raw data rate) over a free-space length of 1.2 m under small bias current of 3.5 mA. Furthermore, decreasing the bias current as low as 2 mA, we can also demonstrate 10.5 Gbps (9.7 Gbps in a raw data rate) OFDM VLC transmission over a 1.2-m free-space link. This proposed VCSEL-based OFDM transmission system could be viewed as a cost-effective and energy-efficient approach for high-speed (> 10 Gbps) laser diode wireless VLC application.

Index Terms: Visible light communication (VLC), vertical-cavity surface-emitting laser (VCSEL), orthogonal frequency division multiplexing (OFDM).

1. Introduction

To date, white light emitting diodes (LEDs) appear to be the most promising technology for next-generation illumination. Moreover, using LEDs, the visible light communication (VLC) has been emerging as a complementary technology for wireless access network [1], [2]. Implementing the LED-based VLC system, however, the data rates are usually limited to a few Gigabits per second due to insufficient modulation bandwidths of LEDs (< 100 MHz). By narrowing down LED diameter to 44 μm (μLED), the modulation bandwidth of the LED has been significantly improved up to 450 MHz [3]; however, such a small diameter leads to high injection current density and may cause the efficiency droop [4]. Compared with LEDs or μLEDs, the visible light laser diodes (LDs) exhibits a larger modulation bandwidth (> GHz) and higher pumping efficiency. Such important characteristics have encouraged much research interest in visible LD VLC systems. In 2008, using a frequency-doubled 1064 nm LD, Hanson *et al.* presented undersea VLC transmission under nonreturn-to-zero on-off-keying (NRZ-OOK) modulation at 1 Gbps through a 2 m water pipe [5]. In 2013, using a homemade GaN-based 422 nm LD, Watson *et al.*

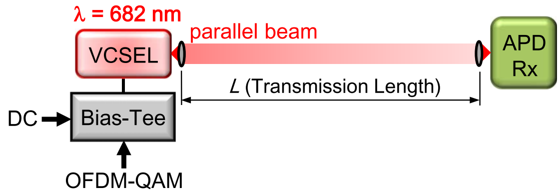

Fig. 1. Setup of the VCSEL-based wireless VLC system.

demonstrated free-space VLC transmission under NRZ-OOK modulation at 2.5 Gbps [6]. In 2015, using a two-stage external-injected vertical-cavity surface-emitting laser (VCSEL), Lu *et al.* demonstrated NRZ-OOK VLC transmission at an impressive data rate of 25 Gbps over a free-space link of 10 m [7]. However, such configuration requires high-speed optical as well as electrical devices, which would inevitably lead to an increase in cost. Compared with NRZ-OOK modulation, orthogonal frequency-division multiplexing (OFDM) modulation usually has narrower modulation bandwidth, thereby the high-speed integrated circuits (ICs) such as wide-band LD driver and photo-receiver circuit may be unnecessary. In 2015, employing a gallium nitride (GaN)-based 450 nm LD, Chi *et al.* demonstrated OFDM VLC transmission at 9 Gbps over a 5 m free-space link [8]. Nevertheless, such LD was operated at a bias current as high as 60 mA, which might lead to energy-consumption and cooling issues.

In this paper, using an energy-efficient and low-cost 682 nm VCSEL with 1 GHz modulation bandwidth under a bias current of 3.5 mA, we demonstrate a 1.2 m free-space VLC transmission at 11.1 Gbps (10.2 Gbps in a raw data rate) under forward error correction (FEC) threshold [9] $(\text{BER} < 3.8 \times 10^{-3})$ by use of OFDM modulation and bit-and-power-loading algorithm. It should be noted that bit-and-power-loading algorithm, in this paper, is used to maximize the data rate and maintain the BER below the FEC threshold of 3.8×10^{-3} simultaneously. Moreover, we also demonstrate 10.5 Gbps (9.7 Gbps in a raw data rate) OFDM VLC transmission over 1.2 m free-space link under a bias current as low as 2 mA. We believe that the proposed VCSEL-based OFDM transmission system could be viewed as a cost-effective and energy-efficient approach for high-speed (> 10 Gbps) LD VLC application.

2. Experimental Setup and Discussion

Fig. 1 presents the proposed red-light VCSEL-based VLC system. In the transmitter (Tx) side, we use the 682 nm VCSEL laser with 1 GHz bandwidth to transmit optical OFDM VLC signal. The threshold and current of VCSEL is 1.2 at room temperature, respectively. In the receiver (Rx) side, a 2 GHz silicon-based avalanche photodiode (APD) is used to detect VLC signal. The active area diameter of APD-Rx is 100 μm. In the measurement, the free space transmission length (L) is 1.2 m long for VLC traffic. The bias current (Idc) and modulation signal are applied on the 682 nm VCSEL simultaneously by using a 2.5 GHz bias-tee (BT). Hence, the VCSEL can be directly modulated by the OFDM signal. Moreover, different bias currents of 2, 2.5, 3, 3.5, and 4 mA are also utilized on VCSEL laser for testing VLC signal performance, respectively.

In the experiment, we utilize OFDM modulation with bit-and-power-loading algorithm to maximize the bandwidth efficiency. The generation of OFDM signal involves quadrature-amplitude modulation (QAM) symbol mapping, inverse fast Fourier transform (IFFT), serial-to-parallel (S/P) conversion, CP insertion, and digital-to-analog (DA) conversion. First, the modulated OFDM signal is with a fast-Fourier transform (FFT) size of 256, training symbol of 4.76%, and cyclic prefix (CP) of 3.03%. Here, 40 subcarriers are used, which corresponds to a signal bandwidth of 1.875 GHz. Afterwards, the OFDM signal is generated by using an arbitrary waveform generator (AWG, Tektronix AWG7122) with a sampling rate of 12 GSample/sec of and a resolution of 8 bits. The OFDM signal is then fed to the 682 nm VCSEL through the 2.5 GHz BT. Using the 2 GHz APD, the VLC wireless signal is detected and converted to an electrical signal. Then, the electrical OFDM signal is amplified by a wideband RF amplifier and subsequently retrieved by a real-time oscilloscope (Tektronix CSA 7404) with 10 GSample/sec sampling rate and 8 bit

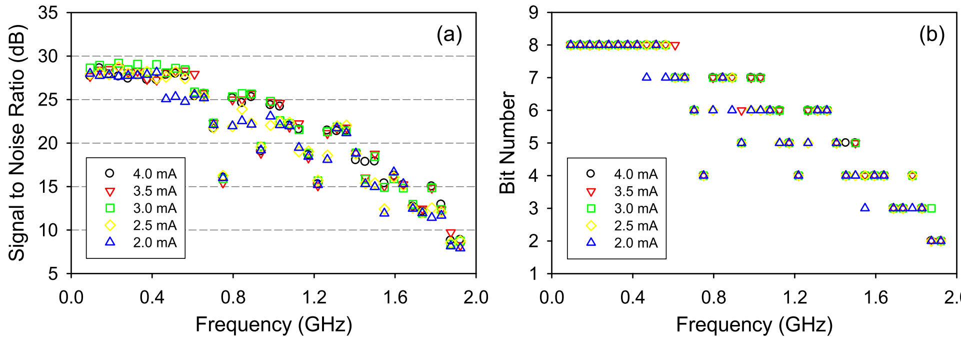

Fig. 2. (a) Measured SNR and (b) obtained bit number versus frequency when the VCSEL laser is operated under various bias currents of 2, 2.5, 3, 3.5, and 4 mA.

resolution for signal demodulation. In the measurement, the demodulation process contains the synchronization, FFT, one-tap equalization, and QAM symbol decoding by employing off-line Matlab programs. Finally, the signal-to-noise ratio (SNR) is measured. The measured SNR value is defined as the ratio of the power of the ideal reference symbol vector to the power of an error vector. The bit error rate (BER) is counted by bit-by-bit comparison. It should be noted that the bit-by-bit comparison is performed after decision by directly calculating the different binary digits of the received signal and the transmitted one, which is a conventional approach to count the actual BER.

Fig. 2(a) presents measured SNR versus frequency when the VCSEL l aser is operated under various bias currents of 2, 2.5, 3, 3.5, and 4 mA. As shown in Fig. 2(a), the observed SNRs nearly resemble to each other under various bias currents. Moreover, those SNRs of > 25 dB can be achieved in the frequency range of 0.0938 to 0.6563 GHz various bias currents. Furthermore, with the increase of measured frequency gradually, the measured SNR would also drop due to the PD bandwidth limitation, as illustrated in Fig. 2(a). All of the SNRs can be obtained between 28.9 and 7.9 dB in the measurement, while the operated currents are 2, 2.5, 3, 3.5, and 4 mA, respectively. According to different SNR values, the QAM-order can be adjusted optimally. Therefore, by applying bit-and-power-loading algorithm, the corresponding bit number of each subcarrier could be allocated, as presented in Fig. 2(b), under various bias currents in a free space transmission of 1.2 m long. Here, 4-QAM to 256-QAM OFDM signal could be used in the effective modulation bandwidth. As seen in Fig. 2(b), 2 to 8 bit numbers are observed. In addition, when the frequency range is from 0.0938 to 0.6563 GHz, the obtained bit number can be larger than 7, as shown in Fig. 2(b). As a result, employing the different obtained bit numbers under different operated currents, we could retrieve the optimal signal performances of proposed VCSEL-based VLC wireless transmission.

According to the measured bit numbers in proposed VLC system, the corresponding data rate also can be retrieved. Fig. 3 shows the obtained traffic data rates of 10.5 to 11.1 Gbps at the different bias currents under the driving voltage (Vpp) range of 0.35 to 0.8 V in a 1.2 m transmission length. As shown in Fig. 3, with the increase of bias current, the Vpp is also increased to accomplish the optimal data rate. The maximum data rate of 11.1 Gbps is measured at 3.5 mA. When the bias current is over 3.5 mA, the traffic rate would drop to 11 Gbps slightly. Hence, in this experiment, we don't need to increase the bias current for wireless VLC signal measurement.

Fig. 4 presents the corresponding BER of proposed VCSEL-based VLC system using OFDM modulation with bit-and-power-loading algorithm at the different operated currents of 2, 2.5, 3, 3.5, and 4 mA, respectively. Here, the corresponding BERs of 3.0×10^{-3}, 3.4×10^{-3}, 3.0×10^{-3}, 2.5×10^{-3}, and 2.5×10^{-3} are also obtained, respectively, as illustrated in Fig. 4. The entire measured BER values are lower than that of the forward error correction (FEC) threshold ($\text{BER} = 3.8 \times 10^{-3}$), as illustrated in Fig. 4.

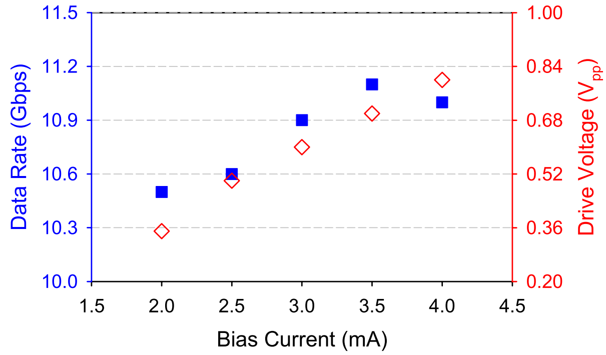

Fig. 3. Maximum data rates at the various bias currents under the driving voltage range of 0.35 to 0.8 V in a 1.2-m transmission length.

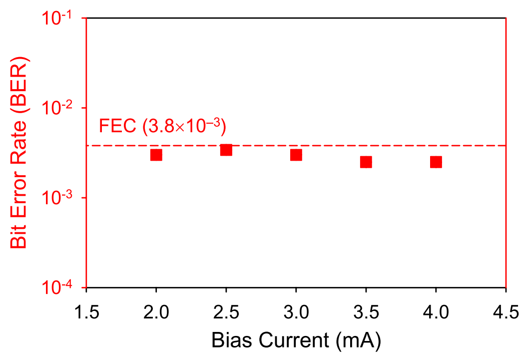

Fig. 4. Corresponding BER of proposed VCSEL-based VLC system using OFDM modulation with bit-and-power-loading algorithm.

In addition, Fig. 5(a) and (b) present corresponding constellations of OFDM signal with bit-and-power-loading algorithm under 4-QAM to 256-QAM formats, under the bias currents of 4 and 3.5 mA respectively. Moreover, the measured constellations of Fig. 5(a) and (b) are clear and concentrate. Due to the limitation of modulation bandwidth in 1 GHz VCSEL, the maximum traffic rate only achieves 11.1 Gbps by using OFDM signal with bit-and-power-loading algorithm. Hence, we believe that the data rate could be enhanced to 20~30 Gbps by the same proposed technology if the bandwidth could be larger than a few gigahertz. As the optical wireless transmission requires relatively high alignment accuracy, using visible LD provides easy alignment between the LD and the detector over infrared LD.

In this measurement, we also demonstrate wireless VCSEL transmission at various free space lengths of 1.2, 1.0, 0.8, and 0.6 m under the bias current of 2.5 mA and the driving voltage of 0.5 V_{pp}. Of course, we also can obtain the corresponding bit numbers via the related SNRs, when the transmission lengths are set 1.2, 1.0, 0.8, and 0.6 m, respectively. As shown in Fig. 6(a), the obtained bit numbers in the same frequency range are between 2 and 8 in various transmission lengths. Besides, the corresponding data rates also can be obtained via the measured bit numbers. Hence, Fig. 6(b) shows the measured data rates of VCSEL VLC signal under the transmission length of 1.2, 1.0, 0.8, and 0.6 m respectively. And the traffic rates are 10.4, 10.6, 10.4, and 10.2 Gbps respectively. Here, a maximum date rate variance of 0.4 Gbps is observed under a 0.6 m length difference, as seen Fig. 6(b). This is because the received power may be too large for < 0.8 m transmission and subsequently lead to the APD photodiode saturation. On the other hand, the received power might be insufficient for > 1.2 m transmission. As a result, wireless VCSEL transmission at 1 m exhibits the highest data rate. The measured BERs are 2.9×10^{-3}, 2.2×10^{-3}, 2.2×10^{-3}, and 2.7×10^{-3} in the lengths of 1.2, 1.0, 0.8, and

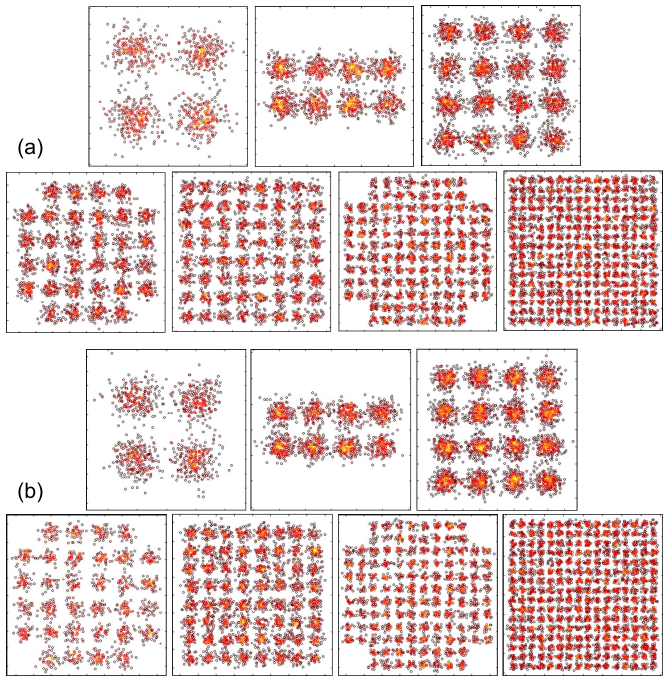

Fig. 5. Measured corresponding constellations of OFDM signal with bit-and-power-loading algorithm at the bias currents of (a) 4 and (b) 3.5 mA.

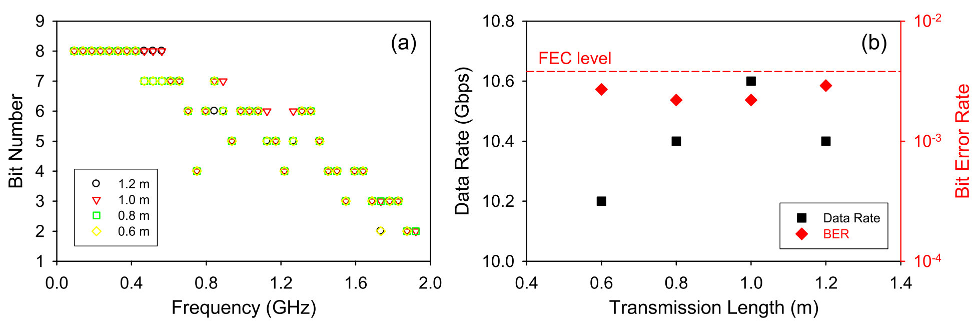

Fig. 6. (a) Obtained bit number versus frequency and (b) maximum data rates and BERs in various transmission lengths.

0.6 m, respectively, as illustrated in Fig. 6(b). The entire observed BERs are below the FEC level $(\mathrm{BER} = 3.8 \times 10^{-3})$. In practical implementation, adding free-space attenuator could increase the receiver cost; and Fig. 6(b) shows that even under power saturation of the receiver, FEC limit can still be satisfied.

3. Conclusion

In this paper, using an energy-efficient and low-cost 682 nm VCSEL with 1 GHz modulation bandwidth, we have successfully demonstrated free-space VLC transmission at a maximum data rate of 11.1 Gbps (10.2 Gbps in a raw data rate) over a 1.2 m free-space link under spectral-efficient OFDM modulation with bit-and-power-loading algorithm. Additionally, by decreasing the bias current as low as 2 mA, we have also presented 10.5 Gbps (9.7 Gbps in a raw data rate) OFDM VLC transmission over a 1.2 m free-space link. We believe that the proposed VCSEL-based OFDM transmission system could be viewed as a cost-effective and energy-efficient approach for high-speed (> 10 Gbps) LD VLC application.

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