25 Gb/s Transmission over 1-km Graded-index Single-mode Fiber Using 910 nm SM VCSEL

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Abstract: We investigate experimentally the feasibility of single-mode VCSEL transmission at 910 nm over a graded-index single-mode fiber and achieve a BER < 10^{-12} for a transmission distance of 1-km at 25 Gb/s. © 2020 The Author(s)

1. Introduction

Multimode fiber (MMF), together with multimode vertical cavity surface emitting lasers (VCSELs), have been extensively used for short-distance optical communications in data center applications [1]. Two of the main reasons are: 1. the low cost and energy efficiency of multimode VCSEL based transceivers and 2. the relaxed requirements for multimode fiber connectivity which impacts the cost of the system, also in a positive manner. Cost is however not only the main driving factor, but also system bandwidth, transmission reach, upgradability and plant complexity, amongst others. For this reason, mega- and hyper-scale data centers tend to choose standard single mode fiber as their only transmission medium [2].

VCSEL transmission at 850 nm has been dominant in data centers for many years. However, in recent years, driven by the need to expand the transmission capacity per fiber, more wavelengths have been used for multimode transmission [3-4]. One approach to expand the capacity is the use of bidirectional (Bi-Di) transmission using two wavelengths, one around 850 nm and one around 910 nm. Using Bi-Di propagation and PAM4 modulation format, 40 Gb/s and 100 Gb/s are now commercially available products [4]. A different approach uses four wavelengths, ranging from 850 nm to 950 nm, to achieve both 40 Gb/s and 100 Gb/s transmission [5-6].

Recently, we proposed the use of a standard single-mode fiber with a graded-index profile for few mode transmissions using a single mode (SM) VCSEL at 850 nm [7-10]. This fiber, while being a standard single-mode fiber at 1310 nm, is bi-modal around 850 nm and has a robust bandwidth capability for VCSEL transmission. We have demonstrated 1.5 km transmission at 25 Gb/s using such high bandwidth fiber [8]. In this paper, we extend this concept by characterizing and evaluating the transmission performance of graded index single-mode fibers using a SM VCSEL at a wavelength of 910 nm. Such fibers can potentially address several scenarios of interest with a single transmission medium, simplifying the complexity of cable plants while still providing the flexibility for upgrade. Potentially low-cost single-mode dual-wavelength SM VCSEL based transceivers at 850 nm and 910 nm (similar to Bi-Di transceivers) could be used for short-reach scenarios, while more expensive transceivers at 1310 nm or 1550 nm could be used for long-reach scenarios.

2. Fiber characteristics

In [8-9], graded-index single mode fibers were used for SM VCSEL transmission. These fibers are fully compliant with the standard single-mode fiber meeting the ITU-T G.652 standard and have a cable cutoff wavelength less than 1260 nm so that the fiber is single-mode in the 1310 nm and 1550 nm transmission windows. Below the cable cutoff wavelength, the fibers are bi-modal and can have very high modal bandwidth around 850 nm. The fibers used here have slightly different bandwidth characteristics designed for 910 nm. They have a mode field diameter of ~9.2 µm at a wavelength of 1310 nm. The attenuation value at 910 nm is ~1.5 dB/km.

The most important fiber attribute for VCSEL transmission is the modal bandwidth of the fiber at 910 nm. We measured the bandwidth of graded-index fibers over a range of wavelengths from 800 nm to 980 nm [10]. For few-mode fibers, the commonly used differential mode delay (DMD) measurement method for MMFs with many modes is not optimal and overly cumbersome to operate. To overcome the limitations, a new bandwidth measurement method for bi-modal fibers was developed in [8] which relies on measuring the frequency-domain transfer function. By analyzing the measured transfer function using an analytical model, the modal delay and the worst-case modal bandwidth can be evaluated to gauge the link performance. Fig. 1 shows the modal delay, modal bandwidth and transfer function of several fibers. The modal bandwidth is obtained through the measured modal delay in Fig. 1 (a)

[10]. Fig. 1 (b) shows the modal bandwidth vs. the wavelength for Fiber1 with high bandwidth at 850 nm used in [9]. However, since the peak wavelength of the fiber is right around 850 nm, the bandwidth falls moving away from 850 nm. Two new experimental fibers (Fiber2 and Fiber3) are used in the current paper and are also shown in Fig. 1 (b). Fiber3 has a peak wavelength at 914 nm. Therefore, it has extremely high modal bandwidth at 910 nm of 23.9 GHz.km. Due to bandwidth fall-off over wavelength, this fiber has a modal bandwidth of 1.4 GHz.km at 850 nm. On the other hand, another fiber, Fiber2, with peak wavelength at 878.7 nm has a more balanced modal bandwidth between 850 nm and 910 nm. The modal bandwidth values are 3.4 GHz.km and 2.7 GHz.km for the two wavelengths respectively.

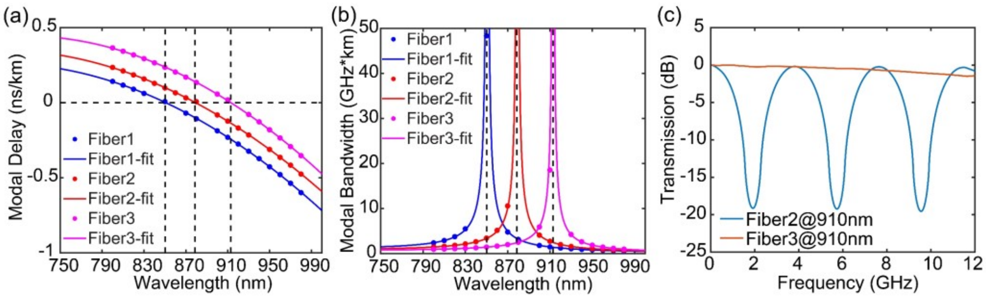

Fig. 1 (a) The modal delay of three experimental fibers vs. wavelength along with fitted curves, (b) The modal bandwidth of three experimental fibers vs. wavelength with fitted curves, (c) Measured transfer functions of Fiber 2 and 3 at 910 nm.

3. Experimental setup and transmission performance

The transmission performance of these fibers is put into test by using a SM VCSEL [11]. The experimental setup used for this experiment is shown in Fig. 2 (a) and is very similar to the one reported in [12]. The bit pattern generator (BPG) generates the signal, which is then amplified by an RF-amplifier with 34 GHz bandwidth and combined with the DC current via the Bias–Tee. The signal is then fed into the single mode VCSEL using a ground electrical probe with 60 GHz bandwidth. The optical signal is collimated with an aspheric lens L_1 which then passes through an optical isolator to minimize back reflections into the VCSEL. This significantly improves signal performance. Two mirrors are used to align the beam to the optical axis of the fiber, improving the coupling efficiency. The optical signal is attenuated by using a variable free space absorptive filter (7) to guarantee uniform attenuation of the beam. The optical beam is then focused into the fiber with an FC/APC connector using a second aspheric lens L_2, which is in turn connected to a 32 GHz bandwidth photodiode. The signal is then amplified by two low noise RF – amplifiers (34 GHz and 55 GHz bandwidth) to achieve the minimal amplitude requirements of the error detector. The eye diagram is captured by using a sampling scope with a bandwidth of 40 GHz.

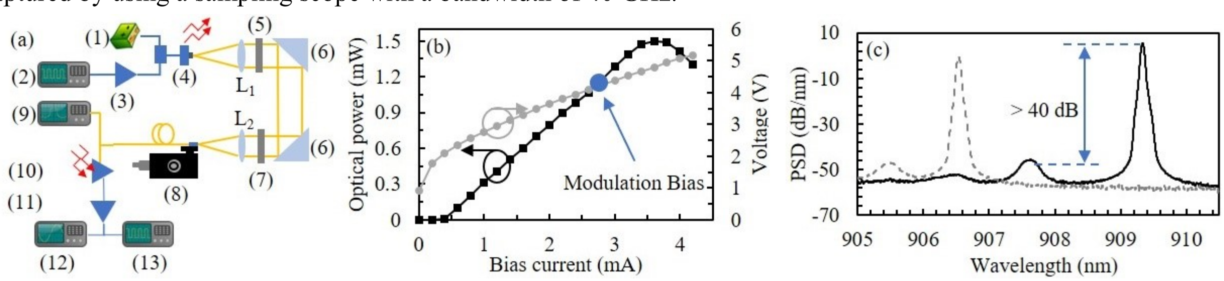

Fig. 2 (a) Experimental setup: (1) DC source, (2) Pattern generator, (3) Amplifier, (4) VCSEL, (5) Isolator; (6) Mirrors, (7) Variable absorbing filter, (8) Translation stage with fiber and APC connector, (9) Optical Spectrum Analyzer, (10) Wideband photo-detector, (11) Two amplifiers from SHF, (12) Sampling scope, (13) Error detector, (b) PI – curve and VI – curve and (c) Optical spectrum at 1.0 mA (dashed) and 2.68 mA (solid) with a side mode suppression ratio of over 40 dB.

Fig. 2 (b) shows the power injection current (PI) curve of the SM VCSEL measured after coupling into the graded index fiber. The VCSEL used here has an oxide aperture diameter of 2.5 µm ± 0.5 µm, a threshold current of 0.4 mA and a slope efficiency of 0.5 mW/mA. Under continuous wave condition, the VCSEL emits a maximum optical power of 1.5 mW at 3.6 mA before it rolls over. The VCSEL is single-mode, has a side mode suppression ratio higher than 40 dB as depicted in Fig. 2 (c) and an RMS linewidth of 0.034 nm. The coupling loss into the fiber is shown in Fig. 3 (a). The average coupling loss value is 1.3 dB for the measured bias current range of 0.5 mA – 4 mA. For the bias current value used for the transmission experiment (2.68 mA), the coupling loss is 1.1 dB. The modulation performance of the VCSEL was evaluated first in a back-to-back (BTB) configuration, where a 1 m fiber patch cord of the fiber under investigation is used. For this purpose, a 25 Gb/s on-off keying PRBS7 signal was generated and transmitted through the fiber. The eye diagram of the BTB signal is shown in Fig. 3 (b) and is clearly error free. This is confirmed by measuring the bit error ratio (BER) over a time of 15 minutes, yielding a BER value of 2.3×10^{-13}. The waterfall curve shown in Fig. 3 (e) was evaluated for the BTB configuration (black squares), by attenuating the free space optical beam with a variable absorptive filter and measuring the BER value. The same procedure was repeated while connecting the 1 km and 150 m fiber to the 1 m fiber patch cord using a single mode type connector. The eye diagram of the signal after transmitting over 1 km distance of fiber 3 is shown in Fig. 3 (c) and looks almost identical. Also, the eye diagram after 150 m transmission using fiber 2 is shown in Fig. 3 (d) without showing any significant degradation. The only noticeable difference in both cases is the smaller signal amplitude which can be attributed to the fiber attenuation and connector loss. The BER curve for the 1 km fiber exhibits the same behavior as the BTB curve (gray diamonds) and has therefore no significant impact on the transmission performance of the system, while the BER curve for the 150 m transmission (blue dots) suffers a slight penalty induced by the fiber. One order of magnitude in BER penalty for an average optical power of -2 dBm is obtained using the 150 m fiber, yielding a best case BER value of 5×10^{-12}.

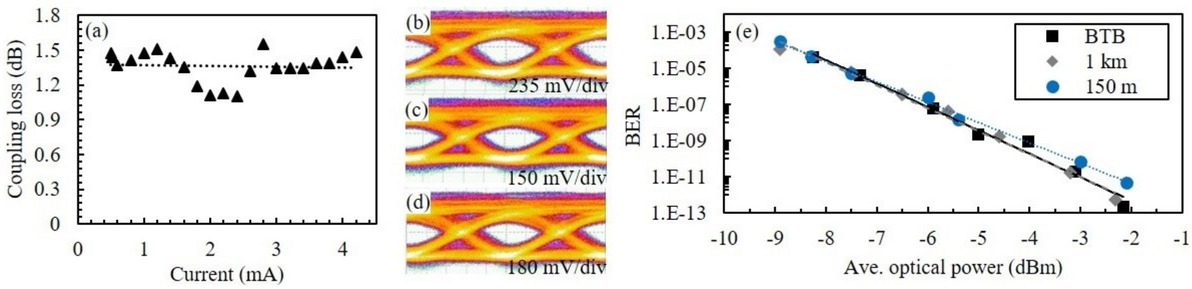

Fig. 3 (a) Coupling loss into 1 m fiber patch cord; (b) Eye diagram of 25 Gbit on-off keying signal in back to back configuration, (c) Eye diagram of 25 Gb/s on-off keying signal after 1 km transmission using fiber 3, (d) Eye diagram of 25 Gb/s on-off keying signal after 150 m transmission using fiber 2, (e) Measured bit – error – ratio in back to back configuration, after 150 m and after 1 km transmission.

4. Conclusion

We have experimentally demonstrated the feasibility of using a single-mode graded-index fiber for errorless transmission around the wavelength of 910 nm up to 1 km. This fiber can also be engineered to have its peak wavelength around 879 nm, to support simultaneously 850 nm and 910 nm transmissions over 150 m with a BER value of 5×10^{-12} at 910 nm as shown in this paper. This fiber presents the opportunity of being used to accommodate low cost transmission at 850 nm and 910 nm for short-reach applications while also being able to support and 1310 nm and 1550 nm transmission for higher-reach and higher bandwidth applications.

5. Acknowledgment

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