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Free-running L-band VCSEL for 1.25 Gbps hybrid radio-fiber cloud optical interconnects

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Abstract: We demonstrate a free-running directly-modulated 1580 nm VCSEL suitable for hybrid wireless/optical interconnects supporting cloud data centers. Error-free transmission at 1.25 Gbps was achieved after 6.5 GHz wireless link and 1 km bend-insensitive fiber.

OCIS codes: (200.4650) Optical interconnects, (060.2360) Fiber optics links and subsystems.

1 Introduction

The demand for higher bandwidth, flexibility and reliability in data center applications has encouraged research into cloud computing architectures, focusing on efficient data centers implementing cost-effective, scalable, parallel optical interconnects [1]. Communication bottlenecks have been considered as one the biggest challenges in growing data centers; this motivates wavelength division multiplex (WDM) optical interconnects [2] for providing data bandwidth scalability [3] in highly-aggregated data traffic links [4–6]. Hybrid wireless-optical interconnect systems can provide alternate data paths between cloud nodes, allowing further traffic scaling or providing improved service reliability [7].

Vertical-cavity surface-emitting laser (VCSEL) devices are suitable for high-density cloud applications due to their compact size and low operating current levels. VCSEL operation without temperature or wavelength controls can further reduce energy consumption and transmitter complexity. In a wavelength division multiplex (WDM) scenario, compact L-band (1565 nm to 1625 nm) VCSEL transmitters enhance bandwidth scaling [3] by increasing wavelength channelization. As physical space constraints in a cloud data center environment encourages high server density, optical fiber of type G.657 [8] bend-insensitive fiber (BIF) is recommended. BIF has optical characteristics similar to G.652 single-mode fiber (SMF), but its reduced macro-bending losses enable tighter installation clearances of the optical plant infrastructure and hence increased node density within the cloud server installation.

Previously, optical injection locking (OIL) enabled VCSEL transmitters operating at 850 nm [9] and 1540 nm [10] wavelength to achieve 3 Gbps modulation in 60 GHz radio over fiber (RoF) systems. Impulse radio ultra wide-band (IR-UWB) transmission over 2 m wireless link was reported at 1 Gbps using a 850 nm VCSEL device [11]. We extend on previous work with L-band VCSELs [12] and hybrid radio/fiber links [11] by introducing a novel free-running L-band VCSEL operating at 1580 nm into a hybrid radio/fiber interconnect. Error-free transmission, with bit error rate (BER) below 10^{-9}, was achieved at a data rate of 1.25 Gbps, after 55 cm air link and 1 km G.657 BIF. This represents the first known demonstration of free-running L-band VCSEL devices in implementing hybrid radio/fiber links for hybrid optical interconnect architectures.

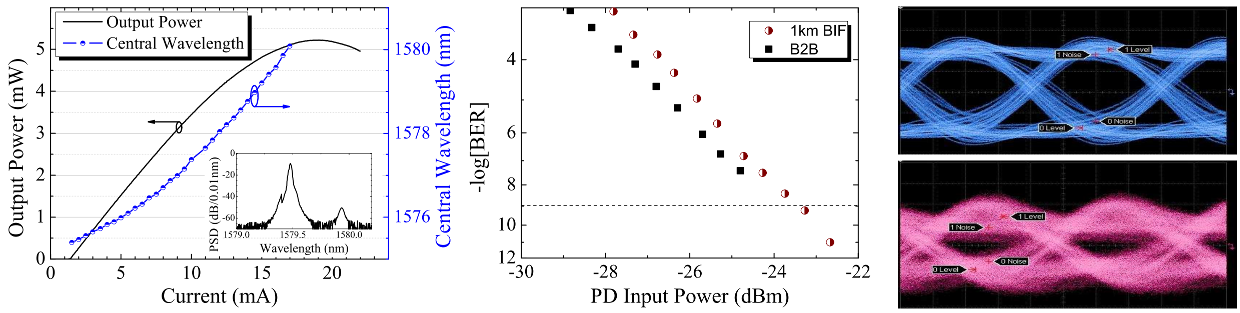
2 1580 nm VCSEL Characterization

L-band VCSELs are suitable for broadband cloud optical interconnects due to their reduced operating current requirements and small size; wavelength tuning of such devices may also be exploited for WDM transmission. We implemented a novel 1580 nm VCSEL of type Vertilas VL-1585-10-SE-T4. This device has threshold current of 0.85 mA, provides 3.9 mW optical power at 25 °C, and is operable without temperature or wavelength control. The prototype VCSEL used was not pigtailed; a cleaved SMF pigtail was aligned to collect the output beam at the device aperture. The DC characterization of this device, in terms of power and wavelength response to applied bias current, are presented in Fig. 1a. The inset shows a sample optical spectrum obtained; un-modulated CW (solid, black) and modulated (red, dash) output. Device wavelength varied between 1575 nm and 1580 nm; the maximum optical power obtained was 0.6 mW (-2.55 dBm); side-mode suppression ratio (SMSR) was 42 dB.

3 System Architecture

WDM optical interconnect infrastructures implementing alternate wireless signaling paths can significantly improve performance in a cloud data server center architecture by relieving communication bottlenecks [2] and improving reliability [7]. The layout of a cloud-server architecture in which the WDM optical interconnects (solid, blue) provide a broadband communication platform is shown in Fig. 2a; alternate wireless connectivity (dash, red) may be implemented to enable continued cloud service operation in the event of link or node failure.

The evaluation layout used is presented in Fig. 2b. At the cluster node, the signal was generated by a pulse pattern generator providing non-return to zero on-off key (NRZ-OOK) pulses; pseudo-random binary sequence (PRBS) data pattern of length $2^7 - 1$ bits was used. Electrical radio-frequency (RF) mixer was used to up-convert the signal onto a 6.5 GHz RF carrier; the amplitude-shift key signal thus obtained and amplified prior to wireless transmission. Omni-directional antennas were used on both ends of the 55 cm wireless link; these were of type Geozondas AU-3.1G10.6G-1, specified for 10 dBi gain at 6 GHz. At the switch node, the received RF signal was amplified and down-converted to baseband by a matched RF mixer. In practice, a phase-locked-loop would eliminate phase offset between the locally-generated 6.5 GHz RF carrier and the received RF signal, however in this evaluation, an electrical delay line was used with a copy of the RF carrier (from the cluster node) to implement the required phase correction. This down-converted signal at the switch node was used to modulate the directly-modulated L-band VCSEL. The free-running VCSEL was biased far from threshold and operated within its linear voltage input range; it operated without temperature control or wavelength stabilization. An optical power meter (OPM) at the VCSEL output was used to ensure that the cleaved fiber and the VCSEL aperture were aligned optimally. An optical spectrum analyzer (OSA) was used to verify a clean optical signal into the BIF. The 1 km BIF used between switch and gateway nodes had an attenuation of 1.2 dB. At the gateway receiver, a variable optical attenuator was used to adjust the input power into the photo diode (PD). Post-PD amplification was used to ensure sufficient voltage swing into the bit error rate tester (BERT) device, and post-PD low-pass filtering at 1.8 GHz was implemented to improve the signal to noise ratio (SNR). System performance was characterized using eye diagram observations and a BER sensitivity to PD input power assessment.



(a) (b) (c)

Fig. 1. (a) DC response of free-running 1580 nm VCSEL; power (black triangles) and wavelength (blue circles) variation with bias current. Inset: sample optical spectrum obtained at the VCSEL output; (b) BER sensitivity to PD input power, for B2B (black square) and 1 km BIF (red, circle); (c) eyes observed at switch antenna (blue, top), after 1 km BIF (pink, lower).

4 Results

The BER sensitivity to PD input power characteristic is shown in Fig. 1b; eye diagram observations are presented in Fig. 1c. We observed error-free transmission through the hybrid radio/fiber link at a received optical power of -23.4 dBm after 1 km BIF transmission; optical transmission margin of 20.95 dB was obtained. From the eye diagrams

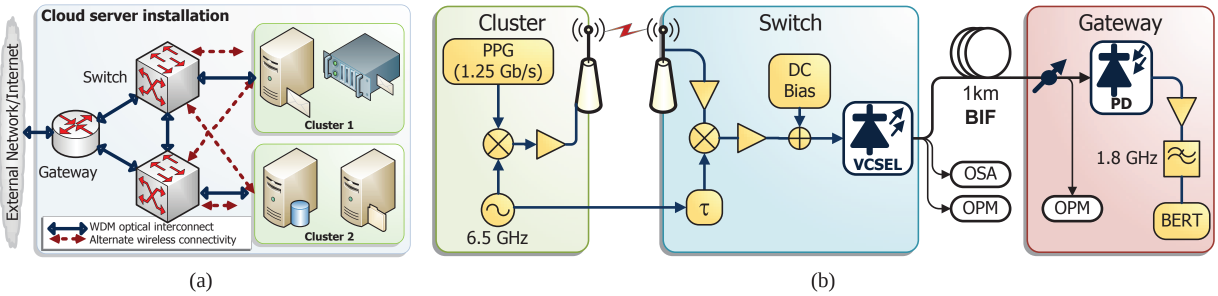


Fig. 2. (a) Cloud-server architecture implementing WDM optical interconnect with alternate wireless connectivity. (b) experimental layout: BERT, bit error rate tester; BIF, bend insensitive fiber; OPM, optical power meter; OSA, optical spectrum analyzer; PPG, pulse pattern generator.

shown in Fig. 1c, the signal obtained after wireless transmission and down-conversion at the switch node had a clear open eye (blue, top) with 6.58 dB SNR and a peak to peak voltage (Vpp) of 340.4 mV. After further transmission through 1 km fiber and photo-detection at the gateway node, the signal obtained (pink, lower) presented a clear open eye and had 2.75 dB SNR. A transmission power penalty below 1 dB was observed after 1 km BIF.

5 Conclusion

We have demonstrated the use of a novel L-band VCSEL device in achieving error-free data transmission over a hybrid radio/fiber link in a cloud optical interconnect; 1.25 Gbps was achieved over 55 cm air link followed by a free-running 1580 nm VCSEL and 1 km G.657 BIF. Longer-distance wireless transmission could have been achieved with higher-gain amplifiers. The L-band VCSEL used was operated without temperature control, enabling it to implement compact, energy-efficient broadband transceivers suitable for deployment in WDM optical interconnects for high-density cloud data service installations. The successful implementation of such hybrid radio/fiber links into a WDM optical interconnect highlights the flexibility of the VCSEL device used, and significantly improves connectivity, reliability and performance of cloud service architectures. The low transmission penalty encourages further investigations of VCSEL usability in interconnect applications. These results encourage further investigations into the potential of WDM optical interconnects to support cloud delivery systems, with reduced energy consumption.

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