VCSELs for datacom applications

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ABSTRACT

The use of oxide confined VCSELs in datacom applications is demonstrated. The devices exhibit low threshold currents of approximately 3mA and low electrical series resistance of about 50Ω. The emission wavelength is in the 850nm range. Life times of the devices are several million hours under normal operating conditions. VCSEL arrays are employed in a high performance parallel optical link called PAROLI™. This optical link provides 12 parallel channels with a total bandwidth exceeding 12Gbit/s. The VCSELs optimized for the parallel optical link show excellent threshold current uniformity between channels of <50µA. The array life time drops compared to a single device, but is still larger than 1 million hours.

Keywords: semiconductor lasers, vertical-cavity lasers, VCSELs, laser arrays, datacom, parallel optical links, reliability

1. INTRODUCTION

Vertical-cavity surface-emitting lasers (VCSELs) have gained a lot of interest in the scientific community and in industry over the last couple of years. In the scope of industrial manufacturing VCSELs are interesting light sources, because they offer potentially low fabricating and packaging cost. This is mainly due to the fact that we can basically employ standard IC fabrication technologies to manufacture the devices. In contrast to conventional edge-emitting lasers we do not have to handle fragile laser bars. All the fabrication and testing is done on wafer level. There is no cleaving of the wafer to form the laser cavity, no additional facet coating. Since there is no cleaving VCSEL wafers are not thinned to a fragile membrane which is difficult to handle in a production environment. We also like the fact that we can mount VCSELs just like LEDs using automated pick-and-place machines. From the production point of view VCSELs just look like LEDs with special properties.

The advantageous VCSEL properties like low threshold current, high efficiency, low power consumption, low output beam divergence, easy fiber coupling, and the easy integration with other optical elements make the devices attractive for a variety of applications. The most explored applications today are optical data links using 850nm VCSELs for distances of a few hundred meters. Besides the datacom market VCSELs are also discussed for sensor and printing applications and as a replacement for conventional CD-lasers in data storage.

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In the scientific environment it is always interesting to explore the limits of device performance. Most of the work on VCSELs concentrates on performance issues in way or another. In industry we have to focus on application aspects. In the VCSEL case we have three TOP TARGETs: high performance, high reliability, and low cost. We have to find a design optimum to achieve all of the three different targets at the same time. We do not aim at record performance, but at performance which satisfies our application requirements. It is important to find a design which provides good reliability. Last but not least we also ask for high yield, because this directly translates to production cost.

2. DATACOM APPLICATIONS

Classically fiber based systems have been used for long-haul telecom applications employing edge-emitting lasers at wavelength of 1.3µm and 1.55µm. For most of the datacom applications distances are much shorter in the range of a few hundred meters. Therefore multimode optical fibers are used to reduce system cost. In general LEDs are the light source for systems running at speeds up to a few hundred Mbit/s. For new systems with speeds up to approximately 1Gbit/s LEDs are not fast enough and lasers must be used. Therefore VCSELs have been investigated for datacom applications by many companies [1], [2] and research groups [3].

We can distinguish serial data links with one optical channel and parallel optical links with multiple optical channels. VCSELs are employed in both systems. Standards for these optical links are discussed and exist to provide some interchangeability of systems from different companies for the customers. The standards Fiber Channel and Gigabit Ethernet are specified for serial links. Parallel links are described by the High Performance Parallel Interface (HIPPI) and the Scaleable Coherent Interface (SCI). In the short wavelength range (<1µm) the standards specify the laser wavelength to be around 850nm to match the working wavelength of GaAs photodetectors. The channel pitch of fibers in the parallel links is set to 250µm. These are two boundary conditions for VCSELs and VCSEL arrays for these applications.

2.1. Parallel optical links

The general trend in optical data links is to move up in speed (now >1Gbit/s) and decrease module size. The parallel optical link PAROLI^{TM} follows this trend. The PAROLI^{TM} system provides 12 parallel optical channels each running at 1.25Gbit/s. Thus the total optical data throughput exceeds 12Gbit/s. Despite the high data rate the module dimensions are quite small: length 50mm, width 18mm, height 10.5mm. Fig. 1 depicts a photograph of the PAROLI^{TM} module.

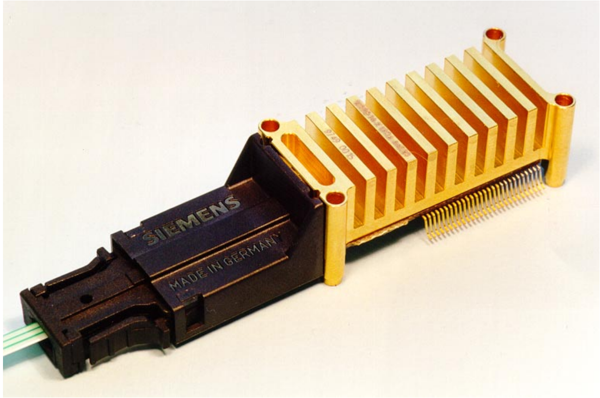

Fig. 1: Photograph of the PAROLI^{TM} parallel optical link module.

The large data transfer capacity of the PAROLI^{TM} module is useful for applications in servers and switches where large bandwidths are required. One of the advantages over copper solutions is the small size which requires only limited board space. The module supply voltage is 3.3V.

The VCSEL array in the transmitter module (Tx) is mounted on a submount. The light output of the VCSEL is directly coupled into the silica fiber of the coupling unit. The coupling unit deflects the light by 90°. Thus, the fiber ribbon cable which connects to the module can be assembled parallel to the board. This concept to bend the photons in the module provides small height and good electrical performance with low crosstalk. Fig. 2 shows a schematic of the module coupling scheme.

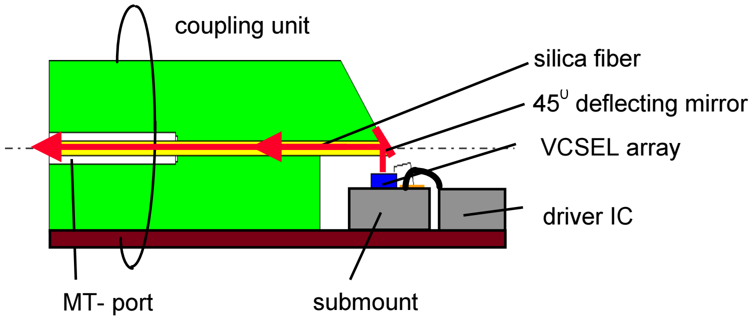

Fig. 2: Schematic of the coupling concept of the PAROLI^{TM} module.

2.2. Eye safety

Most of the datacom application require the system to be eye safe according to Class 1 of the IEC-825 standard. The maximum optical power in the fiber and at the optical port of the module has to be below a certain limit so that it is not harmful to the human eye upon exposure. The near IR wavelength range of 850nm is in particular critical, because the radiation can damage the human eye, but is not visible. Therefore the maximum allowable expose energy is very limited. Table 1 shows calculated numbers for the maximum allowable optical power in the fiber for multimode (MM) fibers of 50µm and 62.5µm diameter core, respectively.

Table 1: Eye-safety limits for optical power in each fiber for MM-fiber connections.

optical power in each fiber	1 channel	12 channels
50µm fiber, NA = 0.2	**443µW**	**118µW**
62.5µm fiber, NA = 0.275	**537µW**	**199µW**

The maximum allowable power for the larger 62.5µm MM-fiber is higher due to its larger numerical aperture (NA). The higher NA causes a larger beam divergence which decreases the radiation energy at a certain distance. In the case of parallel optical links the maximum allowable power decreases even further. The optical power limit can be calculated by taking the number of channels and the channel spacing into account. In the PAROLI^{TM} system with 12 optical channels at 250µm pitch the maximum allowable power is less than 200µW.

2.3. System requirements

Since the optical power in data links is limited by eye safety considerations we have to design the VCSEL for low power operation. From the systems point of view the VCSEL should have a low threshold current. The differential quantum efficiency (dqe) has to comply with the characteristics of the driving circuit. If the dqe is too large, the optical output power is too sensitive to little variations in drive current. Also if dqe is too small the total dissipated power of the module would increase significantly. For high speed operation it is important to keep the electrical resistance of the VCSEL low. Otherwise the dynamic performance of the system would be limited by the RC time constant.

Optical modules must meet certain quality specifications. The modules shall not degrade during storage in damp heat or in an environment with varying temperature between specified extremes. In terms of reliability the devices have to work thousands of hours without failure. It is quite common to express the finite probability of a device to fail by a FIT rate. FIT means Failures-In-Time with the unit 10^9 device hours. For instance, 100 FIT in 10^5 hours corresponds to 100 failed devices within 100,000 hours out of a quantity of 10,000 devices total. To achieve low FIT rates the VCSEL life time has to be large. We will discuss actual data in the following section.

3. VCSEL DESIGN

In this section we will discuss the design issues of VCSELs for datacom application. We focus on oxide confined VCSELs.

3.1. General issues

The basic VCSEL design must provide an optical confinement for the lightwave propagating in the laser and an electrical confinement for the current which drives the laser. This is identical to any other laser. Various approaches have been demonstrated to achieve these two main goals. We show the three mostly favored ones in Fig. 3. The light in the VCSEL bounces up and down between the two highly reflecting semiconductor multilayer stacks on either side of the active layer. The strong feedback from the mirrors leads to an optical intensity within the laser cavity which is about two orders of magnitude stronger than the electrical field intensity of the outcoming light. The light emission is through the top mirror only since the GaAs substrate is absorbing the 850nm radiation.

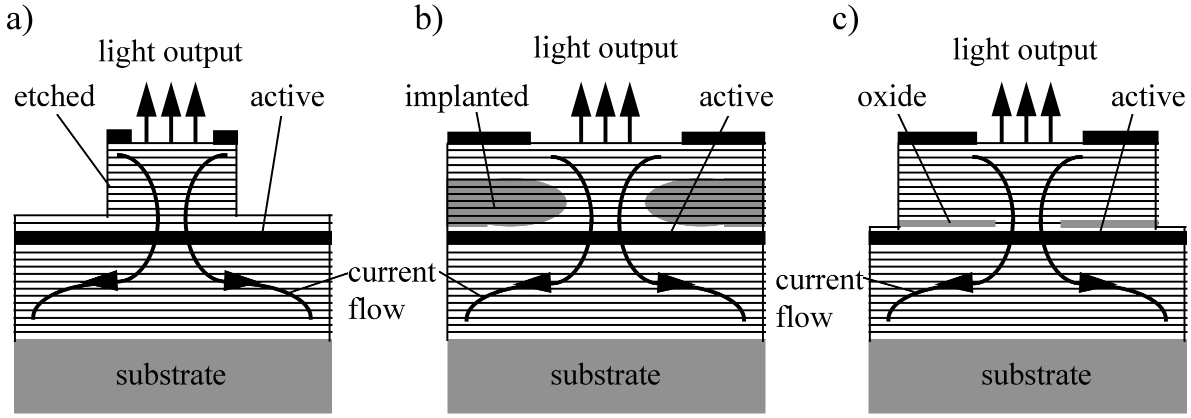

Fig. 3: Schematics of three types of VCSELs: a) etched pillar, b) planar ion implanted, c) etched mesa with AlAs oxidation.

In the etched pillar type VCSEL the fabrication process is non-planar with etch depths in the order of 3 µm. The laser current flows from a contact metallization on top of the etched mesa through the layers of the top mirror into the active layer and then spreads out in the bottom mirror and the GaAs substrate. The mesa structure provides an optical waveguide for the lightwave and concentrates the current in a finite area of the active layer. Etching is terminated well above the active layer to ensure reliable device operation.

The ion implanted VCSEL provides a planar fabrication process. Deeply implanted protons create a highly resistive layer buried in the top mirror which funnels the laser current into the active area. The implantation damage can affect the reliability of the laser. The optical loss associated with the implanted semiconductor regions limits the efficiency of these lasers to approximately 20% for the best devices reported in the literature [4]. Proton implanted VCSELs are favored by a lot of companies due to their relatively easy fabrication process.

The latest VCSEL type employs the selective oxidation of a very thin AlAs layer in the top mirror to create a highly resistive layer of AlO_x just above the active layer. This oxide layer forms an aperture for the laser current and an optical waveguide at the same time. The optical loss is very small in these devices resulting in record performance data of efficiency (>50%) [5], [6] and extremely low threshold currents (<100 µA) [7]. Encouraged by the superior performance data reported in the literature we decided to investigate this advanced type of VCSEL for datacom applications. Our intense work on reliability demonstrates that oxide confined VCSELs can be very reliable despite the possibility of strain from the oxidized semiconductor layer.

3.2. Design of oxide confined VCSELs

We have designed oxide confined VCSEL for datacom applications. Figure 4 shows a schematic of the device.

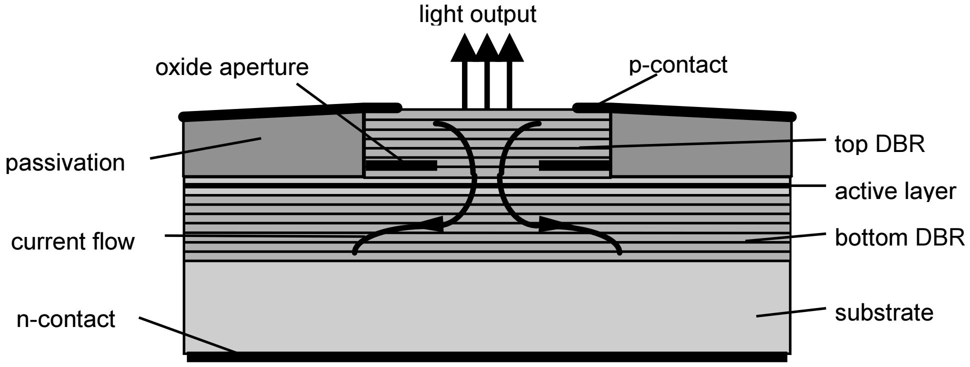

Fig. 4: Schematic of an oxide confined VCSEL for datacom applications.

The active layer is sandwiched between the top and bottom Bragg reflector (DBR). The DBRs consist of quarter wavelength thick AlGaAs layers with varying Al content. Growth is done by metal organic vapor phase epitaxy (MOVPE) on GaAs substrates. We etch a mesa in the top DBR and oxidize AlGaAs layers with a high Al content to form an aperture for the laser driving current. The current is supplied from a ring contact on top of the mesa. The chip surface is planarized by a passivation layer around the mesa.

Ideally the VCSEL should have low threshold current below 1mA. Such devices with a small active area have been reported in literature [7], [8], [9]. In practice small diameter VCSELs are more difficult to produce and exhibit a relatively large thermal resistance [10]. However, the thermal resistance should be low to keep the operating temperature as low as possible, because high temperatures accelerate the aging process of optoelectronic devices. Therefore we have increased the VCSEL diameter to over 10µm. For the PAROLI^{TM} application we employ VCSEL arrays with laser elements of 250µm pitch. Figure 5 shows a scanning electron microscope (SEM) picture of the device. Each VCSEL element on a wafer has an individual device number which enables tracking of every device.

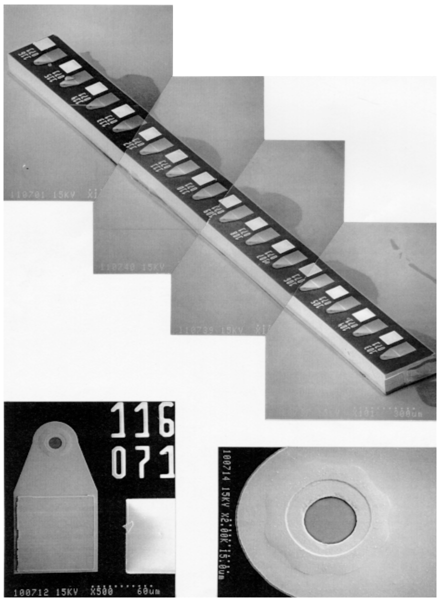

Fig. 5: Scanning electron microscope (SEM) picture of a VCSEL array chip for PAROLI^{TM}. The details show one cell of the array with the individual element number und the output aperture, repectively.

3.3. Performance

The performance of the VCSEL arrays described here is optimized for low power operation in the PAROLI™ system. Figure 6 depicts the light-current-voltage (LIV) characteristics of the device. The threshold current is around 3mA. The differential quantum efficiency (dqe) is approximately 0.2W/A. This provides enough margin in the system to drive the laser. The electrical series resistance is about 40Ω and the drive voltage is less than 2V.

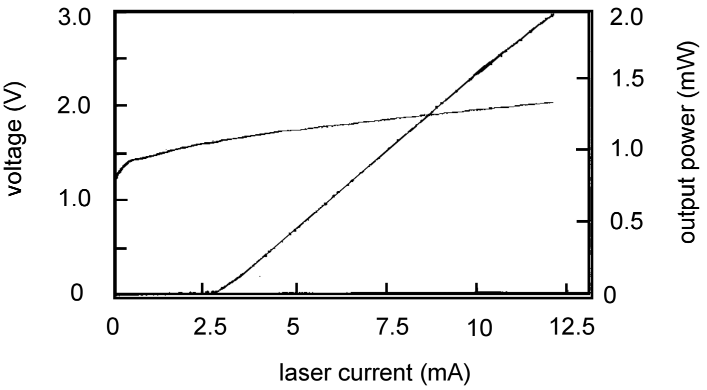

Fig. 6: Light-current-voltage (LIV) characteristics of oxide confined VCSELs for the PAROLI™ system.

The PAROLI™ system employs 12 optical channels for transmitting data. The tight power budget requires very high uniformity between the different channels. Therefore the laser elements must also exhibit good uniformity in terms of threshold current and dqe within an array. This goal requires very good control of epitaxial growth and processing. In Fig. 7 we demonstrate the excellent threshold current uniformity of a typical VCSEL array optimized for PAROLI™. The threshold range of all VCSEL elements of the array is only 50μA. The uniformity in dqe is typically less critical.

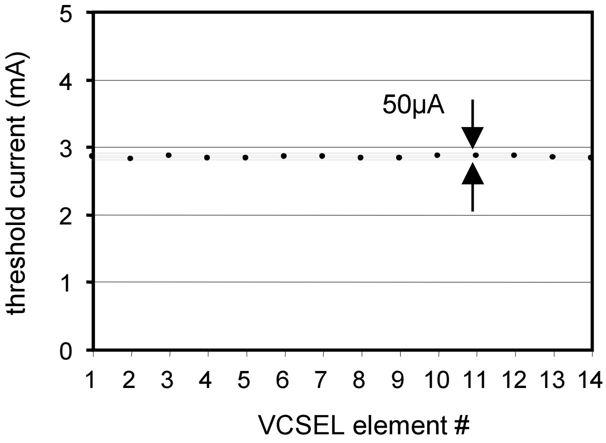

Fig. 7: Threshold current uniformity of a VCSEL array optimized for PAROLI™.

4. RELIABILITY

Reliable operation of the light source is very important for datacom applications. There have been several reports on the reliability of VCSELs, but only limited data was available for oxide confined VCSELs. The concern with oxide confined VCSELs is the mechanical stress from the oxidized layer which might introduce defects in the active layer of the device. Indeed our first devices exhibited some reliability problems with sudden failures and relatively short life times. By consequently improving the device design and processing sequence we are now able to fabricate oxide confined VCSELs with high reliability.

4.1. Aging tests

We performed accelerated aging tests under various drive conditions and different temperatures. Table 2 gives an overview on the numerous devices we tested in an accelerated aging test matrix. The number of devices is the sum of the many VCSELs taken from different epitaxial growth and processing runs. Many additional tests with other test parameters have been performed and are not listed in Tab. 2.

Table 2: Number of VCSELs used for the various test matrix parameters of drive current and ambient temperature.

# of devices	Ambient temperature			
Drive current	**60°C**	**85°C**	**105°C**	**120°C**
4mA	**336**	**336**	**336**	
7mA	**168**	**420**	**336**	**84**
8mA		**336**		
9mA		**24**	**108**	**192**
12mA		**168**		**84**
13mA		**84**	**84**	**84**
18mA		**224**	**84**	**154**

The total number of device hours exceeds 20 million already. The test conditions are chosen to stress the devices beyond normal operating conditions to accelerate the aging process. Figure 8 shows the output power for a group of 168 VCSELs driven at 7mA current at an ambient temperature of 85°C. The output power was measured at 8mA. Up to 2000h no significant degradation is observed.

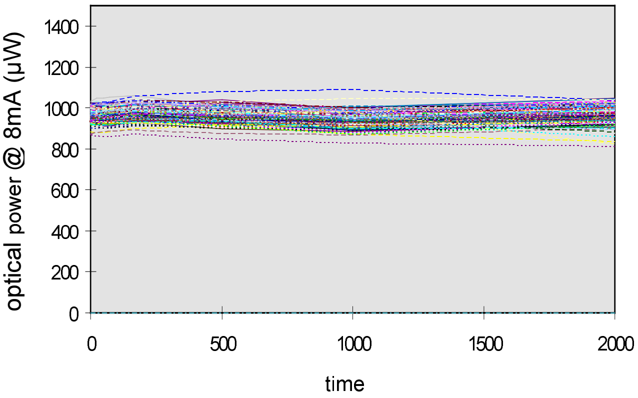

Fig. 8: Optical output power measured at 8mA versus time for 168 VCSELs operating at a constant current of 7mA and an ambient temperature of 85°C.

From the failures occurring at high stress conditions we infer the Mean-Time-To-Failure (MTTF) life time for normal operating conditions. The failure criterion we use is a power drop of the VCSEL to 85% of the initial value. We determine the average life time of a group of VCSELs at a certain test condition using the commonly used Weibull distribution:

$$F(t) = 1 - \exp(t/\tau)^{\beta}, \tag{1}$$

where t is the operating time and τ is the Weibull life time where 63% of all device have failed. The β parameter determines the spreading of the failure distribution around the MTTF life time. The results obtained from the Weibull distribution are comparable to results we get using a Log-Normal distribution which is also quite common.

The life time at normal operating conditions is inferred by comparing life time data for the different aging conditions and fitting the data to a mathematical Arrhenius-Weibull model for life time. Life time t_m can then be determined by the relation:

$$t_m \propto I^{x} \cdot P^{-y} \cdot \exp(E_a/kT_j), \tag{2}$$

where the current I, the optical power P, and the junction temperature T_j have to be taken at the stress and operating condition, respectively. k denotes the Boltzmann constant. The activation energy E_a determines the acceleration of the aging process by temperature. We find an activation energy of 0.7eV for our devices. The current acceleration factor x describes the influence of the laser driving current I on life time. We determined a value of 2.1 from our aging tests. We also included the effect of the optical power P on laser life time by using the power law in the mathematical model. A value of 0.33 for y provides the best fit to our data. From the data of the various accelerated aging tests we infer VCSEL life times of several million hours for normal operating conditions.

4.2. Array life time

For parallel optical links like PAROLI^{TM} we have to consider the life time of a VCSEL array. At 30°C ambient temperature and normal drive conditions a 63% Weibull life time of nearly 10 million hours is inferred for a single VCSEL. For a VCSEL array this number drops as shown in Fig. 9.

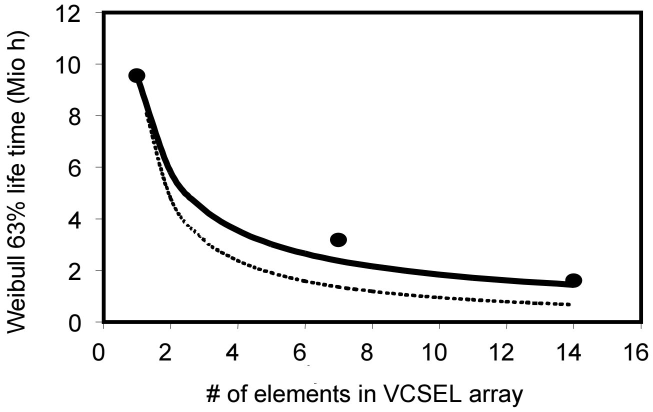

Fig. 9: VCSEL array life time at 30°C ambient temperature and typical optical module power level. Bullets are experimentally derived, the curves are calculated from single VCSEL data.

The bullets denote experimentally derived life time data for a single VCSEL, a 7 channel VCSEL array and a 14 channel array, respectively. The life time of the 14 channel VCSEL array drops to less than 2 million hours. The solid curve is the calculated life time for VCSEL arrays with different number of channels using the data obtained for the single element in the calculation. A good agreement between theory and experiment is observed. The life time for the array is significantly larger than one would guess by simply dividing the single VCSEL life time by the number of elements. This relation is shown by the dashed line in Fig. 9 for comparison.

5. CONCLUSION

We have demonstrated the use of oxide confined VCSELs for datacom applications. The devices are optimized for the low output power requirements of optical data links to comply with eye safety requirements. Low threshold currents of a few mA and a low electrical series resistance in the range of 50Ω make the devices well suited for high speed optical transmission systems. Arrays of these VCSELs are employed in the high performance optical link called PAROLI^{TM} where 12 parallel channels transmit data with a total data rate exceeding 12Gbit/s.

Since reliability is a key issue in datacom application we have performed numerous accelerated aging tests with thousands of VCSELs to ensure high reliability. From the various test conditions of the stress matrix we infer the parameters of a mathematical model to calculate VCSEL life times at normal operating conditions. We found life times of our oxide confined VCSELs of several million hours under normal operating conditions. We compared the life time of single VCSELs to the life time of an array which is significantly shorter, but still exceeds 1 million hours.

We believe the superior properties of VCSELs in terms of performance and easy packaging will further increase the number of applications in the future.

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