Optical-Domain Four-Level Signal Generation by High-Density 2-D VCSEL Arrays

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We propose a novel modulation scheme using three butt-coupled VCSELs per fiber for the generation of four-level signals in the optical domain. The information density, and hence spectral efficiency, is increased by using multiple VCSELs per 50 µm core diameter multimode fiber to generate more complex signals. First experiments are demonstrated using two VCSELs butt-coupled to the same standard glass fiber, each modulated with two-level signals to produce four-level signals at the photoreceiver. A four-level direct modulation of one VCSEL within a triple of devices produced first 20.6 Gbit/s (10.3 Gsymbols/s) four-level eyes, leaving two VCSELs as backup sources.

1. Introduction

We employ high-density high-speed vertical-cavity surface-emitting lasers (VCSELs) with wedge-shaped mesas in flip-chip integrated two-dimensional (2-D) arrays for the generation of four-level digital signals. Multi-level signals make better use of available bandwidth and thus increase fiber channel capacities.

This article first describes layout and structure of dense wedge-shaped high-speed VCSELs in 2-D arrays and gives their basic static and dynamic characteristics. The second part addresses several ways in which high-density VCSEL arrays may be utilized for different types of multi-level signal generation. A novel modulation scheme is proposed which enables four-level digital signal transmission by a two-level modulation of three separate lasers. All three VCSELs launch light into the same multimode fiber where three optical data streams add up to form a four-level signal. This scheme requires extended capabilities of drive electronics. Since only a regular bit pattern generator was available to us, two out of three lasers in a channel were modulated with two-level signals. The modulation parameters were adjusted such that the combined amplitudes of the two output beams produced a four-level signal.

The final section presents experiments where two separate bi-level data streams were combined in the electrical domain before addressing the laser. Similar to what was done in [1] using a single DFB laser, this resulted in a four-level direct modulation of only one of the three available VCSELs per fiber channel, leaving the two spare lasers as a possible backup in case of premature device failure.

2. Densely Packed Wedge-Shaped VCSELs in 2-D Arrays

Figure 1 shows a triple of wedge-shaped VCSELs. The design aims at closest possible center-to-center distances for mesa-isolated VCSELs while maintaining good thermal and dynamic characteristics of these substrate-removed devices. As the dry etch process utilizes the p-contact metallization as the etch mask, arbitrary mesa shapes are possible.

Figure 2 shows a top view of the completed flip-chip structure around the wedge mesas without solder balls. It is crucial for these substrate-removed lasers with substrate-side emission at 850 nm to place the solder balls at least partially on top of the mesas. This creates paths for efficient heat flow hence allowing for high-current VCSEL operation without excessive internal heating.

For development purposes, the cells within the 2-D arrays were not designed to be uniform but many dimensions were varied. A true-to-scale representation of the actual layout can be found in [2]. The mesa separations are between 3.8 and 1.8 µm. The oxidation length is below 4 µm. The biggest devices have active areas of 158 μm^2, corresponding to circular areas with 14 µm diameter. The active area of the smallest mesas is 38 μm^2 (7 µm diameter). This is the size that was used for some of the multi-level signal transmission experiments in this article.

Figure 3 gives the light–current–voltage (LIV) curves of the smallest VCSEL triple. The insets indicate the device dimensions and the measurement configuration. The VCSELs uniformly show a 2 mA lasing threshold, 3.1 mW maximum output power at 15 mA, 20 % differential quantum efficiency, and 77 Ω differential resistance.

The small-signal modulation characteristics of the same VCSELs are displayed in Fig. 4. As is evident from those curves, the flatness of the modulation response improves at high

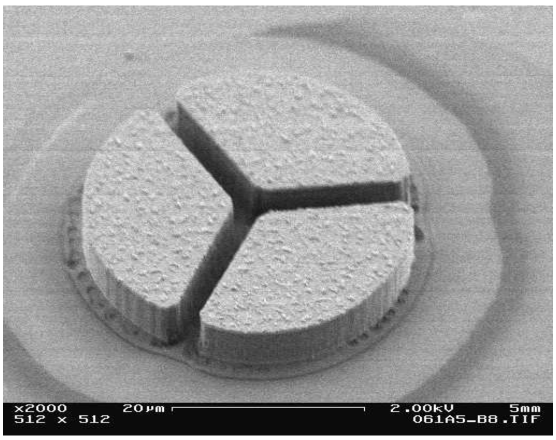


Fig. 1: SEM picture of three wedge-shaped VCSELs in one of 4×4 channels of an array after high-temperature oxidation in humid environment. The VCSELs exhibit smooth and vertical sidewalls and a self-aligned full size p-contact.

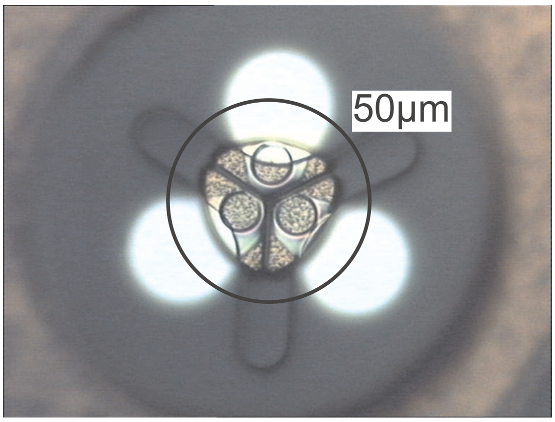


Fig. 2: Epitaxial-side view of completed close-spaced wedge VCSELs prior to solder deposition. The 50 µm circle indicates the relative position of the VCSELs with respect to a centered multimode fiber core.

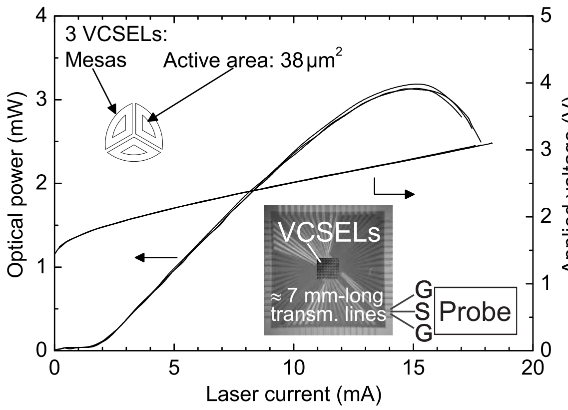


Fig. 3: LIV curves of three VCSELs within one cell of a $(4\times4)\times3$ array. The inset shows a true-to-scale representation of this pixel. The wedge-shaped 38 μm^2 active area corresponds to a 7 μm diameter circular current aperture.

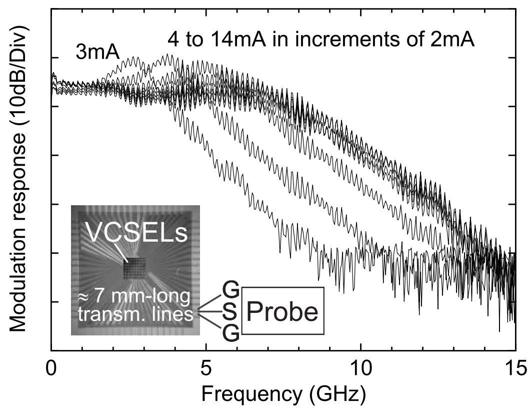


Fig. 4: Bias-dependent transfer functions of a VCSEL from the same pixel indicating 7.7 GHz maximum 3-dB corner frequency, held approximately in the range from 9 to 11 mA, while the 10-dB bandwidth for currents above 10 mA lies between 9.5 and 9.8 GHz.

drive currents. Flat laser transfer functions are important for a consistent signal level definition in large-signal modulation since they contribute to good overall system linearity, especially important when more than two signal levels are present in complex multi-level eye patterns. However, if heat extraction from the laser is insufficient, high power dissipation at high drive currents leads to high junction temperature, diminishing differential gain and quantum efficiency and accordingly the modulation response. Rise and fall times and extinction ratio of digital signals are immediately affected. It is found indispensable, especially for substrate-removed devices, to provide efficient passive cooling. This is done here by solder bonding the VCSELs directly to the mesas.

3. Four-Level Modulation

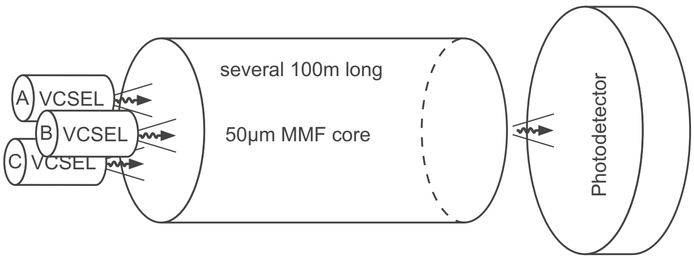
Dense flip-chip VCSEL integration opens up new avenues for the further increase in total data throughput of transmitter arrays, on one hand through built-in redundancy by keeping all parallel channels fully functional for a longer lifespan [3], on the other by increasing the complexity of the sent data in each channel. This section explores the latter possibility as some systems might benefit from the use of signals of higher complexity than the usual binary format. Expanding the symbol alphabet provides higher spectral efficiency.

Signals with four distinct amplitudes correspond to a four-symbol alphabet as opposed to two symbols available with binary transmission by simple on-off keying. The bit rate (twice the symbol rate) for a given bandwidth is doubled. Accordingly, a given data rate can be transmitted with half the line rate of an equivalent binary modulation format. Of course, extra functionality will be needed for the modulation and de-modulation of four-level signals. Dense transmitter arrays with three VCSELs instead of one launching into each fiber lend themselves to the optical-domain generation of four-level signals.

3.1 Four-level signal generation scheme using high-density VCSEL arrays

High-density VCSEL configurations accommodating three direct-bonded lasers in an area of less than one third the core of high-speed optimized multimode fibers were already demonstrated in [3]. Figure 5 illustrates how three VCSELs per fiber may be used to generate four-level signals. The nominally identical lasers are at the three vertices of an equilateral triangle and emit at the same wavelength. The fiber is perfectly aligned to the orthocenter of this triangle, ensuring equal coupling efficiencies. Precise passive fiber alignment can be achieved with the help of mechanical guides on the emission side of the VCSEL array. Development in this regard is currently underway.

In this scheme, every one of the three lasers can be operated with the optimum drive current and two-level modulation parameters, producing nominally identical amplitudes of two-level bit streams. If all bit streams are well synchronized, the optical intensities will add up to a four-level signal on the photoreceiver. On the right of Fig. 5, a model four-level eye pattern is used to associate each level with the required states of the identical VCSELs A, B, and C. For instance, the symbol `1 0` will be obtained if any two of the VCSELs are in `ON`-state while the third one is `OFF`.



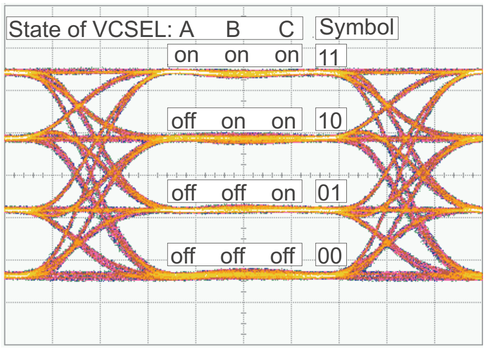


Fig. 5: Schematic showing one fiber channel of an optical link (left) illustrating the idea of four-level digital signal generation in the optical domain. The scheme uses three close-spaced VCSELs that are separately addressable and butt-coupled to one common 50 µm core diameter multimode fiber with equal coupling efficiencies. The optical signals add up at the photoreceiver, resulting in four distinct levels of intensity (right).

The lasers typically used for short-reach optical links have multimode emission. Since all three lasers are nominally identical, there exists a probability that two wavelengths involved are so close to each other that the beating product of co-polarized modes created at the photodetector may interfere with the signal spectrum. At $\lambda = 850\,\text{nm}$, a wavelength difference of $\Delta\lambda = 25\,\text{pm}$ will produce a beating product at $\Delta\nu = 10\,\text{GHz}$, according to $\Delta\nu = (c/\lambda^2)\Delta\lambda$. Normally, fabrication tolerances lead to a certain degree of emission wavelength difference. If the wavelengths are still too close to each other, the VCSELs will have to be slightly modified to prevent beating products at frequencies within the signal spectrum. Beating products of larger wavelength differences are filtered out by the low-pass characteristic of the photodetector.

3.2 Experimental four-level signal generation in the optical domain

The above scheme of four-level signal generation requires additional capabilities of the drive electronics. As usual, when the information density is increased by means of more complex signals, additional "intelligence" is needed on the transmitting and receiving ends of the link. Due to the unavailability of such electronics in our first laboratory experiments, we followed an indirect approach for the optical generation of four-level signals using dense VCSELs.

According to Fig. 6, two of the three VCSELs in one pixel are fed with the `DATA` or $\overline{\texttt{DATA}}$ streams of a pattern generator. Additional attenuators are inserted to avoid the reflections from the pattern generator ports which otherwise degrade the signals. As the names of the ports imply, both data streams are not independent but one is the inverted version of the other. In order for the superposition of both pseudo-random bit sequences (PRBSs) to yield all four cases (both high, both low, one high the other low), one sequence needs to be delayed with respect to the other by integral multiples of one symbol duration at the given modulation rate. Instead of a variable delay line, a fixed delay was introduced in the form of an extra cable and the symbol rate adjusted for all measurements.

The amplitudes of the `DATA` and $\overline{\texttt{DATA}}$ streams can be selected independently. Each of the bit sequences are directly modulating one of the two lasers. The optical bit streams are coupled to the same fiber and detected by a fast photoreceiver. At the photoreceiver, the level separation of one signal must be exactly half of the second signal to give four evenly spaced levels. In the present setup, the VCSEL-to-fiber interface was found to be the weak link. There was no mechanical guide to the fiber and due to some instability of the setup it was found difficult to align the fiber such that both lasers coupled with equal efficiency.

Figure 7 shows a resulting four-level eye pattern for NRZ modulation with a $2^7 - 1$ word length PRBS. The symbol rate is 3.9 Gsymbols/s, corresponding to 7.8 Gbit/s. Both lasers

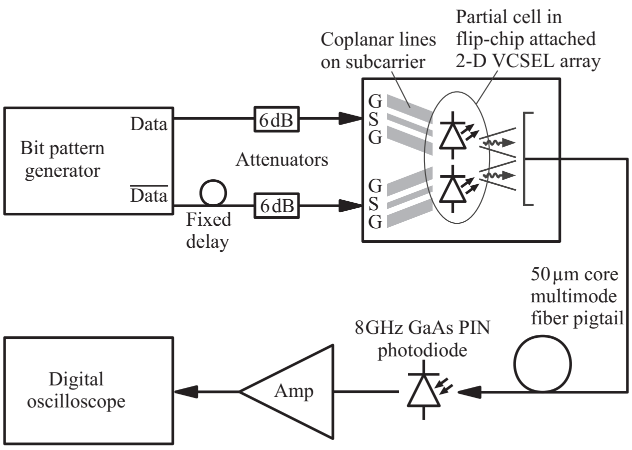


Fig. 6: Experimental setup using two of three available VCSELs per pixel butt-coupled to a standard multimode fiber for the optical-domain generation of four-level signals.

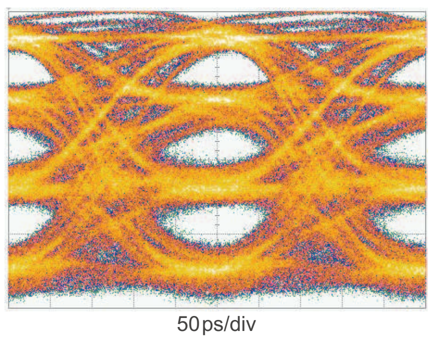


Fig. 7: 7.8 Gbit/s (3.9 Gsymbols/s) four-level eye pattern generated by superposition of two optical signals.

were biased at 8 mA and the peak-to-peak voltages were 2.0 V and 1.0 V. It is evident from the figure that although the eyes are open there is much room for improvement. The maximum achievable signal amplitude is split into four rather than only two levels, making four-level eyes much less robust with regard to noise and system nonlinearities. The particular lasers used for these experiments were circular in shape and had non-flat transfer functions with pronounced ripples from multiple reflections, much worse than the small signal curves in Fig. 4. This is believed to be the main reason for the degradation of the eye pattern. It also limits the bit rate achievable with four-level modulation to less than 10 Gbit/s. The lasers used here were shown to be capable of producing good-quality two-level eyes at 10 Gbit/s in Ref. [3]. Nevertheless, generation of four-level eyes can be beneficial to bandwidth-limited systems. This is true especially when electronics are available to implement the modulation scheme introduced in Sect. 3.1 along with improvements to the VCSEL-to-fiber interface.

3.3 Electrical-domain four-level signal generation experiments

We used a coupler to combine the two 2^7-1 word length NRZ PRBS two-level bit streams from the `DATA` and $\overline{\texttt{DATA}}$ ports in the electrical domain. The resulting four-level signal directly modulated one of three VCSELs. In this scheme, the remaining two VCSELs per array cell are left as backup devices in case of VCSEL failure. Figure 8 shows the setup which is similar to the one in the previous section, only that the two bit streams are combined before reaching the VCSEL array. With this method, higher modulation rates were achieved than with the combination of optical bit streams.

Figure 9 shows a four-level eye at 20.6 Gbit/s (10.3 Gsymbols/s) obtained for 12 mA bias current. The values in the two branches were $V_{\mathrm{pp1}} = 1.63\,\mathrm{V}$, $\alpha_1 = 10\,\mathrm{dB}$ and $V_{\mathrm{pp2}} = 2.00\,\mathrm{V}$, $\alpha_2 = 6\,\mathrm{dB}$, respectively. The modulated optical signal is detected by an 8 GHz PIN photodiode. In the case of the eye pattern shown, the electrical signal was filtered by a 7 GHz low-pass filter inserted between amplifier and oscilloscope. It is clear from the

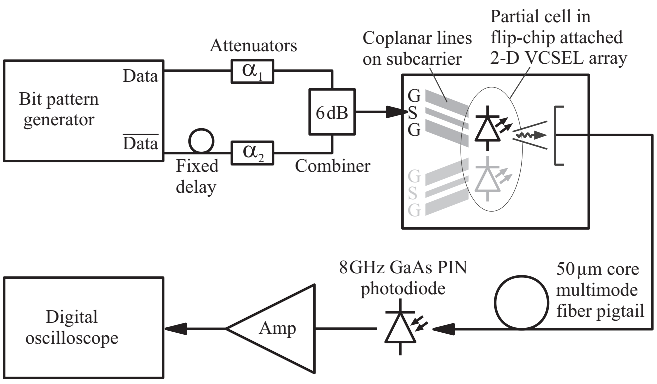


Fig. 8: Experimental setup for the electrical-domain combining of two-level signals of different amplitudes from the `DATA` and $\overline{\texttt{DATA}}$ ports. The electrical four-level signal directly modulates one of three VCSELs in a pixel.

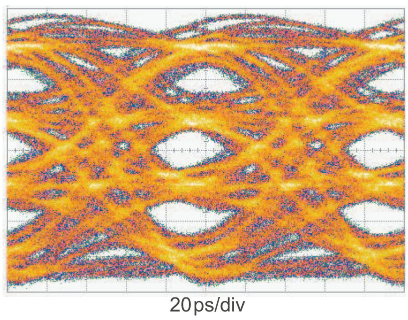


Fig. 9: 20.6 Gbit/s (10.3 Gsymbols/s) four-level eye pattern generated in the electrical domain by superimposing the electrical signals.

eye pattern that there is a lack of symmetry. Slow rise and fall times as well as system nonlinearity strongly reduce the eye openings. This is nevertheless the first time that such extremely close-spaced flip-chip bonded VCSELs in 2-D arrays have been used for the generation of four-level eyes.

4. Conclusion

Ultra-dense wedge-shaped VCSELs showed the ability for single-device four-level modulation at 10.3 Gsymbols/s (20.6 Gbit/s), as well as for the simultaneous operation of two densely spaced mesa-isolated VCSELs at 3.9 Gbit/s each, producing a combined 3.9 Gsymbols/s. A higher VCSEL resonance frequency would have helped to increase the eye openings by shorter rise and fall times. The VCSEL-to-fiber interface limited the performance in the mode of four-level generation in the optical domain. This can be improved by the introduction of mechanical fiber guides to ensure alignment as well as proper index matching to prevent backreflections.

Acknowledgment

Special thanks to Faisal Imam and Alexander Weigl who worked with me toward their theses during this last year. Their many contributions are much appreciated.

References

[1] A. Wonfor, R.V. Penty, I.H. White, K. White, A.E. Kelly, and C. Tombling, "Uncooled 40 Gb/s 4-level directly modulated laser source for datacoms applications", in *Semiconductor Lasers and Laser Dynamics*, D. Lenstra, G. Morthier, T. Erneux, M. Pessa (Eds.), Proc. SPIE 5452, pp. 562–570, 2004.

[2] H. Roscher, P. Gerlach, F.N. Khan, A. Kroner, M. Stach, A. Weigl, and R. Michalzik, "Toward more efficient fabrication of high-density 2-D VCSEL arrays for spatial redundancy and/or multi-level signal communication", in *Micro-Optics, VCSELs, and Photonic Interconnects II: Fabrication, Packaging, and Integration*, H. Thienpont, M.R. Taghizadeh, P. Van Daele, J. Mohr (Eds.), Proc. SPIE 6185, pp. 61850V-1–12, 2006.

[3] H. Roscher, M. Bou Sanayeh, S.B. Thapa, and R. Michalzik, "VCSEL arrays with redundant pixel designs for 10 Gbit/s 2-D space-parallel multimode fiber transmission", in Proc. *31st Europ. Conf. on Opt. Commun., ECOC 2005*, vol. 3, pp. 687–688. Glasgow, Scotland, UK, Sept. 2005.