VCSEL Arrays With Redundant Pixel Designs for 10 Gbit/s 2-D Space-Parallel MMF Transmission

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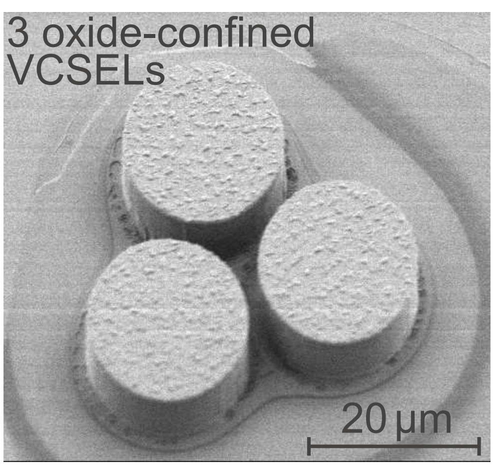
We demonstrate two-dimensional (2-D) flip-bonded 850 nm VCSEL arrays with three close-spaced lasers per channel equally butt-coupled to the same 50 μm core diameter fiber for improved transceiver lifetimes. Quasi error-free 10 Gbit/s signals are transmitted over 500 m of multimode fiber (MMF) under offset launch.

1. Introduction

The direct modulation bandwidth of VCSELs limits serial bit rates to about 20 Gbit/s. Their particular capacity for very high-speed data transmission lies rather in an outstanding integrability making possible the realization of large two-dimensional (2-D) arrays with a large number of simultaneously operated transmit channels, densely packed within a small footprint. As a consequence, the VCSEL count in very high-speed datacom scenarios can be expected to rapidly multiply in the years ahead. VCSEL reliability is thus pivotal for critical applications.



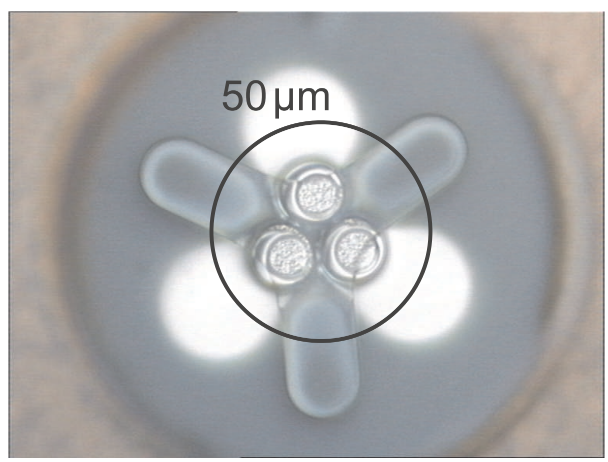


Fig. 1: Epitaxial-side views of three mesa-isolated oxide-confined VCSELs in one channel. Self-aligned p-contacts after mesa dry etching *(left)*. Laser position with respect to the MMF core diameter permits butt coupling with high coupling efficiency *(right)*.

The so-called bathtub curve [1] describes how the probability of failure (or failure rate) develops for a population of devices in the cause of their lifetime. After an initial phase, during which early failures are screened out and the failure rates rapidly drop, a steady state of lowest and nearly constant failure rate is reached. Today's oxide-confined VCSELs possess life spans of around 100 years even at elevated temperatures [2]. However, during this extended period there exists a finite probability for the devices to stop functioning at any point in time. This residual probability of premature failure multiplies with the number of VCSELs in use. It is hence considered a significant constraint for critical applications involving many parallel data channels, each relying on a single VCSEL.

We propose a novel scheme of VCSEL redundancy in each channel where two backup lasers are retained for each multimode fiber to prevent channel outages caused by singular random VCSEL failures. Three direct-mesa flip-bonded VCSELs on record-small VCSEL-to-VCSEL pitches butt-couple to the same 50 µm core diameter graded-index multimode fiber (50MMF) eliminating the need for elaborate beam combining optics, and hence keeping systems simple and cost-effective.

2. Redundant VCSEL Arrays

High-density VCSEL integration was enabled by a dry etch process utilizing the p-contact metallization as the etch mask. In order to test the technological feasibility, the dimensions of the VCSEL triples (see Fig. 1) were varied from channel to channel within the 4×4 channels of each array. The triples of mesa-isolated oxide-confined VCSELs within one array have outer mesa diameters ranging from 19 to 12 µm. Each VCSEL has a self-aligned full-size p-contact which is present during high-temperature wet oxidation. Mesa separations as small as 1.5 µm and oxidation lengths below 3.5 µm enabled, to our knowledge, the highest integration density of oxide-confined VCSELs ever achieved to date with true VCSEL-to-VCSEL pitches that are only 9 µm larger than the active diameters.

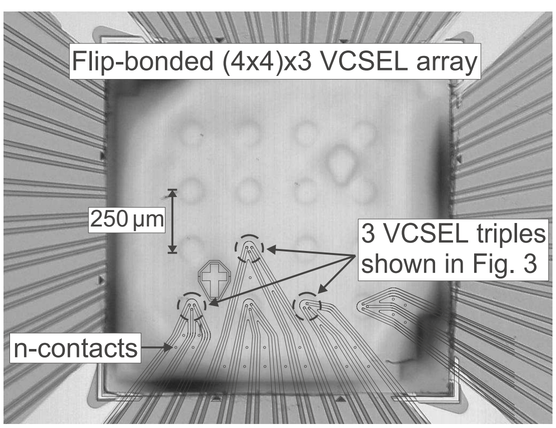


Fig. 2: Photo of flip-bonded $(4 \times 4) \times 3$ array with three close-spaced VCSELs per cell overlaid by schematics showing the routing of some of the coplanar lines.

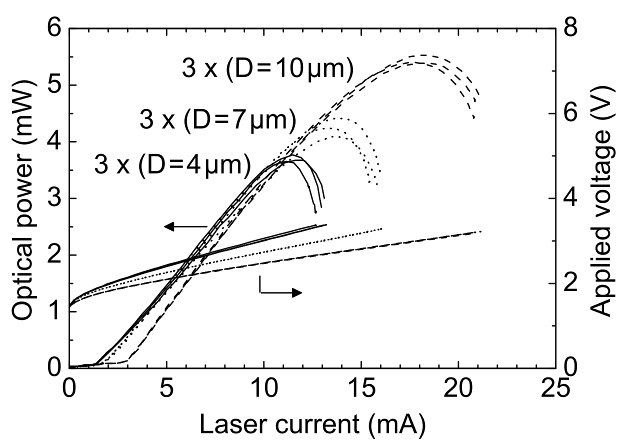


Fig. 3: LIV curves of the three VCSEL triples indicated in Fig. 2 within the direct-mesa flip-bonded 2-D array.

Figure 2 shows one of the bottom-emitting 850 nm VCSEL arrays after flip-bonding to a silicon carrier and removal of the opaque GaAs substrate leaving an epitaxially defined outcoupling facet. The carrier is a demonstration platform with coplanar lines for individual high-frequency electrical input to each of the 48 VCSELs in 16 channels on a 250 µm channel pitch. Only 10 µm high indium solder bumps permit direct-mesa bonding without shortening adjacent devices. Figure 3 gives the light–current–voltage (LIV) curves of the three VCSEL triples indicated in Fig. 2.

Outer mesa diameters and mesa gaps for the 10, 7, and 4 µm active diameter VCSELs are 17 and 3.5 µm, 14 and 2.5 µm, and 12 and 1.5 µm, respectively. The differential quantum efficiencies are between 29 and 31 %. Depending on the VCSEL size, the differential resistances are 77, 95, and 126 Ω with lasing thresholds of 3, 1.8, and 1.3 mA.

3. Data Transmission Experiments

Since within a channel three equivalent VCSELs are coupled into the same 50MMF, there is an inevitable radial VCSEL-to-fiber offset affecting the coupling efficiency. In Fig. 4, measured coupling efficiencies at different radial launch offsets normalized to the maximum coupling achieved for perfect alignment are shown. The built-in radial offsets in the $(4 \times 4) \times 3$ arrays presented are between 12.5 and 7.8 µm leading to acceptable offset coupling penalties below 0.8 dB.

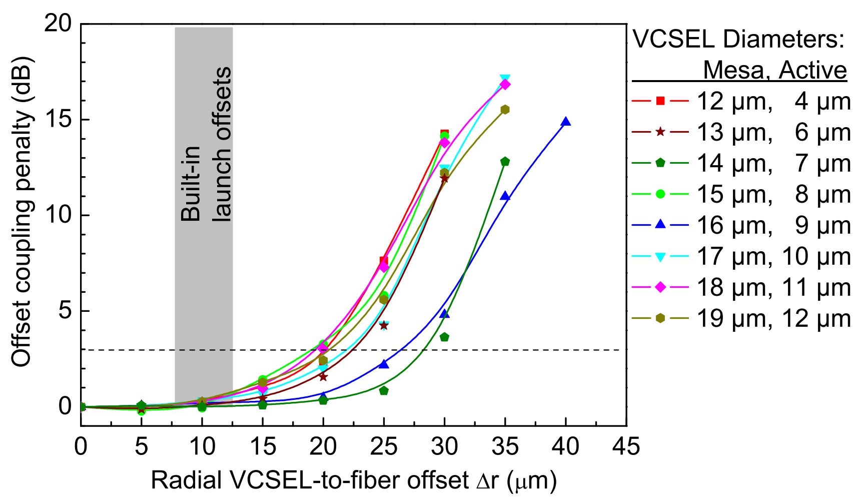


Fig. 4: Coupling efficiency at different radial VCSEL-to-fiber offsets normalized to center launch conditions.

For digital data transmission, the electrical input signals are fed from the perimeter of the silicon carrier via several millimeter-long coplanar lines to individual devices within the flip-bonded VCSEL arrays (see configuration on the left of Fig. 5). Despite the parasitics of those highly dense lines, wide open and symmetric eye patterns as in Fig. 5 were obtained for transmission of $2^{31} - 1$ word-length pseudo-random bit sequence (PRBS) signals at 10 Gbit/s over 500 m of butt-coupled 50MMF. This is well beyond the 300 m specification of the IEEE 10-Gigabit-Ethernet standard [3].

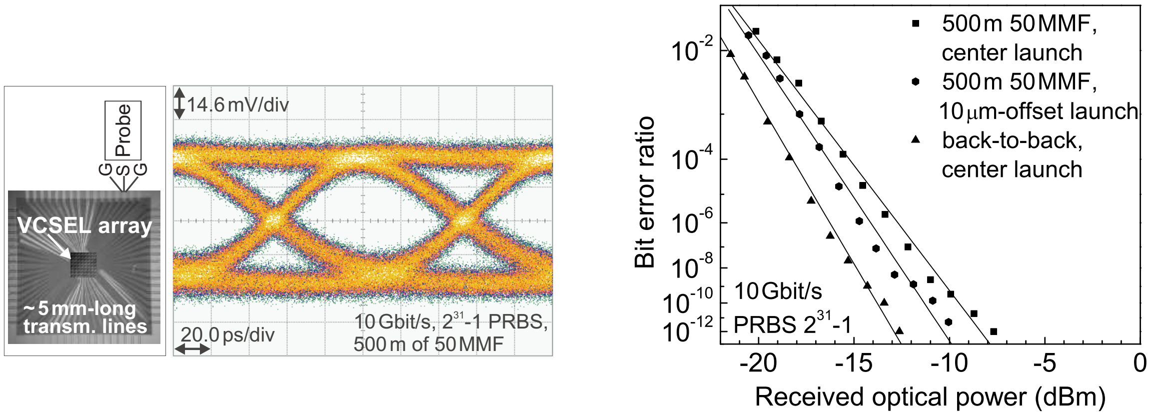


Fig. 5: 10 Gbit/s eye diagram after transmission over 500 m of 50MMF (*left*). The VCSELs are addressed via coplanar lines on the carrier as indicated on the far left. 10 Gbit/s BERs vs. mean received optical power back-to-back and for transmission over 500 m of 50MMF under offset launch and center launch conditions (*right*).

The bit error ratio (BER) curves in Fig. 5 indicate that quasi error-free (10^{-12} BER) data transmission was achieved over 500 m of 50MMF. There is a power penalty of up to 4 dB for transmission over the 50MMF. The 10 µm launch offset even leads to a slight improvement of the BERs as compared to center launch conditions. Such behavior is obtained with fibers of somewhat inferior differential mode delay (DMD) characteristics in the near-axial region.

4. Conclusion

Record-high integration densities of flip-chip bonded oxide-confined VCSELs in 2-D arrays enabled a 3-per-50MMF VCSEL redundancy for potential lifetime improvements of parallel-optic transmitters. Compactness and low module costs are preserved by still permitting butt-coupling to 50MMFs. The concept was proven by successfully transmitting 10 Gbit/s signals over 500 m of multimode fiber even under offset launch conditions as dictated by the redundant pixel designs.

References

[1] "Engineering Statistics: Internet Handbook", http://www.itl.nist.gov/div898/handbook/index.htm

[2] "VCSEL Chip Products Reliability Report", U-L-M photonics GmbH, Oct. 2005. http://www.ulm-photonics.com

[3] IEEE Standard 802.3ae^{TM}, IEEE, Piscataway, NJ, USA, June 2002. http://grouper.ieee.org/groups/802/3/ae/