4x10-Gb/s CWDM Transmission using VCSELs from 1531nm to 1591nm

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Abstract *We demonstrate 4x10-Gb/s coarse wavelength-division multiplexed (CWDM) transmission using commercial vertical cavity surface emitting lasers (VCSELs) over >45 km of standard single-mode fiber without any dispersion compensation. The 10.7-Gb/s bit rate allows for enhanced forward error correction.*

Introduction

Coarse wavelength-division multiplexing (CWDM) is becoming increasingly important for optical access applications [1,2]. It allows to deploy low-cost short-reach links with appreciable capacity using a 20-nm wavelength grid between 1271 nm and 1611 nm. Recent research has pushed per-channel CWDM bit rates to 10 Gb/s with transmission distances of more than 40 km using directly modulated distributed feedback (DFB) lasers [3]. Lately, the use of low-cost vertical cavity surface emitting lasers (VCSELs) has been proposed for such short-reach applications [4]. Combined with electronic dispersion compensation and forward error correction (FEC) single-wavelength transmission over 40 km was demonstrated.

In this paper we report 4-channel CWDM transmission over standard single-mode fiber (SSMF) using commercially available VCSELs that cover the CWDM band from 1531 to 1591 nm. We operate at a bit rate of 10.7-Gb/s, thus enabling enhanced FEC, but we do not use any dispersion compensation, neither optical nor electronic.

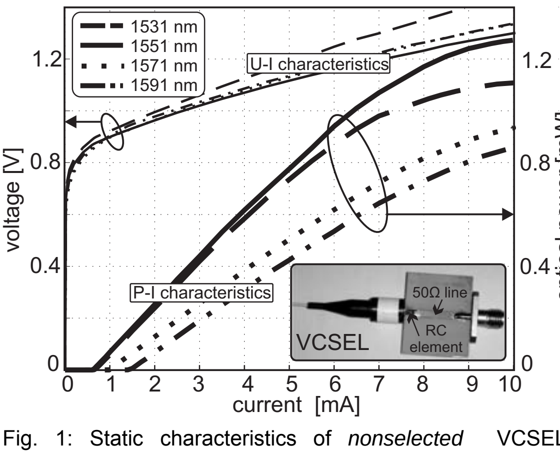

Fig. 1: Static characteristics of *nonselected* VCSELs covering the CWDM band from 1531 to 1591 nm.

Vertical cavity surface emitting laser

To demonstrate 4-channel high-speed CWDM transmission, we used four single-mode pigtailed, uncooled VCSELs (Vertilas), rated for 2.5-Gb/s modulation but here driven at a data rate of 10.7-Gb/s. This was made possible by mounting the VCSELs at the end of a 50-Ω microstrip line, in series with an RC element consisting of a 1 pF capacitor in parallel to a resistor (82 to 150 Ω), as shown in the inset to Fig. 1. The RC element significantly improved the VCSELs' modulation response at frequencies > 3 GHz, which was originally limited mainly by the package. The signals had an extinction ratio of ~4 dB. Our VCSELs were not preselected in any way and had thus widely varying static as well as dynamic characteristics. Fig. 1 shows the DC-characteristics, revealing threshold currents from 0.7 to 1.4 mA, maximum laser output powers from 0.85 to 1.3 mW, and a slope efficiency between 0.1 and 0.19 mW/mA. The linewidth of the VCSELs is some 29 MHz.

Interplay of chromatic dispersion and laser chirp

Figure 2 shows, as a typical example, the required receiver input power as a function of transmission distance for the 1551-nm CWDM channel. The curves are taken at BER = 10^{-9} (solid squares) and 10^{-3} (open circles). For the dashed curves, the laser driving conditions were optimized for best back-to-back performance, while the solid curves represent optimum driving conditions for maximum reach. The improvement between 20 and 50 km was achieved when increasing the bias current to some 5 mA and

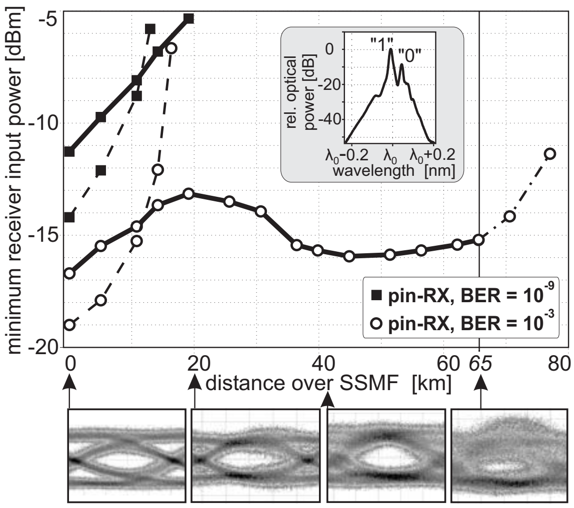

Fig. 2: Receiver input power vs. transmission distance for the 1551-nm VCSEL with driving conditions optimized for maximum reach (solid lines) and for optimum back-to-back performance (dashed lines) at 10.7 Gb/s. *Dashed-dotted line:* An EDFA was used in order to measure the dispersion limited link distance. *Inset:* Optical laser spectrum when modulated with "01"-pattern at 1Gb/s. *Lower part:* Eye diagrams at various distances.

employing a higher modulation swing (solid curves). This behaviour, known as the *self-steepening effect* [5], is caused by the interplay of chromatic dispersion and adiabatic laser chirp and is also observed for directly modulated DFB lasers [3]. Chirp measurements on these VCSELs revealed that the '0'-states ("off"-states) produce a spectral peak at lower frequency (higher wavelength) than the '1'-states (cf. inset to Fig. 2, [6]). In the SSMF, dispersion at 1551 nm accelerates the high frequencies and slows down the low frequencies. Propagation within the fiber leads to a re-compression of the pulses and therefore a wider eye opening at distances between 20 and 50 km. Without any dispersion compensation, a power-limited maximum reach of 65 km was achieved. When using a 39-dB gain Erbium-doped fiber amplifier at the output of the laser in order to emulate a VCSEL with a slightly higher output power of 4 mW, the dispersion-limited reach was found to be around 77 km (cf. dashed-dotted line in Fig. 2).

CWDM transmission

The CWDM system demonstrated in this work is depicted in Fig. 3. It employed four uncooled VCSELs operating at the wavelengths λ_1=1531, λ_2=1551, λ_3=1571 and λ_4=1591 nm, driven with a pseudo-random bit sequence of length 2^{31}-1 using non-return-to-zero modulation at the FEC bit rate of 10.7 Gb/s.

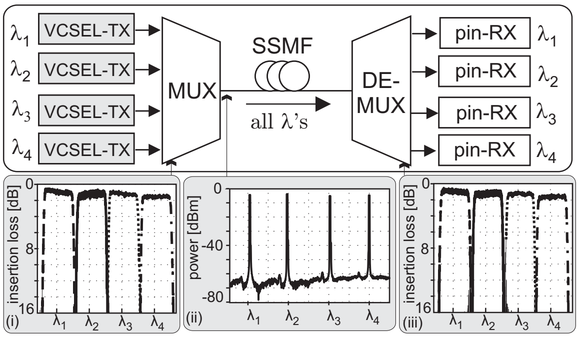

Fig. 4-channel CWDM system: Insertion loss of CWDM thin film (i) multiplexer, (iii) demultiplexer, and (ii) CWDM spectrum launched into the fiber.

The average laser powers varied among the channels from -2.3 to -0.45 dBm. All four lasers were driven simultaneously by feeding them via an electrical power splitting network. Commercial thin-film CWDM multiplexers with channel-dependent insertion losses between 0.85 and 1.8 dB were used to combine the sources. The transfer characteristics of the multiplexers as well as the CWDM spectrum launched into the fiber are shown in Fig. 3. An additional loss of 2-3 dB was due to connectors in the test setup. At 1551 nm the SSMF had an attenuation of 0.22 dB/km and a dispersion of 17.5 ps/nm.km. Figure 4 shows the required receiver input powers (white bars) for BER = 10^{-3} (which can be reduced to BER $\leq 10^{-16}$ using enhanced FEC) after transmission of the optical signal over the maximum possible distance, as well as the available VCSEL output powers (gray bars). Figure 4 also gives the maximum transmission distance (circles) for each CWDM channel, with all but one channel going beyond 51 km. The minimum link distance of 45 km is achieved at 1591 nm due to a relatively high multiplexer insertion loss. The results reported so far where obtained at 25°C. When operating the VCSELs at an elevated temperature of 65°C, the minimum link distance is 25.6 km at 1591 nm, mainly due to a decrease in the laser's output power. Note that all link lengths are attenuation limited and longer reach is possible with higher VCSEL output power.

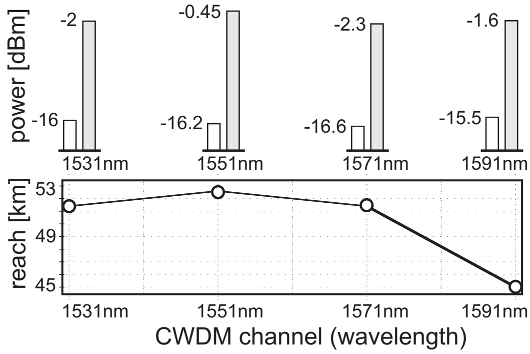

Fig. 4: Available VCSEL power (gray bars) and required receiver input power for BER=10^{-3} (white bars) at maximum transmission distance (circles) and for all CWDM channels.

Conclusion

We have experimentally demonstrated 4-channel CWDM transmission over standard-single mode fiber at the FEC bit rate of 10.7 Gb/s, using commercially available, non-preselected VCSELs without any kind of optical or electronic dispersion compensation. All four channels were transmitted over more than 45 km. The longest CWDM transmission distance (52.6 km) was achieved at 1551 nm. We showed that with increased VCSEL output power this reach could be extended up to the dispersion limit.

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