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Electronics Letters (ISSN: 0013-5194)

Citation for the published paper:
Haglund, E. ; Haglund, Å. ; Westbergh, P. et al. (2012) "25 Gbit/s transmission over 500 m multimode fibre using 850 nm VCSEL with integrated mode filter". Electronics Letters, vol. 48(9), pp. 517-518.

http://dx.doi.org/10.1049/el.2012.0529

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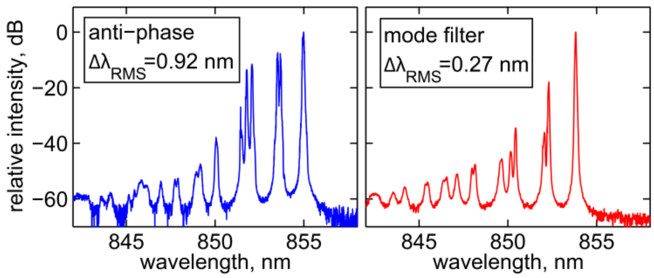
25 Gbit/s transmission over 500 m multimode fibre using an 850-nm VCSEL with an integrated mode filter

E. Haglund, Å. Haglund, P. Westbergh, J. S. Gustavsson, B. Kögel and A. Larsson

An integrated mode filter in the form of a shallow surface relief was used to reduce the spectral width of a high-speed 850-nm vertical-cavity surface-emitting laser (VCSEL). The mode filter reduced the RMS spectral width from 0.9 to 0.3 nm for a VCSEL with an oxide aperture as large as 5 µm. Because of reduced effects of chromatic and modal fibre dispersion, the mode filter significantly increases the maximum error-free (bit-error-rate < 10^{-12}) transmission distance, enabling transmission at 25 Gbit/s over 500 m of multimode OM3+ fibre.

Introduction: Multimode vertical-cavity surface-emitting lasers (VCSELs) operating at 850-nm have become well established light sources for optical interconnects in local area networks, storage area networks and high-performance computing due to low power consumption, circular output beam, fast direct modulation at low currents and low-cost fabrication [1]. Recent years have seen an impressive increase in the speed of 850-nm GaAs-based VCSELs, reaching small signal modulation bandwidths exceeding 23 GHz and enabling error-free transmission at 40 Gbit/s back-to-back [2]. These devices show great promise as transmitters in future short-reach (rack-to-rack and board-to-board, ≲ 300 m) and very-short-reach (module-to-module and chip-to-chip, ≲ 1 m) optical interconnects. Moreover, the low-cost 850-nm GaAs VCSEL technology also has the potential to be used at longer distances of several hundreds of meters, meeting the demand for longer optical interconnects in ever larger data centres. However, for transmission distances exceeding 300 m and data rates above 10 Gbit/s, the effects of modal and chromatic fibre dispersion significantly distort the signal [3]. At higher bitrates, reducing the effects of fibre dispersion becomes increasingly important, becoming a serious concern already at a distance of 100 m at ≳ 25 Gbit/s.

In this letter, we utilize an integrated mode filter to reduce the spectral width of a VCSEL and thereby mitigate the effects of fibre dispersion. The result is a significant increase in transmission distance, enabling error-free transmission at 25 Gbit/s over 500 m of OM3+ fibre. This is to our knowledge the first time an 850-nm VCSEL with an oxide aperture as large as 5 µm has been used to transmit such high bitrates over as long distance as 500 m.



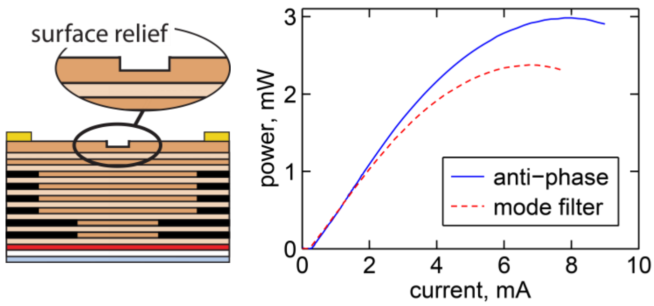
a) b)

Fig. 1 *Optical spectra at 4 mA for 5 µm oxide aperture VCSELs without (a) and with (b) a surface relief mode filter.*

High-speed design: The VCSEL structure is the same as in [2, 4] with the addition of a regrown 59 nm thick p-doped GaAs layer. The active region contains five strained InGaAs/AlGaAs quantum wells for high differential gain and a separate confinement heterostructure designed for fast carrier capture and low gain compression. Two selectively oxidized $Al_{0.98}Ga_{0.02}As$ layers provide electrical and optical confinement, while an additional four shallow $Al_{0.96}Ga_{0.04}As$ oxidized layers reduce mesa capacitance to decrease parasitic impairments. The top distributed Bragg reflector (DBR) has a λ/2-thick top layer for anti-phase surface reflection to shorten the photon lifetime for enhanced bandwidth by reduced damping [4]. Because of the large transverse dimensions and strong index guiding from the multiple oxide layers, VCSELs without mode filters are transverse multimode with a large root-mean-square (RMS) spectral width in excess of 0.9 nm, see Fig. 1a. The currently used IEEE-803.2ae standard (10 Gbit/s over up to 300 m OM3 fibre) requires an RMS spectral width < 0.45 nm. At higher bitrates an even smaller spectral width will be required.

Integrated mode filter: Many different techniques have been applied to reduce the spectral width of VCSELs. By using a small oxide aperture of ~3 µm, researchers at TU Berlin and VI Systems GmbH, Germany, could transmit 25 Gbit/s over 300 m of OM3 fibre [5]. A small oxide aperture, however, leads to large differential resistance and thereby increased self-heating which limits the output power. Other methods include metal apertures, extended cavities, curved mirrors and complex structures such as photonic crystals [1]. Most of these methods have the drawback of making VCSEL design and fabrication considerably more complex and may not be suitable for high-speed direct modulation.

The surface relief technique used in this work constitutes a small change to the standard VCSEL fabrication process. The method is described in detail in [6]. By etching away the top DBR anti-phase layer locally in the centre of the waveguide (see Fig. 2a), the mirror loss is reduced for the best confined modes (in particular the fundamental mode). This leads to suppression of higher order modes, thereby making the surface relief an integrated mode filter. This enables the fabrication of low spectral width VCSELs with relatively low differential resistance thanks to the relatively large oxide aperture of 5 µm. Fig. 1 shows the optical spectra of an anti-phase VCSEL and a mode filter VCSEL with a 1.5 µm diameter surface relief etched through the 59 nm thick anti-phase layer. The mode filter reduces the RMS spectral width by over 70 %, from 0.92 to 0.27 nm.



a) b)

Fig. 2 *a) Schematic cross-sectional view of a VCSEL with a surface relief mode filter. b) Output power vs. current.*

Since the mode filter increases the reflectivity of the top DBR, it increases the photon lifetime, resulting in lower threshold current, reduced slope efficiency and lower maximum output power (see Fig. 2b). A longer photon lifetime increases the probability that a photon is absorbed before being transmitted through the top DBR, leading to an increased internal optical absorption rate and self-heating, which is seen by a lower thermal rollover current. Longer photon lifetime also leads to a larger damping of the modulation response, slightly decreasing the bandwidth [4]. The maximum small signal modulation 3 dB bandwidth is reduced from 22 GHz for the anti-phase VCSEL to 19 GHz for the mode filter VCSEL. A larger damping may, however, be beneficial thanks to a reduction of jitter due to a faster decay of the relaxation oscillations when settling to a new power level.

Transmission experiments: The system performance of the mode filter VCSEL was verified by transmission experiments. A 900 mV_{pp} non-return-to-zero pseudorandom binary sequence of 2^7-1 bits was generated with an SHF 12103A bit pattern generator and fed to the VCSEL through a bias-T and an RF high-frequency probe. The output light was captured using an anti-reflection coated lens system and an angled facet fibre to minimize reflections from the setup and then transmitted through high-speed OM3+ multimode optical fibre or a short patch-cord for the back-to-back (BTB) configuration. A JDSU OLA-54 variable optical attenuator was used to control the received optical power for the bit-error-rate (BER) measurements. The signal was detected with a 25 GHz NewFocus 1481-S-50 photodetector followed by an SHF 804TL amplifier (22 dB gain, 55 GHz bandwidth) to boost the voltage amplitude of the signal. Eye diagrams were recorded with a 70 GHz Agilent 86100C digital oscilloscope with a precision timebase and BERs were measured using an SHF 11100B error analyser.

Fig. 3 shows the BER as a function of the received optical power at 25 Gbit/s. The mode filter VCSEL was biased at 3.5 mA (18 kA/cm^2) and the anti-phase VCSEL at 5.5 mA (28 kA/cm^2), since the shorter photon lifetime requires a larger bias current to establish a high enough photon density for good high-speed properties. The large RMS spectral width (> 0.9 nm) of the anti-phase VCSEL severely limits the transmission distance, preventing error-free transmission even over 100 m of OM3+ fibre. The low spectral width (< 0.3 nm) mode filter VCSEL, however, enables error-free transmission at BTB, 100 m and 300 m with only minor power penalty. With a 3 dB penalty, error-free transmission was even possible over 500 m of OM3+ fibre.

a)

b)

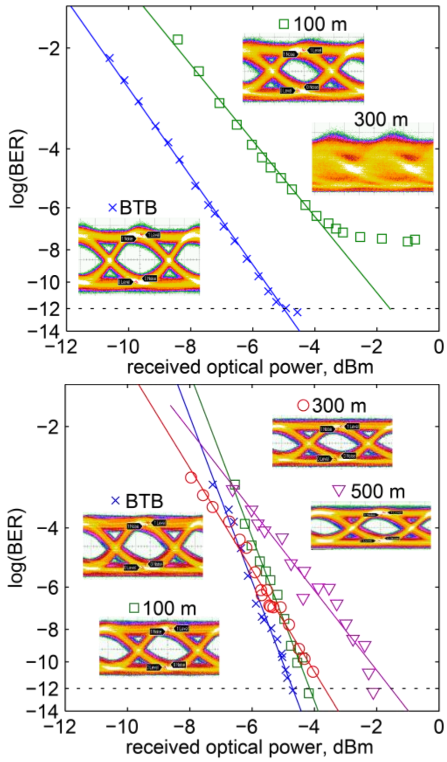


Fig. 3 *BER vs. received optical power at room temperature for the anti-phase VCSEL (a) and mode filter VCSEL (b) with eye diagrams.*

Conclusions: We have demonstrated a significant increase in error-free transmission distance of high-speed 850-nm VCSELs by incorporating an integrated mode filter. The surface relief mode filter does not degrade the electrical properties and enables fabrication of low spectral width VCSELs with oxide apertures as large as 5 µm. The reduced spectral width, and therefore lessened effects of chromatic and modal fibre dispersion, enabled error-free transmission at 25 Gbit/s over 500 m of multimode OM3+ fibre, while a high-speed VCSEL, without mode filter, fails to transmit error-free even over 100 m of fibre.

Acknowledgments: This work was supported by the European FP7 project VISIT (224211) and the Swedish Foundation for Strategic Research project LASTECH.

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