VCSEL Arrays for Fiber Optical Interconnects

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In this paper, we report on transmitter technologies for Gb/s speed datacom systems. Primarily to enable direct flip-chip integration with silicon CMOS circuits for highly parallel inter-chip interconnects, we have fabricated two-dimensional vertical-cavity surface-emitting laser (VCSEL) arrays featuring $4 \times 8$ elements on a 250 $\mu$m pitch. Arrays emitting in the 980 nm spectral region exhibit excellent homogeneity and operation data like 0.8 mA threshold current, below 1.5 V threshold voltage, 1 mW output power at 2 mA current, and more than 35 % conversion efficiency in the 2 to 5 mW power range. Bottom emission of 850 nm arrays is enabled by etching holes into the opaque GaAs substrate. Due to less efficient heat removal, devices are currently limited to about 2 mW light output at 6 mA current.

1. Introduction

Similarly as in telecommunications, the demand for higher bit rates is also prevalent in the optical local area network (LAN) arena. Within the latest deployed technology generation, the Gigabit Ethernet (GbE) solution is on its way to find widespread use in local area backbone networks. Among the different physical realizations, GbE transceivers based on short-wavelength 850 nm VCSELs combined with graded-index multimode fibers (MMFs) are especially cost-effective and can be almost considered as commodity products. Since past trends indicate that current backbone speeds will move to the desktop level with a few years delay, intensive work on 10 Gb/s LAN systems has been initiated.

The present paper focuses on some of our latest progress in the fabrication of two-dimensional VCSEL arrays. The devices themselves have been mainly developed within the framework of a joint project funded by the European Commission, aiming to provide solutions for the direct optical interconnection between electronic integrated circuits [1]. Whereas clock frequencies of the latest available data processors have already reached the 1 GHz range, the layout of the VCSELs even allows for modulation speeds in excess of 10 GHz.

2. Two-Dimensional VCSEL Arrays

Apart from single-transmitter modules as for GbE or fiber ribbon based one-dimensional links [2], the much esteemed VCSEL capabilities are most obviously exploited in two-dimensional arrayed systems, which can offer massively parallel data transmission and might thus help to avoid the electrical interconnect bottleneck to be expected in future high performance computer
environments [3]. For this application space, we have fabricated two-dimensional VCSEL arrays, which allow direct flip-chip hybridization onto electronic circuits. Device and array design and processing as well as static and dynamic characteristics of 980 nm wavelength arrays have been described in [4] in some detail. Prototype arrays are delivered to partners in the joint European OIIC (Optically Interconnected Integrated Circuits) project [1] and are integrated into system-level interconnect demonstrators. Continuous improvements in the design and fabrication routine have led to present devices characteristics shown in Fig. 1.

![Laser characteristics of a 990 nm wavelength, 4 × 8 elements bottom-emitting VCSEL array (left) and optical spectrum of a single device at 2 mA driving current, corresponding to 1 mW optical output power (right).](image)

The left hand side summarizes optical output power, driving voltage, and power conversion efficiency for all 32 elements of a 4 × 8 VCSEL array, where an individual active diameter of 6 μm has been adjusted through selective oxidation of a single AlAs current aperture layer. Devices are arranged with 250 μm pitch and each unit cell of the array contains individual bondable p- and n-contacts. The molecular beam epitaxially grown arrays show excellent homogeneity and feature average threshold currents and voltages of 0.8 mA and 1.45 V, respectively, and provide 1 mW optical output power at 2 mA driving current. A peak power conversion efficiency of 37% is achieved for output powers of about 3 mW. By direct microwave probing, previous generation array elements have already been employed for 12.5 Gb/s data transmission over 100 m multimode fiber or 1.6 km standard singlemode fiber [4]. For the present application, where optical interconnection between laser and detector arrays is accomplished through large area POF bundles placed on top of the chips without additional optics, transverse multimode VCSEL operation, as seen in the optical spectrum in the right hand side of Fig. 1, is perfectly acceptable. If required, transverse singlemode operation can be achieved with smaller active diameter arrays. Devices with about 3 μm diameter delivering up to 3 mW fundamental mode output power at 30 dB sidemode suppression ratio have been demonstrated before [4].

Mainly for reasons of compatibility with the 770 to 860 nm wavelength range, defined in GbE as a standard on the below-1 μm side of the optical spectrum [5], there is also interest to provide integrable short-wavelength VCSEL arrays. Unfortunately, since the GaAs substrate is now highly absorptive, hybrid integration with the driving circuits demands for additional processing steps. As one of the alternatives, bottom-emitting arrays have recently been realized by
means of wafer bonding to a transparent substrate [6], [7], so that devices can be conveniently handled like their 980 nm counterparts. As an intermediate solution, we have fabricated bottom-emitting VCSEL arrays by partially removing the GaAs substrate for light output coupling, as schematically shown in Fig. 2.

![Fig. 2. Schematics of a 850 nm wavelength bottom-emitting VCSEL array element suitable for flip-chip bonding.](image)

The device layout is equivalent to that of the 980 nm arrays [4], except for an additional transparent n-AlGaAs contact layer and a AlAs etch-stop layer. After mechanically polishing down the substrate to about 120 μm thickness, chemically assisted ion beam etching with argon and chlorine gas is employed to define about 80 μm diameter holes centered to the active laser area. Roughly the last 10 μm of the substrate are removed with a citric acid based etchant, before the AlAs etch-stop layer is selectively etched with hydrofluoric acid in the exposed area.

![Fig. 3. Operation characteristics (left) and emission spectrum (right) of a 856 nm wavelength bottom-emitting VCSEL.](image)

For testing, arrays were fixed to a copper plate with a recess for light emission. Unfortunately, in conjunction with insufficient heat removal from the array holder, the increase of thermal resistance induced by the etched hole underneath the device prevented the VCSELs from lasing in continuous wave (cw) mode at room temperature. The critical role of heat removal is evidenced
by the fact that cw lasing is possible with just a drop of water being put on the substrate surface. Fig. 3 shows the light-current-voltage characteristics as well as the optical spectrum of a 6 \mu m active diameter device under this operation condition. Threshold current and voltage are around 1.4 mA and 1.7 V, respectively, and about 2 mW optical output power is emitted at 6 mA driving current. Even at 1 mW output power, lasing at 856 nm wavelength is observed predominantly in the fundamental mode before higher order modes emerge. Considerable improvements in lasing behavior are expected from a revised VCSEL design with an intracavity contact and a smaller outcoupling window. Likewise, the final flip-chip bonding process should assist in heat removal from the emitter array.

3. Conclusion

In this paper, we have first presented operation characteristics of two-dimensional integrable 4 \times 8 elements VCSEL arrays for use in highly parallel short-distance optical interconnects. Whereas 980 nm wavelength arrays are routinely fabricated at high quality and are currently employed in interchip interconnect prototypes, 850 nm bottom-emitting arrays still require more careful consideration of heat spreading properties.

References


[5] IEEE 802.3z Gigabit Ethernet standard, 1000BASE-SX physical layer
