Design and Communication Applications of Short-Wavelength VCSELs

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ABSTRACT

We report on recent progress in the design of short-wavelength vertical-cavity surface-emitting lasers (VCSELs) for 10 Gbit/s datacom applications. Topics of interest include differential mode delay characterizations of high-performance multimode fibers and their interplay with transverse single- and multimode VCSELs, flip-chip integrated two-dimensional arrays at 850 nm wavelength, as well as experiments toward the realization of optical backplanes. In the latter case, reliable 10 Gbit/s data transmission has been achieved over low-loss integrated polymer waveguides with up to 1 meter length. Moreover we present VCSELs with output powers in the 10 mW range that are employed in multi-beam transmitters for free-space optical data transmission with Gbit/s speed over distances of up to about 2 km.

Keywords: Surface-emitting lasers, VCSELs, semiconductor laser arrays, optical interconnections, multimode fiber, 10-Gigabit Ethernet, differential mode delay, optical backplane, free-space optics, optical wireless communications

1. INTRODUCTION

Short-wavelength VCSELs[1] emitting predominantly in the 850 nm spectral region are firmly established devices in the optical datacom market. As of today, main applications are found in local area networks and the interconnection within computer clusters and telecom gear, where single or parallel links with channel data rates of up to about 3 Gbit/s satisfy the demand for increased bandwidth density, scalability, and immunity to electromagnetic interference, among others. Current research in this domain is focused on the optimization of VCSELs for 10 Gbit/s data rates, two-dimensional arrays and their integration with electronics and waveguide arrays, as well as solutions for ultra-short reach optical interconnects within single computer frames. As for 850 nm oxide-confined VCSELs for serial 10 Gbit/s transmission, convincing results have been obtained in terms of high-speed modulation,[2] operation at elevated temperatures,[3] and multimode fiber transmission,[4,5] both for single elements as well as one-dimensional arrays.[6]

The present contribution deals with the use of gain-switched singlemode and multimode VCSELs for differential mode delay measurements of high-bandwidth graded-index fibers, where chromatic dispersion is expected to become a limiting factor in future km-long links operated at 10 Gbit/s data rate. As an application example in ultra-short reach interconnection, we then look into the upcoming optical backplane technology and review recent demonstrations of VCSEL based 10 Gbit/s data transmission over low-loss polymer waveguides of up to 1 m length. A massive increase of data throughput is enabled by two-dimensional VCSEL arrays, where we will briefly illustrate the progress in flip-chip integrated bottom-emitting devices for the standardized

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850 nm wavelength regime. Finally we note that the properties of short-wavelength VCSELs as well as two-dimensional matrix configurations are favorably exploited in free-space optics for inter-rooftop or inter-window communication at Gbit/s data rates, recently experiencing an upsurge of interest.

2. HIGH-SPEED MULTIMODE FIBER CHARACTERIZATION

The vast majority of short-wavelength VCSELs is employed for data communication relying on silica graded-index multimode optical fiber (MMF), where 1 to 1.25 Gbit/s is today's dominant data rate for high-speed links. With the adoption into standards like 10-Gigabit Ethernet (10-GbE)[7] that was approved in June 2002, an important milestone has been reached that will most likely ensure the continued penetration of 850 nm solutions into local area networks. In 10-GbE, short-wavelength options exist for the transport of 10 Gbit/s signals over either up to 65 m of regular quality (bandwidth–length product BLP = 500 MHz·km) MMF or up to 300 m of 850 nm bandwidth-optimized (BLP $\geq$ 2 GHz·km) MMF, both with 50 µm core diameter. Selected MMFs with bandwidths markedly exceeding average production quality have been shown to support data rates of 10 Gbit/s over lengths of 1.6 km[8] and 2.8 km[9] or 15.6 Gbit/s over 1 km.[10] Beyond the above specifications, the data throughput might in future further be increased by applying the wide or coarse wavelength division multiplexing technique, as demonstrated with 4×10 Gbit/s transmission over 310 m of high-bandwidth MMF.[11]

The suitability of a high-performance MMF for laser based data transmission is tested by time-domain differential mode delay (DMD) measurements[12] that are performed as follows. For characterization at 850 nm wavelength, a singlemode fiber with about 5 µm core diameter is scanned over the input end of the fiber under test, where at each radial offset position the impulse response is recorded. Since for varying launch positions different mode groups are excited in the fiber, the overall group delay behavior can be studied in detail.

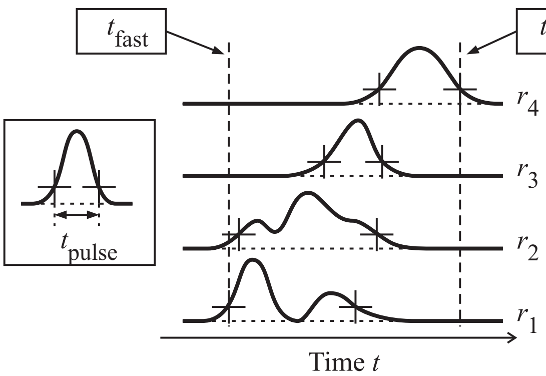

Figure 1. Extraction of differential mode delay data from pulse shapes measured at different radial coupling offsets $r_{1...4}$. The input pulse is shown with a relevant pulse width of Δt_{pulse} (from Ref. 12).

According to Fig. 1, 25 % threshold levels of leading or trailing pulse edges are used to determine a combined overall pulse spreading for a certain range of offset positions. With the nomenclature of Fig. 1 and for an input pulse with a nearly Gaussian spectrum, the relevant mode delay is calculated as

$$\Delta t_{\text{DMD}} = t_{\text{slow}} - t_{\text{fast}} - \sqrt{\Delta t_{\text{pulse}}^2 + \Delta t_{\text{chrom}}^2} \ , \tag{1}$$

where Δt_{pulse} is the full width at 25 % of the input pulse and

$$\Delta t_{\text{chrom}} = 4\sqrt{\ln 2} \cdot \delta\lambda \cdot D(\lambda) \cdot L \tag{2}$$

accounts for the contribution of chromatic dispersion at a given root mean square spectral width of the source $\delta\lambda$ and a fiber length L. At $\lambda = 850$ nm wavelength, the chromatic dispersion coefficient to be expected amounts to $D = 107$ ps/(km·nm).

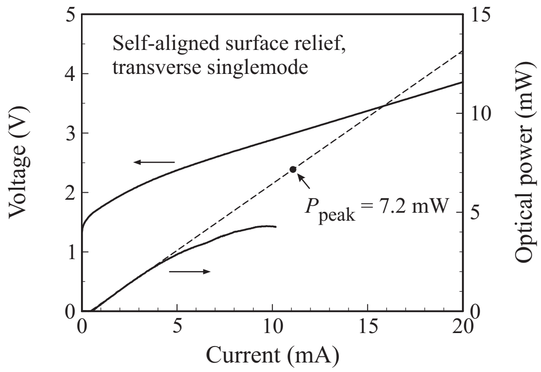

Figure 2. Continuous-wave operation characteristics of a surface-etched singlemode VCSEL with 4.5 µm active diameter and 2.6 µm relief diameter. The dashed line indicates the hypothetical pulsed output power curve and includes the measured peak power for a single 100 ps-long voltage pulse.

In order to allow for different optimizations of the graded-index profile, two intervals are defined over which the mode delay has to stay within given limits. For the so-called *inner mask*, output pulses at launch radii from 5 to 18 µm are evaluated, whereas the *outer mask* extends from 0 to 23 µm. Several alternative templates for the differential mode delay $\Delta t_{\mathrm{DMD}}/L$ normalized to the fiber length are then imposed as qualification criteria. The differential mode delays allowed by the templates are the more strict over the outer mask the more forgiving they are over the inner mask. In numbers, they range from 0.23 and 0.70 ps/m for the inner and outer mask, respectively, to 0.33 ps/m for both masks. Meeting one of the templates, the fiber is then expected to be suitable for 10 Gbit/s transmission over $L = 300\,\mathrm{m}$, provided that the laser launch conditions are such that the encircled flux of the input beam is smaller than 30 % at a radius of 4.5 µm and larger than 86 % at a radius of 19 µm.

Usually, DMD measurements are performed with a mode-locked Titanium–Sapphire laser as a pulse source.[5] However, a more elegant and cost-effective solution is the use of a gain-switched 850 nm VCSEL coupled to a singlemode fiber for MMF mode excitation. In order to get a well-defined spectrum, as required for the accurate application of (1), the VCSEL has to emit in a single transverse mode. Singlemode VCSELs offer numerous advantages over multimode devices like lower noise, higher modulation efficiency, or lower threshold currents. The incorporation of an etched relief into the surface of the top Bragg mirror has proven to be an efficient method to obtain stable and high-power singlemode operation at larger active diameters compared to conventional designs.[13] Figure 2 depicts the operation characteristics of such a VCSEL with 4.5 µm oxide-confined active diameter and 2.6 µm diameter of the surface relief.

The VCSEL shows a threshold current of 600 µA and in continuous-wave mode delivers a maximum singlemode output power of about 3 mW with a side-mode suppression ratio exceeding 30 dB at a current of 5 mA. In order to obtain short pulses, the VCSEL is periodically gain-switched by 100 ps-long pulses from a bit pattern generator, where the bias is set slightly above threshold and voltage modulation occurs with an amplitude of $2\,\mathrm{V_{pp}}$. A resulting pulse, as measured with a 20 ps rise and fall time optical sampling oscilloscope is displayed in the left-hand part of Fig. 3.

The pulse is characterized by a full width at half-maximum (FWHM) of 33 ps which is close to the expected resolution limit, whereas the pulse width defined by the decrease of the maximum intensity to 25 % amounts to $\Delta t_{25\,\%} = \Delta t_{\mathrm{pulse}} = 60\,\mathrm{ps}$. The emitted optical peak output power equals 7.2 mW. As illustrated in Fig. 2, this value is obtained for a modulation current of 11 mA provided that the light–current curve is strictly linear with suppressed internal heating. The right-hand part of Fig. 3 shows the dynamic emission spectrum under the above driving conditions. The root mean square (RMS) spectral width amounts to $\delta\lambda = 0.16\,\mathrm{nm}$ at a resolution of the optical spectrum analyzer of 0.01 nm. Higher order transverse modes are suppressed by more than 35 dB.

Figure 4 shows a two-dimensional representation of the DMD profile of a 1.9 km-long MMF with 50 µm core diameter. For the measurement, one period of the employed 10 Gbit/s bit pattern consists of a single "Ones" followed by a number M of consecutive "Zeros", where M is chosen large enough that the arrival times of

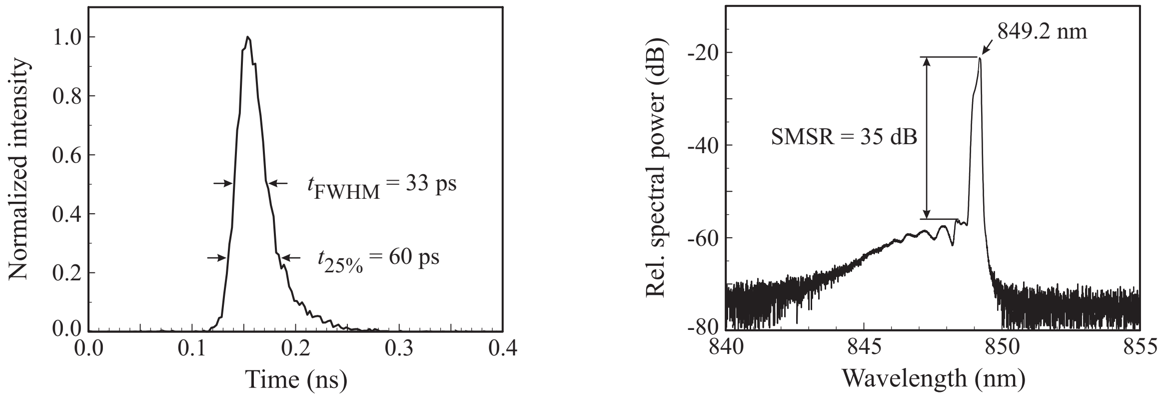

Figure 3. Optical pulse shape obtained by gain-switching the VCSEL from Fig. 2 with a single bit from a pattern generator clocked at 10 Gbit/s (*left*) and pulsed optical spectrum corresponding to $P_{\mathrm{peak}} = 7.2\,\mathrm{mW}$ in Fig. 2 (*right*). Side-mode suppression ratio (SMSR) and root mean square spectral width are 35 dB and 0.16 nm, respectively.

output signals induced by different input pulses are sufficiently separated. For each radial coupling position, the maximum pulse intensity has been normalized to unity.

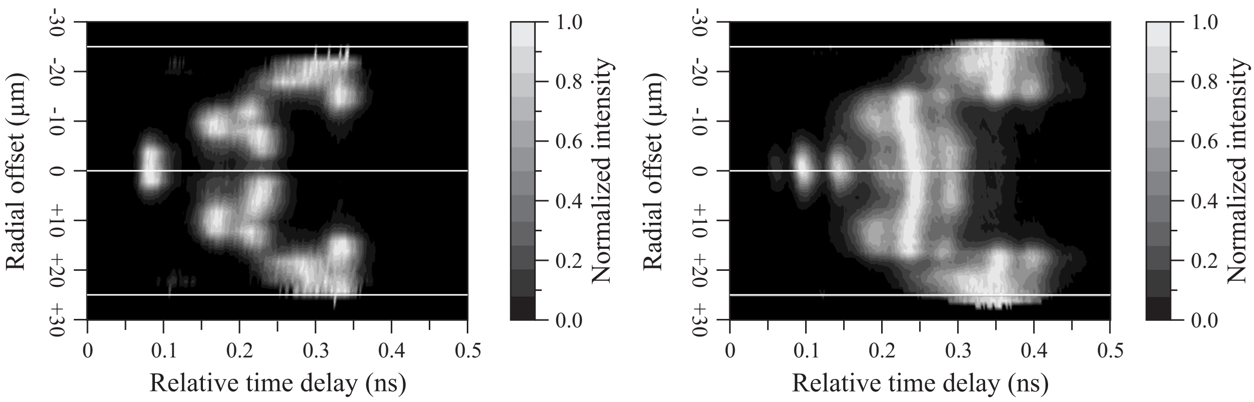

Figure 4. Differential mode delay characteristics of a 1.9 km-long MMF with 50 µm core diameter as obtained with the singlemode VCSEL source from Fig. 2 (*left*) and with a multimode VCSEL (*right*).

On the left-hand side of Fig. 4, the profile has been taken with the singlemode source according to Fig. 2, whereas for the right-hand part, a transverse multimode VCSEL with 12 µm active diameter and an RMS spectral width of $\delta\lambda = 0.31\,\mathrm{nm}$ (as emitted from the 5 µm core diameter singlemode fiber) has been employed. The broadening of the DMD profile as a result of chromatic dispersion is clearly visible. For the singlemode VCSEL, the normalized differential mode delays $\Delta t_{\mathrm{DMD}}/L$ corresponding to the inner and outer masks are 0.096 and 0.101 ps/m, respectively. In case of the multimode source, figures of 0.125 and 0.128 ps/m — increased by more than 25 % — are determined. Both sets of delays well satisfy the templates for 10 Gbit/s transmission over 300 m distance. On the other hand, with increasing MMF profile control through methods like plasma-activated chemical vapor deposition and thus higher fabrication yield, as well as improved receiver sensitivities enabling relaxed power budgets, km-long distance high-speed MMF transmission will be in reach and might be of much interest, e.g. for residential area networks. In this case, singlemode 850 nm VCSELs will be ready to serve as low-cost key enabling components.

3. OPTICAL BACKPLANES FOR 10 GBIT/S/CHANNEL THROUGHPUT

The roadmap of optical data communications envisages photonic technologies to become useful even for tasks like chip-level interconnection. Among the different hierarchies of intra-system links, optical backplanes interconnecting various printed circuit boards within a computer rack are most likely to be implemented in the near future.[14] A rather straightforward implementation concept that has gained considerable maturity, relying on free-space coupling and 45° beam deflection into polymer based waveguides, is illustrated in Fig. 5.

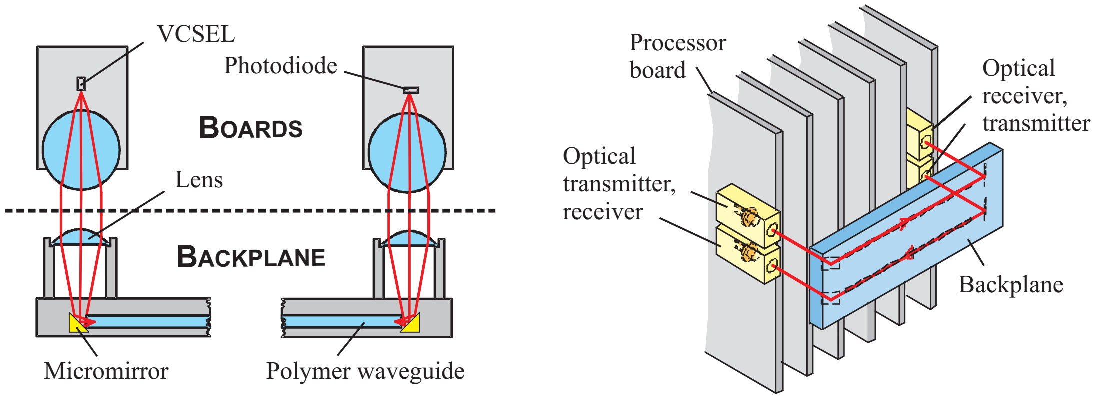

Figure 5. Optical backplane concept developed by DaimlerChrysler, as described in Ref. 15.

We have investigated the suitability of multimode VCSELs emitting at 850 nm wavelength for high-speed data transmission over various waveguide (WG) configurations.[16] As an example, in this paper we report on the characteristics of quasi straight WGs of 0.5 and 1 m length with a numerical aperture (NA) of 0.35 and a cross-sectional area of $250 \times 200\,\mu m^2$ as well as a 1 m-long spiral WG with a radius of curvature ranging from about 3.3 to 4.4 cm, a $100 \times 100\,\mu m^2$ core size, and $NA = 0.3$.

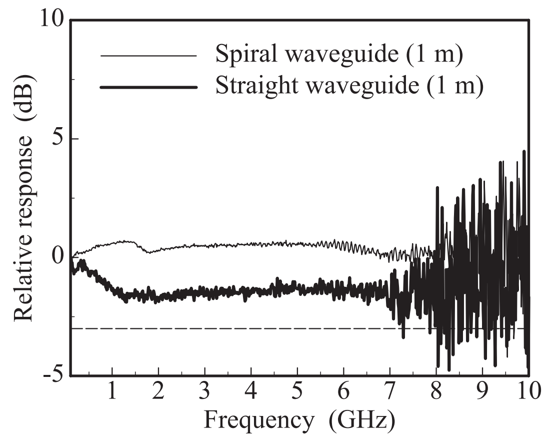

Figure 6. Small-signal frequency responses of two 1 m-long polymer waveguides.

Figure 6 shows the small-signal frequency responses of the two 1 m-long WGs, determined with the VCSEL source. The -3 dB limits exceeding 10 GHz indicate a BLP of at least 10 GHz·m so that digital data transmission at 10 Gbit/s is expected to be feasible, provided that requirements of minimum received optical power are met.

The results of bit error rate (BER) measurements performed at 10 Gbit/s data rate are summarized in Fig. 7. In case of the spiral waveguide, quasi error-free transmission is achieved with 1.5 dB power penalty at

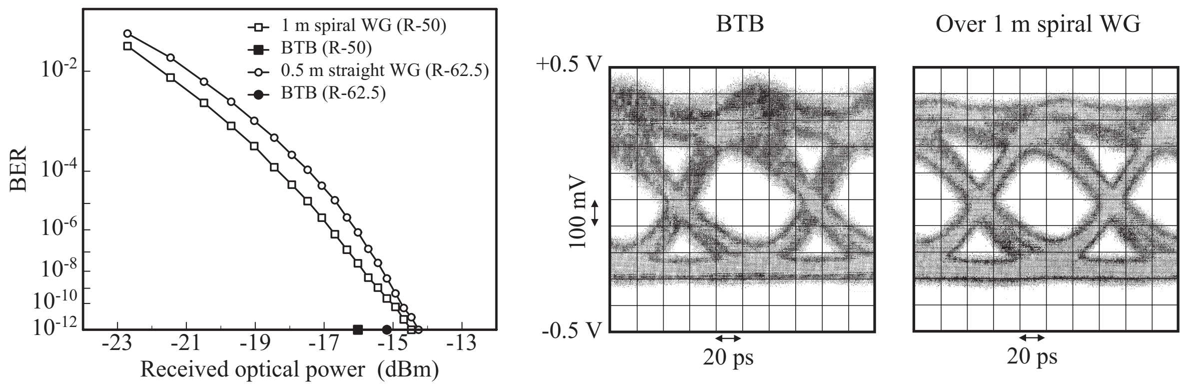

Figure 7. Bit error rate characteristics for 10 Gbit/s data transmission over backplane-type polymer waveguides of 0.5 and 1 m length. Photoreceivers with 50 µm (R-50) and 62.5 µm (R-62.5) core diameter MMF inputs have been used in conjunction with the longer or shorter waveguide, respectively. For both experiments, the received power for back-to-back (BTB) transmission at BER $< 10^{-12}$ is indicated by a corresponding filled symbol (*left*). 10 Gbit/s eye diagrams for BTB transmission (*center*) and over a 1 m-long spiral waveguide (*right*), both recorded at quasi error-free conditions.

BER $= 10^{-12}$. Excluding a loss of each 0.5 dB for the Au-coated micromirrors,[15] the attenuation coefficient of this WG is as low as 0.02 dB/cm. Under comparable conditions, a power penalty of only 0.5 dB has been observed for a similar spiral WG with a larger core size of $250 \times 200\,\mu\text{m}^2$.[17] The straight WGs originating from previous non-optimized fabrication runs showed larger attenuation. With losses of about 0.07 dB/cm for the 1 m-long WG, the received power was too small for the present setup, even if the light at the output facet was collected by a MMF with larger core diameter and *NA*. On the other hand, with a 50 cm-long WG of lower loss (0.036 dB/cm), 10 Gbit/s transmission proved to be possible with 0.9 dB power penalty at the lowest BER. In a more realistic system environment, the receivers will employ large-area high-speed photodetectors, e.g. of the metal–semiconductor–metal type, so that the overall power budget will benefit from greatly reduced output coupling losses.

4. TWO-DIMENSIONAL 850 NM VCSEL ARRAYS

High-density two-dimensional (2-D) space division multiplexed optical interconnection through MMF bundles for data throughput in the above 100 Gbit/s range is an attractive solution exclusively enabled by VCSEL technology. 2-D VCSEL arrays have already been realized in a rather early stage.[18] However, in order to be applicable for high-frequency modulation, electrical signals have to be fed to the individual lasers, where conventional configurations featuring bondpads at the periphery of the chip face a wiring bottleneck with associated problems of impedance matching and electrical crosstalk, among others. Flip-chip bonding the laser chip directly onto the driver circuitry, realized, e.g. in Si CMOS technology,[19] is an obvious solution, however enforcing bottom emission toward the substrate side and requiring both contacts to be accessible from the epitaxial surface. Finally, the standardization of the 850 nm wavelength regime for MMF based Gbit/s range datacom imposes a further fabrication challenge since the standard GaAs substrate is opaque to the laser light. To allow for bottom emission, we have implemented a substrate removal process that is applied after In solder based flip-chip integration*.

The left-hand part of Fig. 8 shows the operation characteristics of a latest generation 8×8 elements VCSEL array with 10 µm individual oxide aperture diameter after flip-chip mounting and GaAs substrate removal. Very good homogeneity is achieved with an average threshold current of 1 mA and a maximum slope efficiency exceeding 0.6 W/A. At a current of 4 mA and an associated output power of 1.6 mW, applied voltage and differential resistance amount to 2.05 V and 70 Ω, respectively. Instead of PbSn, as reported in Ref. 21, In solder bumps have been applied here. The emission spectrum on the right-hand side of Fig. 8 reveals the existence of

*For alternative approaches to 850 nm bottom-emitting VCSELs see, e.g. Ref. 20.

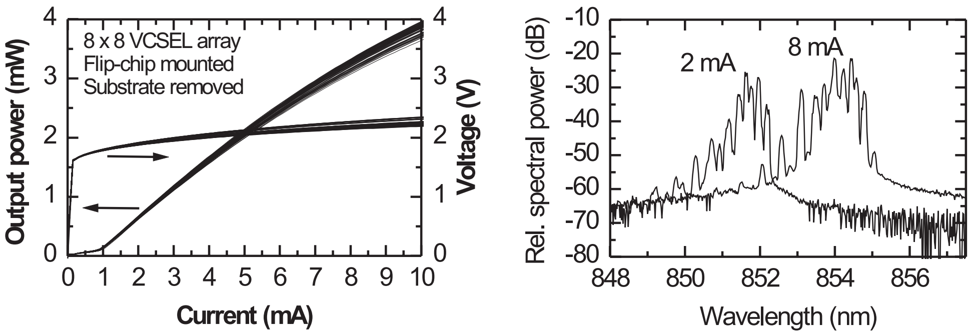

Figure 8. Operation characteristics of an oxide-confined 8×8 bottom-emitting VCSEL array after flip-chip bonding to a Si carrier and subsequent substrate removal. Individual device diameter is $10\,\mu$m (*left*). Typical transverse multimode emission spectrum at two different driving currents (*right*).

several transverse modes and may be characterized by a $-10\,$dB width of about 2 nm. The typical red-shift of the spectrum corresponds to a thermal resistance of roughly 2.5 K/mW.

5. VCSEL BASED FREE-SPACE OPTICAL DATA LINKS

Apart from their use in optical fiber based data communications, VCSELs are more and more frequently employed in systems relying on data transmission with free-space optics (FSO), sometimes also denoted optical "wireless" systems.[22] In this section we will first discuss some general characteristics of FSO, then introduce a multi-beam configuration based on 850 nm VCSELs, and finally conclude with remarks on opportunities for operation at longer wavelengths.

5.1. General Considerations

Due to increasing demand for broadband services by users at the end of the so-called "last mile" in telecommunication networks, FSO technologies are expected to gain considerable importance over the next years. This is due to favorable properties like

- rapid set-up time on rooftops or behind glass windows of just a few hours,
- large transparency with respect to bit rate and coding,
- moderate cost,
- data transmission speeds in the Gbit/s range similar to fiber optics,
- security against eavesdropping due to side lobe-free radiation characteristics, and
- relief from obtaining trenching permits and radio frequency spectrum licenses,

where especially the latter three items give FSO an edge over competing millimeter-wave systems. Apart from applications in the optical access domain, like interconnection of corporate networks, optical wireless solutions are employed, e.g., by television companies to establish video links at stadium events, or by mobile phone operators to connect base stations to the fixed-line backbone. On the other hand, compared to fiber optical solutions, challenges and restrictions of FSO are given by

- intervisibility requirements between transmitter and receiver,
- atmospheric conditions, where fog and snow in particular can limit the link availability,
- atmospheric scintillation causing variations of the received power, and

- achievable link lengths of only a few 100 m for maximum availability of 99.999 % as achieved in fiber based telecommunications. Under relaxed requirements, distances up to some km can be bridged.

Historically, both light emitting diodes and edge-emitting laser diodes have been used in the short-wavelength 850 nm spectral range, whereas modern systems mainly rely on highly matured VCSELs, where much appreciated features include small threshold currents and high efficiency, direct modulation capability exceeding 10 Gbit/s, circularly symmetric beam profiles with divergence angles between 5 to 20 degrees, low coupling losses to optical fibers even without external optics, feedback insensitivity, small temperature drift, and simplifications of driving circuits that often render automatic power control unnecessary. Currently, 850 nm VCSEL based products are available with data rates up to 1.25 Gbit/s. The underlying principle of FSO transmission is rather simple. Either the digitally modulated VCSEL itself or the endface of its fiber pigtail is placed in the focal point of the transmitter optics. Correspondingly at the receiving end, a lens or a parabolically shaped mirror is used to focus the beam directly onto a photodiode or a fiber that feeds the signal to a remote detection unit.

Since changes of meteorological conditions can induce considerable variations of the signal level at the receiver, a large system margin is necessary for reliable operation. This margin is dependent on the geographical location with its specific weather conditions as well as the required average availability of the link. To give a rough indication, Fig. 9 shows the system margin at 850 nm for typical conditions found in Central Europe, where the average has been taken over one year. As an example, a 600 m-long link requires a margin slightly exceeding 30 dB to ensure an average availability of 99 %, whereas already 50 dB have to be provided for a distance of 1 km.

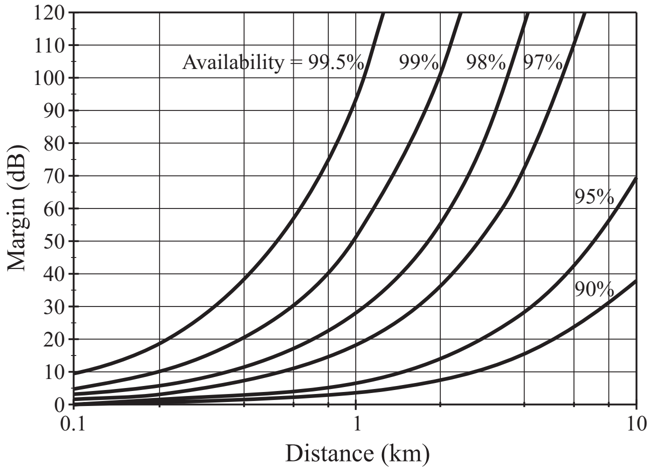

Figure 9. Required system margin for a given link availability (averaged over one year) at 850 nm wavelength and weather conditions typical for Central Europe.[23]

A sufficient system margin is especially obtained with high optical output power, low beam divergence, as well as a receiver with large cross-sectional area and high sensitivity. Concentrating on the transmitter side, power restrictions are imposed by the requirement that even direct exposure of the human eye to the laser beam ought to be harmless, i.e. eye safety regulations demand conformity to laser class 1M standard IEC 60825-1. At an operating wavelength of 850 µm, the beam intensity must thus not be larger than 2 mW/cm^2. In order to fulfill this requirement at high optical power, large diameter beams have to be used. As an example, a single VCSEL with Gbit/s modulation capability may deliver 5 mW output power, as introduced in the following section. Expanding the beam to a diameter of 2 cm will then satisfy class 1M conditions. Should higher output power be needed, a parallel arrangement of several lasers with corresponding collimating optics may be provided. Naturally due to surface-normal emission, VCSELs are ideally suited for this kind of multi-beam FSO transmission. By applying wavelength division multiplexing, multi-beam configurations can also be used to greatly increase the data throughput of a single link.

5.2. Multi-Beam VCSEL Transmitter Module

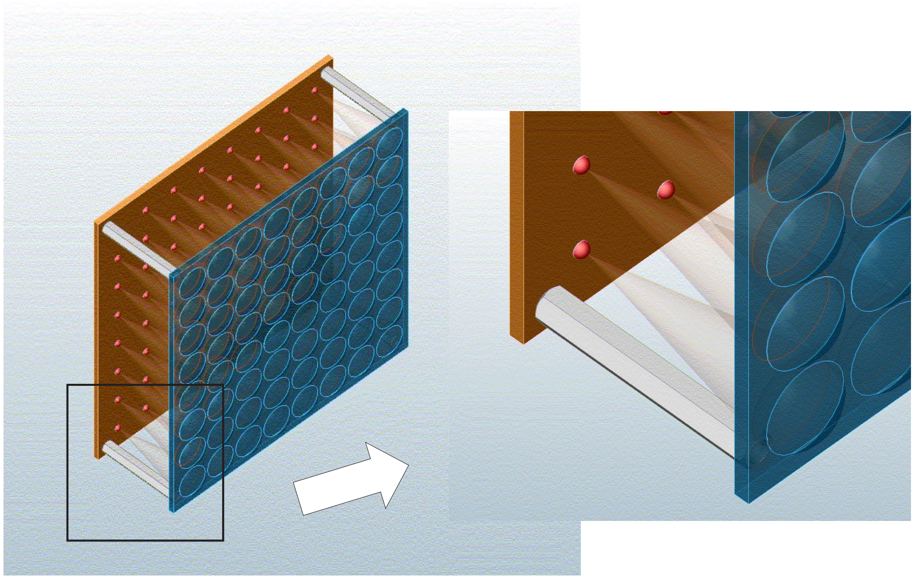

Figure 10. Schematic of an 8×8 multi-beam transmitter module consisting of an array of solitary VCSELs on a circuit board and overlayed optics, individually collimating the laser beams.

Figure 10 illustrates the design of a transmitter module with 64 VCSELs and a suspended optical plate for beam shaping. With 5 mW output per VCSEL, the total output power of the module would amount to 320 mW or 25 dBm. Nevertheless, with board dimensions of $160 \times 160\,\mathrm{mm}^2$, the source is eye-safe according to laser class 1M. By adjusting the distance between VCSEL board and optical layer, the divergence angle can be adjusted between 0.3 and 10 mrad, where angles larger than about 2 mrad are recommended in systems without automatic beam tracking.

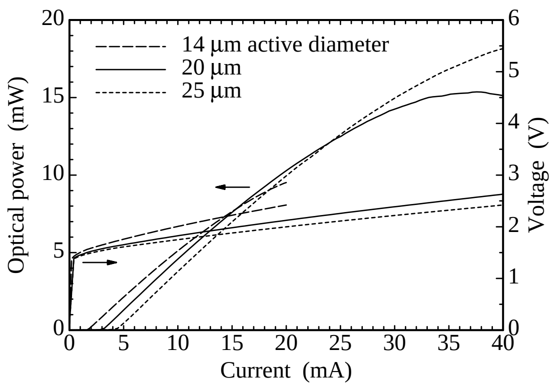

Figure 11. Typical operation characteristics of oxide-confined 850 nm VCSELs suitable for free-space applications. The active diameters are 14, 20, and 25 µm.

Figure 11 depicts the operation characteristics of several 850 nm VCSELs designed for FSO rather than optical datacom applications. By means of selective wet oxidation, active diameters of 14, 20, and 25 µm are defined. Threshold currents are 1.8, 3.2, and 4.5 mA and maximum output powers amount to approximately 10, 15, and 19 mW, respectively. The slope efficiency ranges between 0.6 and 0.68 W/A, so that the driving current for 5 mW output has to be adjusted to 9.8, 10.7, or 11.9 mA at applied voltages of 2.0, 1.85, or 1.8 V, respectively. With the given layout, the modulation bandwidth easily exceeds 5 GHz. The actual achievable maximum bit rate also depends on the mounting technology, where simple TO can or advanced chip-on-board solutions are among the choices. Both the spectral width and the divergence angle slightly increase with driving current and take typical values of < 1 nm root mean square and about 20° full width at $1/e^2$ maximum intensity, respectively.

As a practical realization, Fig. 12 shows the intensity distribution of a LightPointe transmitter module incorporating 16 VCSELs. In the plane of the optical layer, the individual beams are clearly visible, whereas in a distance of 18 m, the chosen divergence angle of 7 mrad results in an overlapping intensity profile. Beam propagation with a virtual waist located behind the transmitter board ensures compliance with the maximum class 1M power density along the entire beam array. The module is targeted for applications requiring either increased availability or transmission distance compared to current products, or to enable higher bit rates that require increased received optical power.

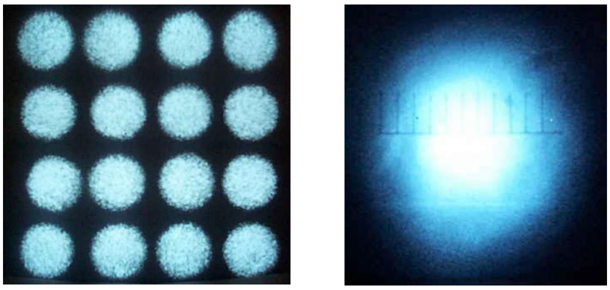

Figure 12. Intensity distribution of a 16-elements VCSEL transmitter, as measured in the plane of the transmission optics (*left*). Intensity distribution at a distance of 18 m and a divergence angle adjusted to 7 mrad (*right*).

5.3. Alternative Wavelength Choices

The dominance of the 850 nm wavelength range in FSO technology arises from the availability of standard low-cost optoelectronic transmitters (AlGaAs based VCSELs) and photodetectors (Si based *pin*- or avalanche-type photodiodes). On the other hand, the standard telecommunication wavelengths of 1.3 or 1.55 µm offer advantages of decreased atmospheric attenuation at haze and light fog conditions as well as greatly relaxed eye safety margins. FSO systems at 1.55 µm are designed with distributed feedback (DFB) edge-emitting lasers and offer the potential for wavelength division multiplexing transmission, both, however, at increased cost. With recent successful demonstrations of long-wavelength VCSELs,[24–27] it is expected that the combined benefits of surface emission and improved power budget can favorably be exploited in future FSO modules.

It should be mentioned that FSO transmission in the several-µm wavelength mid-infrared spectral range could further increase the link availability under most adverse weather conditions due to reduced Rayleigh and Mie scattering. With the advent of quantum cascade lasers (QC), this approach might become feasible in the future.[28, 29] Apart from the fact that QC lasers are still in a rather juvenile stage of development with continuous-wave operation at room temperature being demonstrated just recently,[30] the need for uncommon long-wavelength photodetectors and low absorption Ge and ZnSe lenses might prove as considerable drawbacks.

6. CONCLUSIONS

In this paper we have briefly summarized recent progress in selected optical datacom-related application areas of 850 nm short-wavelength VCSELs. For use in local area networks, research into components for serial 10 Gbit/s data transmission over multimode fiber is well underway. According to upcoming standards, multimode VCSELs are suitable sources for link lengths of 300 m that are sufficient for the majority of in-building backbones. We have shown, however, that singlemode VCSELs can on the one hand be conveniently employed for fiber testing through differential mode delay measurements and on the other hand will become indispensable once that further improved fiber quality will allow for km-long link spans.

In the field of ultra-short reach interconnects, hybrid electrical–optical backplanes are close to be implemented in practical processing system environments. Using 850 nm VCSELs, we have demonstrated 10 Gbit/s data transmission over low-cost polymer waveguides with up to 1 m length, where further progress is most urgently needed on the receiver end. Two-dimensional integrable VCSEL arrays are constantly improving in performance and are already implemented in transceiver prototypes or free-space interconnect demonstrators with high channel count. Here, reduction of power consumption is an issue for further optimization.

As a rather different application field with considerable anticipated growth opportunities, free-space inter-building optical data transmission also favorably applies short-wavelength VCSEL technology. We have briefly indicated how multiple devices designed for output powers in the 10 mW range may be arranged in order to achieve Gbit/s data rates over km-long distances at very high link availability.

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