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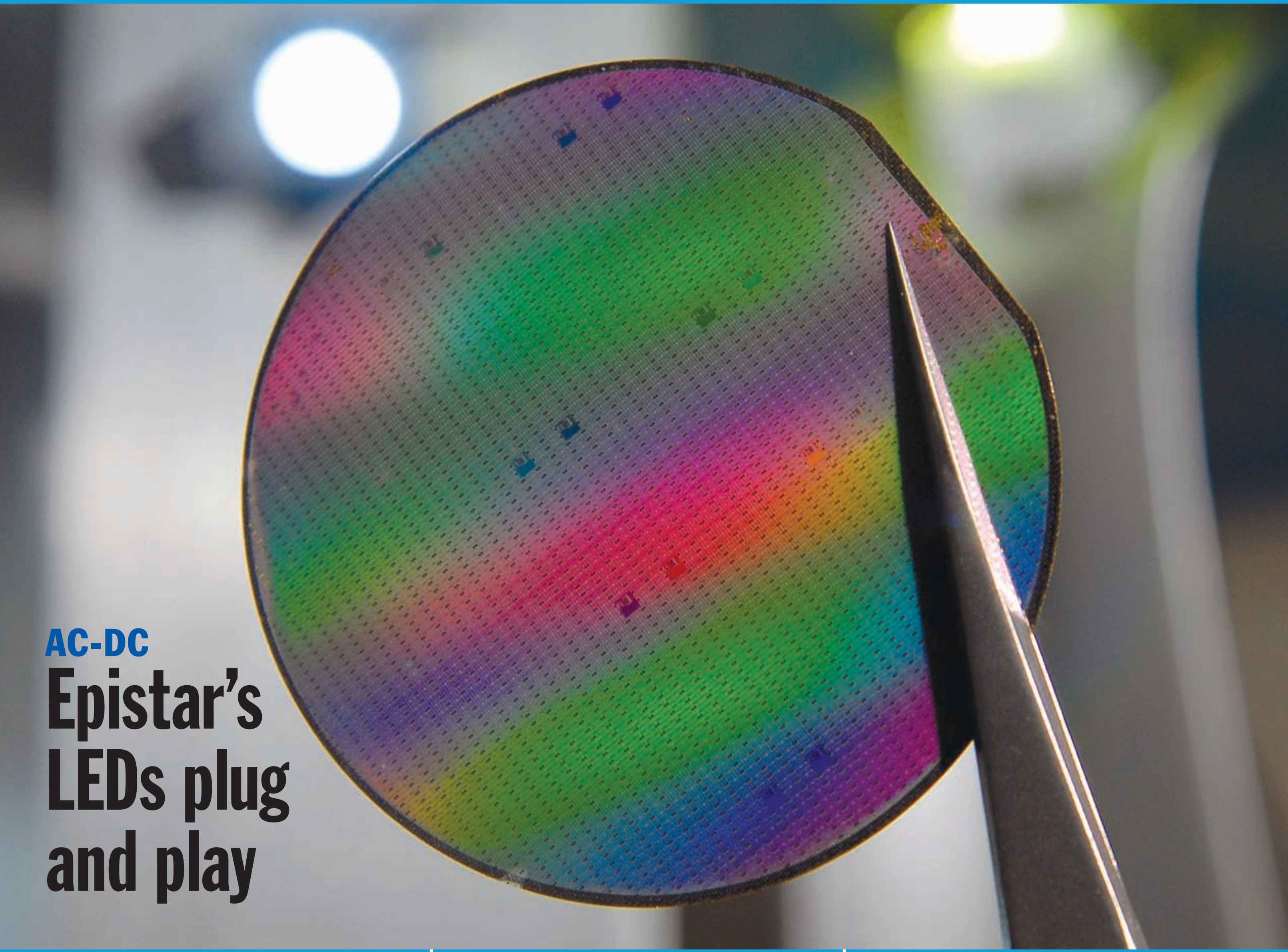
CONNECTING THE COMPOUND SEMICONDUCTOR COMMUNITY



AC-DC

Epistar's LEDs plug and play

HEADLINE NEWS

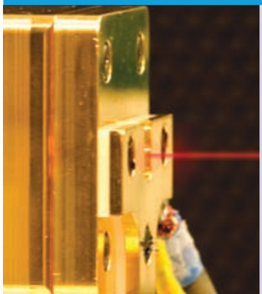
RFMD diversifies into GaN foundries and solar p5

BEHIND THE HEADLINES

Solar futures

Can the concentrated photovoltaics industry address the issue of reliability and go on to be a success? p17

HIGH-POWER LASERS



Great shape

Alfalight's curved gratings give laser chips a brighter, cleaner emission profile. p21

Dots speed datacom VCSELs

Transmitters operating well beyond 10 Gbit/s are needed for emerging communication standards. Quantum-dot VCSELs can operate at four times this, and even higher rates are promised with a design incorporating a modulator in the top mirror, says VI Systems' **Nikolai Ledentsov**.

Serial transmission speeds in data communications undergo a four-fold hike every five years, which is driven by silicon scaling and increased demand on processor bandwidth. 3–8 Gbit/s transmission is becoming increasingly common in electrical interfaces for consumer and personal computer applications, and further upgrades are on the way.

Copper is the traditional medium for routing the data, but it suffers from significant drawbacks. Links made from this material dissipate a lot of power and can cause unacceptable electromagnetic interference. At bit rates of 30 Gbit/s or more, copper links are limited to just a few centimeters on printed circuit boards. However, all of these issues can be avoided by switching from copper to optical fiber for signal delivery.

One option for the optical source is the 850 nm VCSEL, a reliable, low-cost, low-power-consuming laser that's suitable for short-distance data communication networks based on multimode optical fiber. This device can potentially produce transmission speeds of 40 Gbit/s or more when it is positioned on top of or embedded within a silicon chip, and directly merged and interconnected to the upper copper-based metal interconnecting layers.

VI SYSTEMS

VI Systems' 850 nm quantum-dot VCSELs are suitable for ultra-high-speed data communication.

Obstacles to faster speeds

However, if directly current-modulated 850 nm VCSELs are going to fulfill their promise, their producers will have to address significant reliability challenges that have impeded increases in data bit rates. At VI Systems, which is based in Berlin, Germany, we have found a route to higher speeds via quantum-dot (QD) VCSELs that can operate reliably at 40 Gbit/s. We are also developing another type of VCSEL with a radical design, which features a modulated top mirror that should be even faster.

At high excitation densities, current-modulated VCSELs, which are the most common form of the device, have a transmission speed limit that is governed by the stimulated radiative recombination rate. When the device is operated in this excitation regime, shorter radiative lifetimes produce a faster response to the changes in the input voltage that create the "1s" and "0s" of the binary code. If VCSEL data rates need to increase, then shorter radiative lifetimes are possible by injecting more carriers, but a two-fold reduction in radiative lifetimes demands a quadrupling of the injected carriers.

Increasing the number of injected carriers also produces a dramatic hike in non-radiative recombination, alongside greater defect generation. Faster device degradation results, and even at speeds of 10 Gbit/s reliable operation demands significant compromises in design and overall efficiency.

Reliability can be improved at the expense of performance by increasing the size of the VCSEL's oxide-confined aperture. Higher injected current densities can then be realized, which lead to higher switching speeds without severe degradation. But if the current gets too high, this begins to limit the operating temperature range of the VCSEL. Higher currents also diminish spectral purity, shortening the maximum length of the optical fiber link.

Excessive output powers are another penalty that stems from the switch to higher current densities and larger apertures. Optical attenuators can reduce output power to the required level, but also diminish the power efficiency of the VCSEL and its driver IC. Reduced efficiency, combined with the weaknesses that we have highlighted, has led most current-modulated VCSEL manufacturers to conclude that this form of laser cannot provide degradation-free operation at data rates beyond 10 Gbit/s.

In contrast, single-mode 850 nm VCSELs driven under external intensity modulation can produce

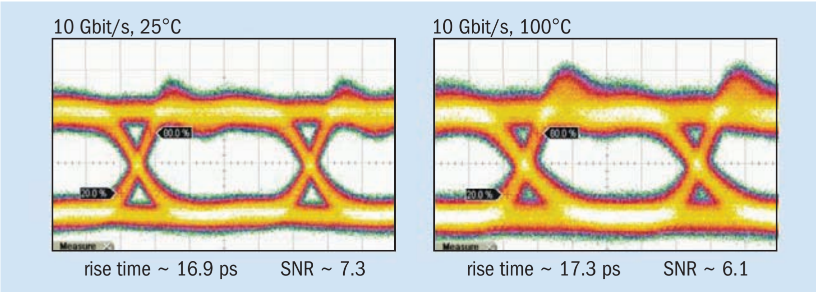


Fig. 1. Optical eye diagrams from an 850 nm VCSEL at room and high temperatures. The measured rise time (20–80%) is 16–17 ps and weakly dependent on temperature. The system-deconvoluted VCSEL rise time is below 9 ps at all of the temperatures studied. Open eyes are obtained from large signal modulation experiments using a non-return-to-zero data pattern with a 2^7–1 pseudorandom bit sequence at the given data bit rate. The resultant signal-to-noise ratios (SNRs) are greater than 6.

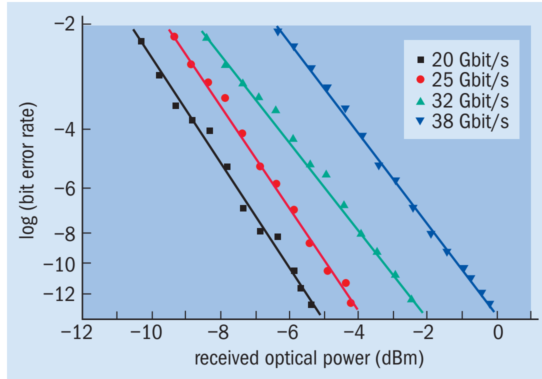


Fig. 2. Bit error ratio (BER) measurements as a function of received optical power show that error-free transmission, defined as −log(BER) <1 × 10^{12}, is possible at low received optical powers. BER measurements were performed in a back-to-back configuration for a 9 µm diameter oxide-confined InGaAlAs VCSEL at 20, 25, 32 and 38 Gbit/s bit rates with a bias current of 9 mA and an operating temperature of 20 °C. The current density is 10 kA/cm^2 and the root-mean-square spreading of the emission spectrum is less than 0.3 nm. True minimum power values can only be defined when amplifiers and drivers are optimized for the particular transmission speed measurement.

40 Gbit/s error-free transmission over 2 km lengths of photonic crystal fiber. Single-mode, degradation-robust devices are realized because the VCSEL is operated in continuous-wave mode at low current densities. However, there are downsides with this approach. Traditional external electro-optic modulation is power hungry and typically restricted to long-distance 1.3 and 1.55 µm telecom applications. In addition, modulators are bulky and modulated systems require complex coupling optics and optical isolation, which makes them rather expensive.

To improve VCSEL speed and reliability, researchers have turned to new materials for the active region. These include InGaAs strained quantum wells (QWs), which are widely used in edge-emitting lasers emitting in the 1 µm range and are well known for high degradation robustness, even at very high power levels. Larry Coldren's group at the University of California, Santa Barbara, has had success with this approach and fabricated 35 Gbit/s, 980 nm VCSELs operating at relatively small current densities (see *Compound Semiconductor* June 2008 p29).

The wavelength of these VCSELs is outside the range for multimode fiber (840–860 nm) and GaAs PIN photodetectors cannot operate above 0.9 µm. One way around this is to add small concentrations of indium to the QW of an 850 nm VCSEL, which push the emission to the required spectral range, but this reduces the benefits of the new active medium. For example, the confinement potential for the injected carriers is the same as that for GaAs QWs.

Our view is that it is far better to turn to an entirely different material system for the active region – InAs QDs. These nanostructures significantly increase material gain and differential gain, thanks to the switch from electron-hole plasma recombination that occurs in layered materials to inherently excitonic lasing. This in turn reduces the radiative lifetime at comparable current densities. QDs also have a secondary benefit – they improve reliability by localizing many carriers and preventing their diffusion towards defects where they could create dislocations in the material.

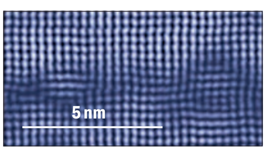
The first high-performance QD VCSELs were 1.0–1.3 µm devices that were fabricated by the Ioffe Institute in St Petersburg, the Technical University of Berlin and the Air Force Institute of Technology in Dayton. High-power single-mode operation at 1.25–1.30 µm has followed, and we have recently demonstrated 20 Gbit/s error-free operation up to 150 °C.

Our latest efforts have focused on the development of the first 850 nm InAs QD VCSEL, which produces data bit rates in excess of 20 Gbit/s, has good temperature stability and has the potential for high degradation robustness.

High-speed VCSEL operation can be limited by parasitic impedance. Non-optimal mask design, an improper planarization process and an imperfect oxide-confined aperture design can all compress the electrical bandwidth. To compensate for the bandwidth deficiency in conventional VCSELs, excessive current density is applied to the device to maintain the modulation amplitude. However, this also accelerates the degradation process and often reduces the mean time to failure. A far better approach, which enhances electrical bandwidth and simplifies production of degradation-robust VCSELs, is to lower the device's intrinsic capacitance and resistance.

We used this approach to fabricate 850 nm VCSELs that operate over a wide temperature range. Eye diagrams at room temperature and 100 °C show that the two signal levels, "0" and "1", are well separated in intensity (figure 1). Measurements of bit error ratios as a function of the received optical power reveal that current-modulated 850 nm-range VCSELs, when driven at moderate current densities, are capable of high bit rates over a wide temperature range (figure 2).

Efforts have also been directed at developing a radically different modulation technology that promises to deliver incredibly high transmission



The InAs-GaAs-AlGaAs submonolayer (~0.9 monolayer thick) that is inserted in VI Systems' 850 nm VCSELs is revealed by atomic lattice transmission electron microscopy. Chemically sensitive conditions were chosen for the imaging. This produced a lattice contrast reversal at an average InAs composition above 20%. You can clearly see lattice contrast reversal in two regions of the image, with a height and a lateral size of 2 nm.

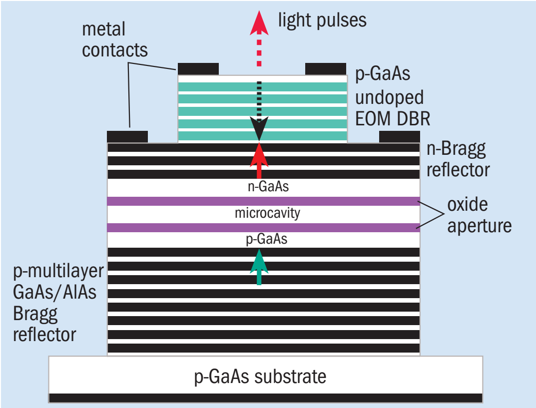


Fig. 3. Very fast bit rates could be realized with VI Systems' electro-optically modulated distributed Bragg reflector (DBR) VCSEL. Modulating the voltage across the upper DBR reflector makes it behave as a chopper (essentially a semi-transparent shutter) that interrupts the light from the microcavity. The laser is driven at a small steady-state current density.

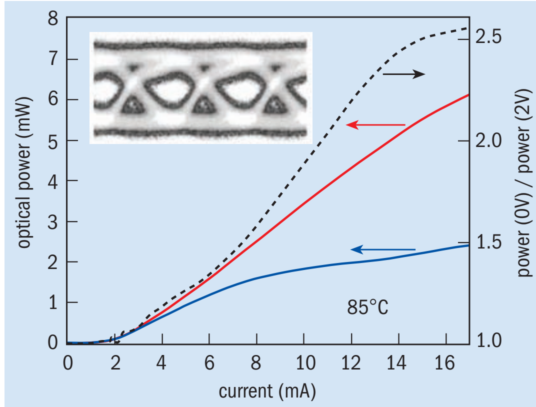


Fig. 4. VI Systems' electro-optically modulated VCSELs can deliver transmission speeds of 6 Gbit/s or more using a modulating voltage of 2 V. Devices feature 10 μm circular apertures and deliver similar performance from 25 to 100 °C.

speed. This approach, which could also enhance LED modulation speeds, involves modifying the upper VCSEL mirror – a distributed Bragg reflector (DBR) – so that it behaves like a beam chopper, interrupting the light exiting from the microcavity (figure 3). The principal changes to a standard VCSEL design include: the insertion of an active medium into several layers in the upper DBR; and the addition of a metal contact below this part of the upper mirror. Applying a modulated voltage between this contact and the one at the top of the mirror creates an electric field across the electro-optically active section of the DBR, which modifies the refractive index contrast. This in turn alters the reflectivity of the semi-transparent Bragg reflector mirror and the width of the DBR's reflectivity band, leading to adjustments in the output of the VCSEL.

In the past, researchers at other institutions have attempted to build a high-bit-rate VCSEL by adding a modulator section based on absorbing QWs. In this case the application of an electric field can shift, enhance, reduce or broaden the strong exciton absorption peak, and ultimately lead to some absorption of light at the VCSEL lasing wavelength.

This electro-absorption effect is strong only in the vicinity of the exciton resonance. Changes in refractive index, however, occur over a broader spectral range. This means that any increases in temperature lead to an exciton absorption red-shift that tracks the change in bandgap, and a shift in VCSEL cavity wavelength that moves in the same direction, but at a much slower pace. Because the absorption peak must never match the lasing wavelength, even at the highest operation temperature, say 85 °C, these features have to be well separated at lower temperatures. Consequently, the modulation effects are insufficient in this type of device unless a massive voltage is used. In addition, the VCSEL can suffer from overheating, lasing-induced transparency, self-pulsations and parasitic frequency resonances, due to a strong absorption of carriers in the modulator section.

However, with our design – the electro-optically modulated DBR VCSEL – the changes in exciton oscillator strength affect the refractive index across a very broad spectral range. That's because the exciton absorption peak adds a resonance contribution to the refractive index that slowly decays away from the resonance and is superimposed on a background refractive index. Even when the exciton absorption peak is dramatically enhanced or reduced in intensity, the resonance contribution to refractive index is proportionally affected across the spectrum.

The upshot of this is that absorption does not significantly degrade the modulation characteristics of QD VCSELs with an electro-optically modulated DBR, and these devices can exhibit a smooth, featureless small signal modulation curve up to 100 °C.

We have recently built a prototype that can produce 50–70% modulation with a modulation voltage below 2 V and deliver error-free transmission beyond 6 Gbit/s. This enables our low-capacitance electro-optical modulator DBR to operate with a very low power consumption of the modulator driver IC.

One of the key strengths of our electro-optically modulated DBR VCSEL is that it allows the realization of devices with a uniform, robust performance. These lasers can be produced on 3 inch diameter wafers and feature active regions based on either QDs or QWs. Further optimization of our structure should produce VCSELs with operational data bit rates of 40 Gbit/s at 1.0–1.5 V modulation voltages, which will be strong contenders for filling the gap for on-chip optical input/output devices for new generations of multicore processors.

Further reading

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About the author

Nikolai Ledentsov is founder and CEO of VI Systems. He is the most cited active Russian scientist and is currently on leave from the Ioffe Institute in St Petersburg, Russia. This feature is written in co-operation with J A Lott, V A Shchukin, A Mutig, G Fiol, T Germann, S A Blokhin, A M Nadtochyi, L Ya Karachinsky and D Bimberg. The team has enjoyed the support of the VISIT project – a Seventh Framework Program of the European Commission – the HiTrans project funded through the Program to Promote Research, Innovation and Technology of the Investitionsbank Berlin (IBB); the NanOp program of the German Ministry for Education and Research (BMBF); and the German Aerospace Center (DLR).