20 Gb/s data transmission over 2 km multimode fibre using an 850 nm mode filter VCSEL

R. Safaisini, E. Haglund, P. Westbergh, J.S. Gustavsson, and A. Larsson

Error-free data transmission over 1.3 km and 2 km multimode fibre at 25 Gb/s and 20 Gb/s, respectively, are demonstrated using a high speed, single mode, 850 nm VCSEL with an integrated mode filter. This result presents a bit rate-distance product of 40 Gb/s-km, a new record for multimode fibre VCSEL-based interconnects.

Introduction: Rapidly growing data centres for cloud computing services require longer reach optical links up to ~2 km at data rates of 20 to 25 Gb/s [1]. Vertical-cavity surface-emitting lasers (VCSELs) operating at 850 nm and multimode fibres (MMFs) have been an ideal combination for short reach interconnects and are a potential solution for extended-reach optical links [2]. This is due to tolerant optical alignment of MMF links and the numerous advantages of VCSELs such as excellent high-speed properties, low power consumption, and low-cost fabrication.

Effects of chromatic and modal dispersion in MMFs set the main limitation on increasing the bit rate over long distances. The effects of chromatic dispersion can be reduced by employing VCSELs with a smaller number of transverse modes and consequently narrow spectral width. Various approaches have been investigated to enable high speed long distance data transmission over MMFs by using single mode (side mode suppression ratio (SMSR) >30 dB) or quasi-single mode (SMSR ~20 dB) VCSELs. High speed error-free transmission over >500 m MMF (defined as bit error rate (BER) $<10^{-12}$) has been reported for small aperture VCSELs [2-4], photonic crystal VCSELs [5], and mode filter VCSELs [6]. The latter utilizes a shallow surface relief (SR) to form an integrated mode filter, allowing low spectral width VCSELs with larger oxide apertures. SR VCSELs offer a number of advantages including less complex structure than photonic crystal VCSELs, lower differential resistance than small aperture VCSELs for better impedance matching to 50 Ω loads and possibly more reliable operation than small aperture VCSELs (lower current density and internal temperature). However, small aperture VCSELs have been shown to be more energy efficient [4].

In this letter we report data transmission over 1.3 km and 2 km OM4 MMF at 25 Gb/s and 20 Gb/s respectively, using a high-speed, single mode 850 nm SR VCSEL. To the best of our knowledge, the bit rate-distance product of 40 Gb/s-km (20 Gb/s over 2 km) is the highest reported for a link employing directly modulated VCSELs and MMFs.

VCSEL design and characteristics: The high speed VCSEL structure reported here is a long cavity version of the design presented in [7], aimed at reducing electrical resistance and optical absorption by introducing a new grading and doping schemes for p- and n-type distributed Bragg reflectors (DBRs). Most of the bottom n-DBR employs binary AlAs as the low index material to facilitate effective heat transport from the junction through bottom DBR. The 1.5-λ thick cavity employs five 4-nm thick InGaAs strained quantum wells separated by 6-nm thick AlGaAs barriers. The top p-DBR contains two deep selectively oxidized $Al_{0.98}Ga_{0.02}As$ layers just above the active region for electrical and optical confinement and four additional shallow oxide layers from $Al_{0.96}Ga_{0.04}As$ above the aperture to reduce parasitic capacitance. An extra λ/4-thick anti-phase GaAs layer added to the top DBR allows for fine adjustment of photon lifetime and mode filter integration in a post processing step. VCSELs were fabricated through a standard high speed process flow with an extra step for precisely defining a circular SR in the centre of VCSEL mesas using e-beam lithography. The SR processing and operation are explained in more detail elsewhere [8]. The mode filter is formed by etching away the top DBR anti-phase layer in the centre of the waveguide, resulting in an increased top DBR reflectivity for the fundamental mode with the best overlap with the central region, as seen in Fig. 1a. Higher order transverse modes with more overlap with the unetched region experience a higher loss and are suppressed.

A ~6 µm aperture diameter VCSEL with 3 µm diameter SR is compared with a VCSEL with the same aperture size but no SR (anti-phase surface reflection). The room temperature output power-current-voltage (LIV) characteristics of the VCSELs with and without SR are presented in Fig. 1b. The SR VCSEL has lower output power, slope efficiency, and threshold current, compared to the anti-phase VCSEL, as a result of increased overall top mirror reflectivity and consequently reduced cavity loss. The SR VCSEL shows a roll-over output power of 5.2 mW with a 0.78 W/A slope efficiency and 0.4 mA threshold current. The optical emission spectra measurement reveals that the anti-phase VCSEL operates in multi transverse modes with RMS spectral width ($\Delta\lambda_{RMS}$) greater than 0.6 nm. On the contrary, the SR VCSEL is single mode with SMSR >30 dB for currents up to 7 mA with $\Delta\lambda_{RMS} < 0.35$ nm for currents from 2 to 8 mA. The optical emission spectra of both VCSELs at 4 mA are presented in Fig. 2. The narrow spectral width and single mode operation of the SR VCSEL reduce the effects of chromatic and modal dispersion and together with relatively high output power allow for long distance transmission over MMF. The lower cavity loss leads to a longer photon lifetime and thus larger damping of the relaxation oscillation. Even though low damping is required to reach higher bandwidths in VCSELs, a certain amount of damping is needed to reduce ringing and timing jitter for high speed data transmission. The S_{21} measurement shows that the SR VCSEL has a maximum 3 dB bandwidth of ~19 GHz.

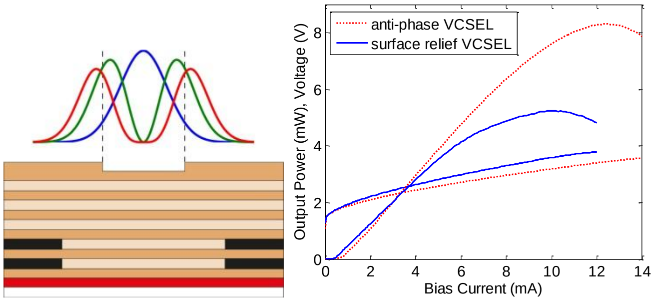


Fig. 1 *a) Schematic figure of the etched surface relief mode filter with the overlap of the three lowest order transverse modes. b) LIV characteristics of the ~6 µm aperture anti-phase and SR VCSELs.*

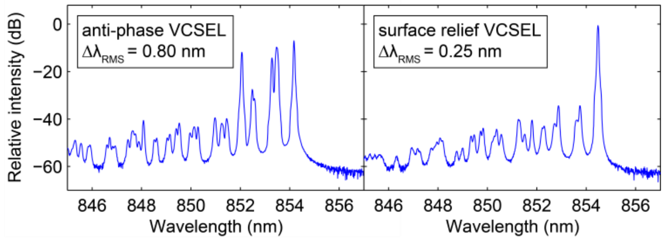
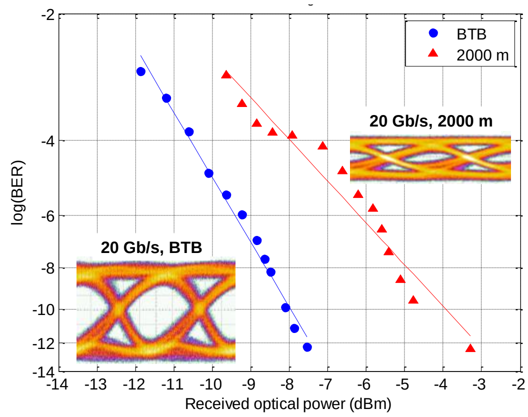


Fig. 2 *Optical spectra of the anti-phase and SR VCSELs at 4 mA.*

Transmission experiments: The large signal modulation characteristics of the SR VCSEL were measured using a non-return-to-zero data pattern with a 2^7-1 bits pseudorandom binary sequence from a SHF 12103A bit pattern generator. The signal was amplified using a linear SHF 807 amplifier in combination with attenuators to generate a peak-to-peak modulation voltage of 750 mV before feeding the signal into the VCSEL through a bias-T via a high speed probe. The output light was butt-coupled to a 50 µm core diameter OM4 MMF with a maximum coupling efficiency of ~60%. The fibre was then connected to a JDSU OLA-54 variable optical attenuator, either directly for back-to-back (BTB) measurement or via long OM4 fibres for long distance transmission. A New Focus 1484-A-50 photoreceiver with 22 GHz bandwidth and a linear integrated transimpedance amplifier was used to detect and amplify the optical signal from the variable attenuator before recording eye diagrams using an Agilent Infiniium DCA-J 86100C 70 GHz digital communications analyzer or performing BER analysis using a SHF 11100B error analyzer. Using a photoreceiver with an integrated amplifier is essential for reducing the noise level in measurement and improving the signal quality.

BER measurements and eye diagrams for 20 Gb/s and 25 Gb/s data rates are presented in Fig. 3. Open eyes and error-free operation were achieved over up to 2000 m at 20 Gb/s and 1300 m at 25 Gb/s with corresponding VCSEL energy dissipations of 323 fJ/bit and 258 fJ/bit. For all measurements the VCSEL was biased at 3.5 mA (~12 kA/cm^2), only slightly above the 10 kA/cm^2 industry standard for reliable operation [9]. The power penalty for increasing the transmission distance from BTB to the maximum distance is ~4 dB and ~3 dB at 20 Gb/s and 25 Gb/s, respectively. The mode filter scheme presented here yields the best mode selectivity due to the λ/4 step between the etched and unetched surfaces. However, one can adjust the etched step for a desired photon lifetime (mirror loss) and yet high mode selectivity, resulting in an optimum amount of damping for reduced jitter and (quasi) single-mode operation. This could potentially allow for even higher speed data transmission over long MMFs when using SR VCSELs.



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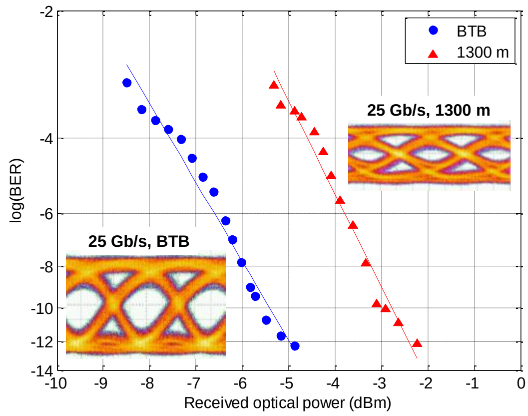

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Fig. 3 *BER measurements for (a) 20 Gb/s BTB and over 2000 m MMF and (b) 25 Gb/s BTB and over 1300 m MMF .*
Insets: Eye diagrams for BTB and over 2000 m and 1300 m MMF.

Conclusion: Integrating SR mode filters on high-speed, oxide-confined, 850 nm VCSELs enabled single transverse mode operation with narrow spectral width and relatively high output power. Error-free data transmissions up to 2000 m at 20 Gb/s and 1300 m at 25 Gb/s were demonstrated with the record bit rate-distance product of 40 Gb/s-km, at a current density of just ~12 kA/cm^2.

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