Red vertical cavity surface emitting lasers (VCSELs) for consumer applications

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ABSTRACT

There are many potential applications of visible, red (650nm – 690nm) vertical cavity surface emitting lasers (VCSELs) including high speed (Gb) communications using plastic optical fiber (POF), laser mouse sensors, metrology, position sensing. Uncertainty regarding the reliability of red VCSELs has long been perceived as the most significant roadblock to their commercialization. In this paper we will present data on red VCSELs optimized for performance and reliability that will allow exploitation of this class of VCSEL in a wide range of high volume consumer, communication and medical applications.

VCSELs operating at ~665nm have been fabricated on 4" GaAs substrates using MOCVD as the growth process and using standard VCSEL processing technology. The active region is AlGaInP-based and the DBR mirrors are made from AlGaAs. Threshold currents are typically less than 2mA, the devices operate up to >60C and the light output is polarized in a stable, linear characteristic over all normal operating conditions. The 3dB modulation bandwidth of the devices is in excess of 3GHz and we have demonstrated the operation of a transceiver module operating at 1.25Gb/s over both SI-POF and GI-POF.

Ageing experiments carried out using a matrix of current and temperature stress conditions allows us to estimate that the time to failure of 1% of devices (TT1%F) is over 200,000h for reasonable use conditions – making these red VCSELs ready for commercial exploitation in a variety of consumer-type applications. Experiments using appropriate pulsed driving conditions have resulted in operation of 665nm VCSELs at a temperature of 85^{o}C whilst still offering powers useable for eye-safe free space and POF communications.

Keywords: VCSEL, red, visible, sensor, reliability, POF, single mode, AlGaInP

1. INTRODUCTION

Vertical Cavity Surface Emitting Lasers (VCSELs) operating at 850nm have found wide acceptance as the emitter of choice for high speed (>10Gb/s), short distance data communications over multimode glass fiber in Local Area Network (LAN) and Storage Area Network (SAN) applications. The VCSELs domination over Fabry-Perot (FP) lasers in this market is undoubtedly down to its superior reliability, better beam quality and low power consumption. Allied to this is the simplification of the manufacturing process which makes producing VCSELs much more like producing LEDs. Since the commercialization of the technology in 1996 by Honeywell up until early 2007 more than 50million VCSELs had been shipped by one company alone[1]. A new application has arisen for single mode 850nm VCSEL in the last few years due to the appearance of the laser mouse in 2004 from Agilent. Whilst the mouse market continues to be dominated by LED-based devices, the market for VCSEL-based mice is expanding and is expected to soon exceed the market available to multi-mode datacomm VCSELs. To gain market share, the manufacturers of single mode VCSELs are having to increase device yields and to move away from costly (and traditional) TO-46 style of package to plastic and surface mount packages more common in low cost LED manufacture[2].

Visible, red, VCSELs operating at wavelengths between 650nm and 690nm have many potential applications that include high speed (Gb) communications over plastic optical fiber (POF), laser mouse sensors, metrology, position sensors, medical and printing. Home networking and, in particular, Ethernet connections for IPTV is a potentially high volume application where POF is deployed[3] thanks to its ease of installation and immunity from electromagnetic interference. The current enabling technology for data transmission over POF is based around the use of a conventional red LED or higher speed resonant cavity LED (RCLED). However, as bandwidth hungry consumer applications, such as

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Gigabit Ethernet, become more prevalent then Gb transceivers operating in the visible, red (~650nm) need to be available. A DVD laser might be considered as a candidate for use in these high speed applications but suffers from being noisy, producing an elliptical beam, needing a high drive current and not offering the packaging flexibility of its VCSEL counterpart. A red VCSEL, on the other hand, is an almost ideal source for these high bandwidth applications as long as it demonstrates good reliability over the operating temperature range of 0^oC to 60^oC, with the additional constraint of operation at 85^oC being necessary for some applications.

To date, the commercialization of visible VCSELS has been hindered by two main characteristics, firstly their inability to operate at the elevated temperatures familiar from the operation of IR VCSELs and secondly and probably more seriously, doubts about their long term reliability. In this paper we present data which, we believe, removes any lingering doubts about the reliability of visible, red VCSELs operating at ~665nm and should remove this roadblock to commercialization. Whilst the ideal, continuous wave (cw), operating temperature range of a visible VCSEL remains at 0^oC – 60^oC, we show that under pulsed conditions consistent with the transmission of data at Gigabit speeds, a red VCSEL can deliver useful power at an elevated temperature of 85^oC.

2. RED VCSEL DESIGN, EPITAXY AND PROCESSING

Firecomms' red VCSELs are based on an (AlGaIn)P active region which contains compressively strained (InGa)P quantum wells (QWs). The DBR mirrors are made from combinations of (AlGa)As layers. A schematic of the device is shown in Figure 1.

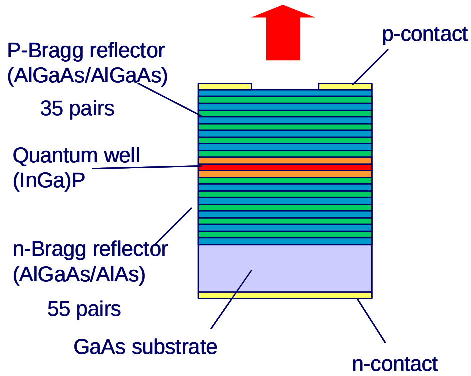


Fig. 1: Schematic structure of a Firecomms visible VCSEL.

The VCSELs are grown epitaxially on 4" n-type GaAs substrates using MOCVD. The substrates are misoriented from the conventional (001) plane by 10^o toward the <111A> direction. Most of our designs have featured a lower n-type DBR of 55 pairs of alternating quarter-wave layers of AlAs/Al(0.5)Ga(0.5)As doped with Si. The active region of the one λ cavity contains either 3 or 4 compressively strained QWs of (InGa)P material sandwiched between a separate confinement heterostructure (SCH) of Al(0.5)GaInP and Al(0.7)GaInP layers that are lattice matched to the GaAs substrate. The higher bandgap regions of the SCH are doped with Si on the n-side and Zn on the p-side. The upper p-type DBR is doped with C and consists of alternative quarter-wave layers of Al(0.95)GaAs/Al(0.5)GaAs layers. A thin Al(0.98)GaAs layer is present in the p-type DBR this will be steam oxidized to form the current confining aperture. Finally the upper GaAs contact layer is heavily doped with C to facilitate a good Ohmic contact.

Standard VCSEL processing steps of photolithography, etching, steam oxidation and metallization are used to form a mesa, current confinement and emission apertures and n-type and p-type contacts. For the single mode version of the VCSEL the active diameter would be between 4µm and 8µm, whilst it would be slightly larger for higher power, multi-mode versions. The VCSEL wafers are thinned to approximately 200µm and diced and mounted onto either an industry standard TO-46 header or into an industry standard PLCC4 package which is a familiar form factor for the packaging of high brightness LEDs. Examples of these two packages are shown below.

Fig. 2: VCSELs are mounted onto either (left) a TO-46 header which can be fitted with a cap and flat glass window, or a surface mount type PLCC4 package.

3. EMISSION CHARACTERISTICS

Figure 3 shows the light output versus drive current of a 665nm VCSEL as a function of ambient temperature. This particular VCSEL is designed with motion sensor applications in mind and so remains single mode over those drive currents and operating temperatures where the output power of the VCSEL is less than the Class 1 eye-safety limit of 390µW. At around 20°C it delivers a maximum output power of ~1mW but this drops to <0.2mW at 60°C. This variation in output power over temperature is significantly more than found in 850nm devices of similar dimensions and reflects two things (1) the smaller conduction and valence band offsets in the AlGaInP materials system compared to that of (AlGa)As heterostructures[4], and (2) the greater thermal impedance of the quaternary materials used in the active region and the low mobility of the Al(0.5)GaAs material used to construct DBR mirrors appropriate for visible, red emitters.

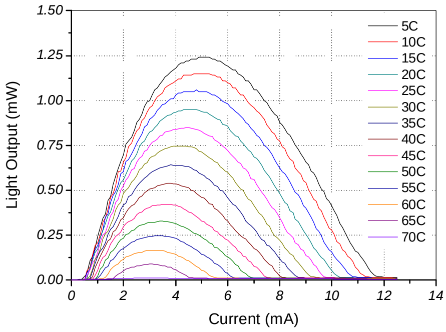


Fig. 3: Light output power versus drive current for a 665nm VCSEL operating at a variety of ambient temperatures. The VCSEL stops working at temperatures above 65°C.

This device is suitable for use in a VCSEL mouse tracking application and as such needs to remain class 1 eye-safe and must operate single mode and polarization stable in that regime. Figure 4 depicts the spectrum recorded from the device shown in figure 3 when operated in the single mode regime. Over the temperature range 5°C to 45°C the side mode suppression ratio (SMSR) is always >15dB which should be more than sufficient for mouse sensor applications.

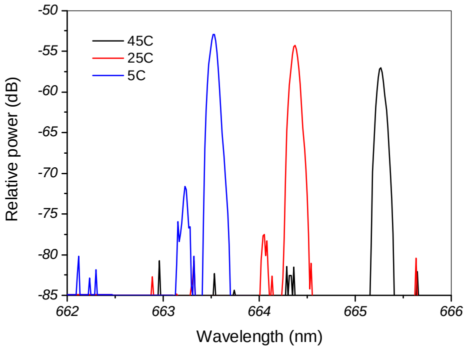


Fig. 4: Spectra of a red VCSEL when operated in the class 1 eye-safe limit of <390µW. Even at the lowest temperature the SMSR is >15dB. As the temperature increases the SMSR improves and the spectrum shifts to longer wavelengths.

Figure 5 demonstrates the polarization discrimination of a 665nm VCSEL as a function of drive current. A polarizer is rotated between 0^o and 90^o and the light output recorded as the drive current is increased.

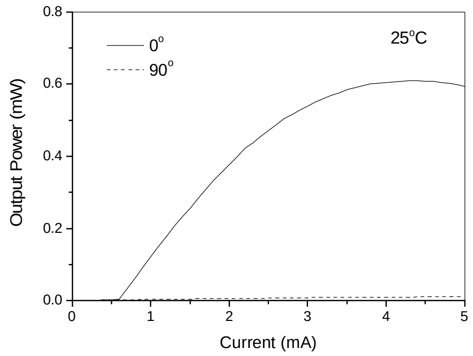


Fig. 5: Polarization resolved light output from a 665nm VCSEL as a function of drive current at 25^{o}C. There is almost complete discrimination of the output as the polarizer is rotated from 0^o to 90^o.

It is clear from this figure that there is almost complete discrimination between the two orthogonal modes. Spectrally resolved measurements have shown that the polarization mode suppression ratio between the two polarized states is >20dB. The polarization behaviour of the visible VCSEL contrasts strongly with that seen from 850nm VCSELs where the laser tends to lase either in both polarization states or will favour one state only to spontaneously flip to the other state as either drive current or temperature are varied[5]. To avoid spontaneous ordering of the AlGaInP materials during MOCVD growth, the epitaxy is performed on off-orientation substrates. This introduces anisotropy of the electro-optical properties of the crystal and a non-isotropic gain which results in highly polarized[6] and stable output from the VCSEL. It means that unlike 850nm VCSELs no additional complexity of fabrication or added processing of the VCSEL is necessary to achieve stable polarization and makes the red VCSEL an ideal candidate for polarization preserving applications like free space optics and optical recording applications.

Often a key parameter in the VCSEL performance is the quality of the far field and its variation with drive current. Figure 6 depicts the typical far field for a single mode red VCSEL as a function of various drive currents. CCD camera images of the far field are shown in Figure 7.

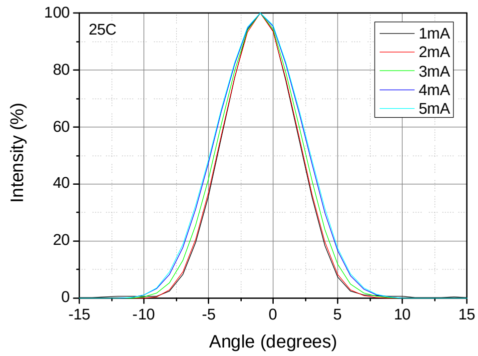


Fig. 6: Room temperature measurements of the far field of a 665nm VCSEL for a variety of drive currents.

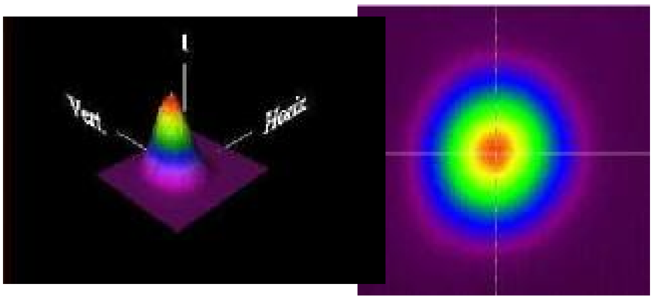


Fig. 7: CCD camera images of the far field of a 665nm VCSEL. The images emphasize the circularly symmetric nature of the far field.

From the two preceding figures it is clear that the far field is circularly symmetric and the FWHM increases from its value of ~7° at a drive current of 1mA to a value of almost 8° when the drive current is increased to 5mA. This circular far field contrasts strongly with the highly elliptical nature of the far field seen from a low power DVD laser where the FWHM can easily be at least 32° in the vertical direction and ~8° in the horizontal direction. The superior beam profile of the VCSEL offers simplification in both the number of and design of optical elements of collimating optics, for example, which is advantageous in applications such as displacement sensors and even laser pointers.

4. HIGH SPEED PERFORMANCE

Visible red RCLEDs are deployed as the transmitter in optical communications over POF at data rates up to 250Mb/s. Higher data rates require the use of a laser to achieve the necessary modulation bandwidth.

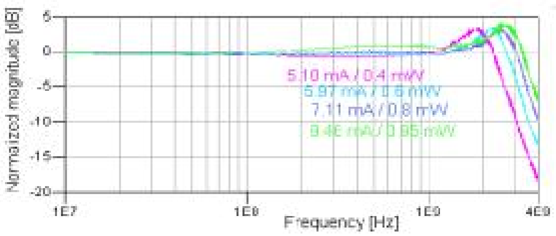


Fig. 8: Small signal modulation characteristics of a multi-mode red VCSEL at various bias currents. (*Courtesy of Bernd Offenbeck, Fraunhofer Institute, Erlangen, Germany)*

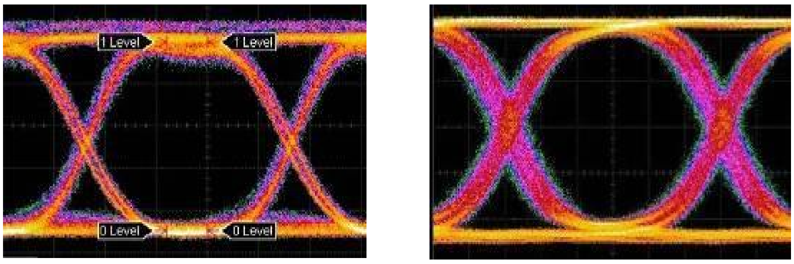
Figure 8 illustrates the room temperature, small signal modulation characteristics of a 665nm VCSEL mounted on a TO-46 header as a function of the drive current. It should be noted that there has been no attempt thus far to optimize the VCSEL design or fabrication to achieve even higher speed performance. A 3dB bandwidth in excess of 3GHz can be achieved at relatively low bias currents of less than 10mA. The high bandwidth and low current consumption makes this device an ideal optical source for a low-cost gigabit transceiver.

4.1. Gigabit Transceiver Module

We have developed a fiber-optic transceiver suitable for gigabit transmission of data over POF. Figure 9 shows a photograph of the prototype device.

Fig. 9: Prototype gigabit POF transceiver module with an *OptoLock*^{TM} bare fiber connector. Prototypes have also been constructed using a Small Media Interface (SMI) connector.

Similar to conventional 850nm datacomm transceivers, the POF transceiver consists of two major parts; an optical sub-assembly (OSA) and interfacing electronics. The POF tranceiver consists of a 665nm VCSEL source and a large-area photodiode co-packaged with a trans-impedance amplifier (TIA) as the detector. The interfacing electronics is mounted on a separate PCB which conforms to an industry standard 1x9 footprint. On the PCB a commercially available high-speed VCSEL driver IC (3.3V) is used to convert the incoming electrical differential signal to a current signal that drives the VCSEL and at the receiver side a limiting amplifier amplifies the received signal to a standard differential common mode logic (CML) signaling level.



(a) (b)

Fig. 10: Optical waveforms of (a) the transmitter and (b) the receiver outputs at 1.25Gb/s using a (2^7 – 1 PRBS) waveform.

Figure 10 shows the typical back-to-back transmitter and receiver eye diagram of the module at a data rate of 1.25 Gb/s at room temperature taken over 1m of standard 1mm step index (SI) PMMA POF. The rise and fall time of the optical signal is less than 200ps. The receiver we are using has a typical back-to-back sensitivity of -18dBm. A clear, open eye is seen for both the TX and RX. The transceiver is capable of operating over the temperature range -20^{o}C to 60^{o}C. To account for the variation of the VCSEL output power over temperature, a temperature dependent bias/modulation current control scheme has been implemented in the module. Figure 11 shows that a clear eye-opening can be maintained over this operating temperature range.

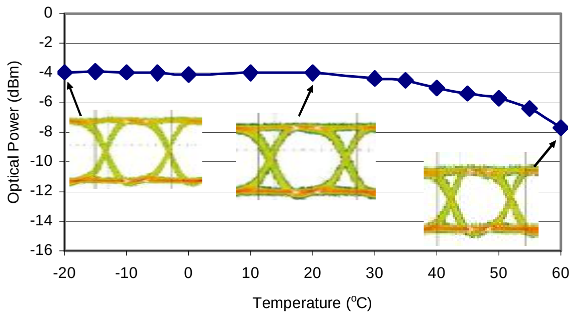


Fig. 11: Average optical power from a red VCSEL over temperature. The inset shows the 1.25Gb/s data rate eye-diagram at -20^{o}C, 20^{o}C and 60^{o}C.

The optical power is kept just below -4dBm to ensure that the VCSEL is class 1 eye-safe. Due to the characteristics of the red VCSEL (see Fig. 3) the output power of the VCSEL drops to around -8dBm at 60^{o}C, however a clear, wide-open eye is maintained even at this temperature.

Our initial demonstration (Fig. 10) was made over only 1m of SI PMMA POF; however we have carried out transmission testing to measure the performance of the module with several types of POF. The transmission distance is significantly enhanced by using graded index (GI) POF and we have demonstrated a successful link at 40m using GI-PMMA POF and 100m using GI perflourinated POF[7] making the red VCSEL a key component for the realization of GB/s links over POF.

5. RELIABILITY

Published information on the reliability of visible VCSELs is scarce[8-11]. In Ref. 8 the authors estimated the median lifetime of 670nm VCSELs to be ~2000h of operation at use conditions of 7mA and 25^{o}C. It was argued that since many of the applications envisaged at the time required pulsed operation with perhaps a 1% duty cycle then this would equate to a median lifetime of 200,000h of actual elapsed time. The data in Ref. 9 is limited to only two devices, neither of which would demonstrate reliability indicating the promise of commercialization of the device. Ref. 10 reports on two device designs and reveals quite different behaviour of the initial burn-in of the devices with one design having a slow reduction in threshold current accompanied by an increase in output power for 100h. The second design degrades rapidly at the ageing conditions of 100C and 6mA. Neither design could be considered as ready for commercialization. Ref. 11 details the reliability behaviour of 670nm devices with apertures of 8μm at stress conditions of (20C,5mA) and (80C,5mA). Up to ~2000h, devices at the lower stress conditions showed a gradual degradation whereas devices at the second stress level showed different levels of linear degradation up to between 800h and 1000h, after which they degrade very rapidly. Below, we discuss the reliability of Firecomms' red VCSELs which far exceeds the results that have been previously reported.

5.1. Ageing Conditions

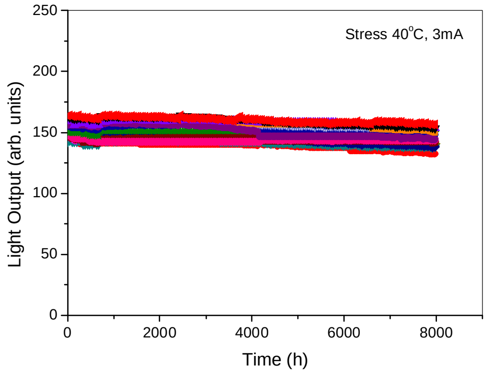
The VCSELs tested here are not hermetically sealed and consist of chips mounted on TO-46 headers using silver loaded epoxy. The devices are then loaded into a commercial lifetest system which can accommodate up to 1024 devices. Devices are tested in groups of 16 per module where each module can be independently programmed to tailor the drive current and temperature of the group of devices.
We have used a combination of ambient temperature and drive current to stress the devices and accelerate the aging process. The temperature of the devices which is relevant in the aging process is the junction temperature which is a combination of the ambient and the internal heating due to the thermal resistance of the materials. Table 1 shows the matrix of conditions we have used.

Table 1: Number of VCSELs tested at each of the stress conditions defining the accelerated ageing matrix of drive current and ambient temperature.

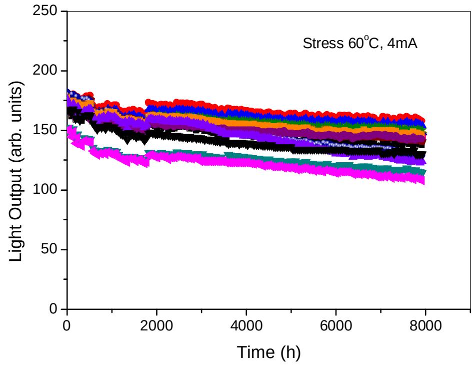
	Ambient Temperature (^{o}C)		
Drive Current (mA)	*40*	*60*	*85*
3	16	16	16
4	16	16	16
5	16		16

Devices on test "soak" using the combination of heatsink temperature and drive current shown in Table 1. The light output, current and voltage from the device is measured by a photodiode mounted directly above every device. Every 24hrs the devices are measured by performing a sweep of L-I-V at 40^{o}C.

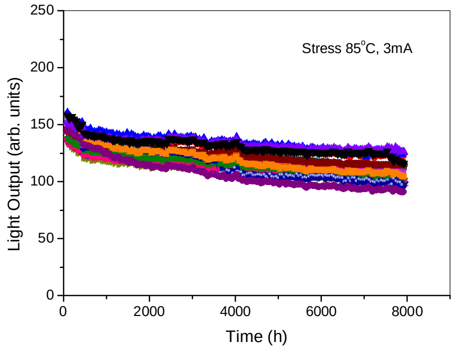
Figure 12 shows the VCSEL output power at 40^{o}C and 3mA as a function of time for a few examples of the tests performed. No random failures have been observed.



(a)



(b)



(c)

Fig. 12: High temperature operating life (HTOL) test results for 665nm VCSELs under various stress conditions (a) 40°C, 3mA (b) 60°C, 4mA and (c) 85°C, 3mA. Each panel shows the results from 16 devices tested at 40°C and 3mA.

5.2. Lifetimes and Failure Rates

VCSEL device failures that are due to "wear-out", statistically follow either a lognormal or Weibull distribution[12]. A fit to the cumulative failure rate of devices allows us to extract a mean time to failure (MTTF) for devices under particular stress conditions. We find that the fits to a lognormal distribution are marginally better that fits to the Weibull distribution. To calculate the lifetime under normal operating conditions from the MTTF determined at the accelerated stress conditions we need to have a model of how the TTF varies with temperature and drive current. It is common practice to assume that the TTF follows an Arrhenius behaviour with temperature and a power law behaviour with the stress of drive current. This is usually expressed as an acceleration factor *(A.F)* which takes the form:

$$A.F = \left(\frac{I_1}{I_2}\right)^n \exp\left(\frac{E_A}{k_B}\left(\frac{1}{T_{j1}} - \frac{1}{T_{j2}}\right)\right)$$

E_A is the activation energy, n is a number to be determined experimentally and k_B is Boltzman's constant. $I_{1,2}$ is the drive current at junction temperatures $T_{j1,2}$. The junction temperature T_{ji} is given by, for example

$$T_{ji} = T_{ambient} + R_{th} * I_i$$

where

$$R_{th} = \left(\frac{dT}{dI}\right)$$

is the thermal resistance of the VCSEL, which is determined to be ~9.89K/mA for the small aperture devices studied here.

From the determination of the MTTF for different ensembles of devices with the same junction temperature we can determine n. We find a value of n equal to 2. By examining the MTTF of ensembles of devices and plotting these versus $1/T_j$ we determine an activation energy of 0.6eV. Table 2 shows the predicted "wear-out" lifetimes of red VCSELs using a variety of values of the degradation in light output power as the criteria that defines a device failure.

Table 2: Predicted wear out time-to-failure (TTF) in hours for 1% and 0.1% of 665nm VCSELs at use conditions of 40°C ambient temperature and 1.5mA operating current.

	Percentage drop in light output power		
	30	*20*	*15*
TT1%F	457,163	304,775	228,581
TT0.1%F	292,561	195,041	146,281

To the best of our knowledge, these results are far better than any other previously published data. The values are certainly comparable with and in many cases exceed those of edge emitting diodes at similar wavelengths. We believe that these values should remove uncertainty over device reliability as an obstacle to commercialization of red VCSELs in consumer applications.

In addition to VCSELs failing via a wear-out mode, devices can stop working in a spontaneous or random fashion. We have seen no random failures in almost 1 million elapsed test hours from devices tested using the matrix shown in Table 1. We have calculated the FIT rate for spontaneous failures using the Telcordia method[13], using an activation energy of 0.35eV – which is the value recommended when the method of failure is unknown. The FIT rates are shown in Table 3.

Table 3: Predicted FIT rates for red VCSELs at temperatures of 25°C and 40°C, assuming an activation energy of 0.35eV.

Temperature (°C)	*Confidence Limit (%)*	*FIT (per billion device hours)*	*MTTF (h)*
25	60	17	58,823.529
	90	42	23,809,524
40	60	31	32,258,065
	90	76	13,157,895

Whilst the FIT values here are not as low as those reported for 850nm VCSELs[2,14], they are still significantly better than those for an edge emitter and indicating that the red VCSEL is ready for commercial deployment.

6. HIGH TEMPERATURE, PULSED OPERATION

Firecomms' visible VCSELs have been designed for relatively low maximum output power (~1mW at 25°C) and in particular they are designed to operate cw in a single longitudinal and transverse mode whilst remaining Class 1 eye safe over all operating temperatures. However, operating the VCSEL in a pulsed mode can lead to the achievement of significantly higher output powers and laser operation at a temperature of 85°C. If the pulse length applied to the VCSEL is shorter than the thermal time constant of the VCSEL[15,16] then the junction temperature does not rise as much during the pulse as it would if it were driven cw. This lower junction temperature postpones the onset of thermal rollover and allows the VCSEL to be operated to higher powers. Similarly, the lower junction temperature also results in reduced carrier leakage from the active region which in turn allows the laser to continue operating to significantly higher ambient temperatures.

Figure 13 shows the over-temperature performance of a Firecomms visible VCSEL operating under cw conditions and contrasts it with the same device operating under pulsed conditions. The pulse length was 500ns and a duty cycle of

10%. For pulsed operation we are plotting the peak output power detected and the peak drive current. Two things are quite clear from these curves; (i) the *peak* power at any ambient temperature of operation is at least a factor of two greater in pulsed mode than it is when operating cw, and (ii) pulsed operation continues to significantly greater ambient temperatures compared to cw. Operation, cw, ceases at ~70°C whereas pulsed operation, with useable peak powers, continues to 90°C.

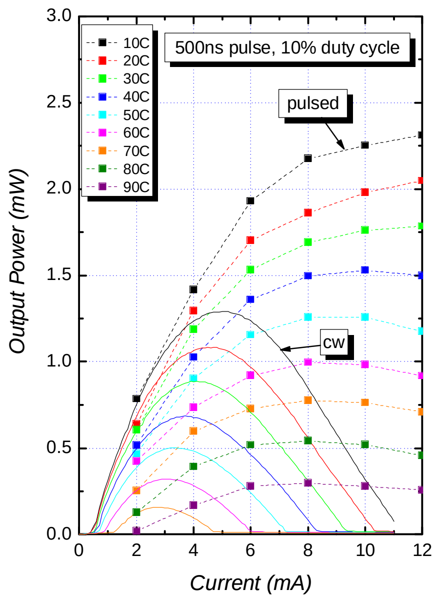


Fig. 13: Comparison of the pulsed and cw operation of a 665nm VCSEL over temperature. The current pulse width was 500ns and the duty cycle was 10%.

Operating the red VCSEL in a pulsed mode should facilitate their use in applications where it was previously thought their lack of high temperature (85°C) operation excluded them. In Figure 14 we show how the peak output power of a red VCSEL varies at 85°C when operated in a variety of pulsed modes.

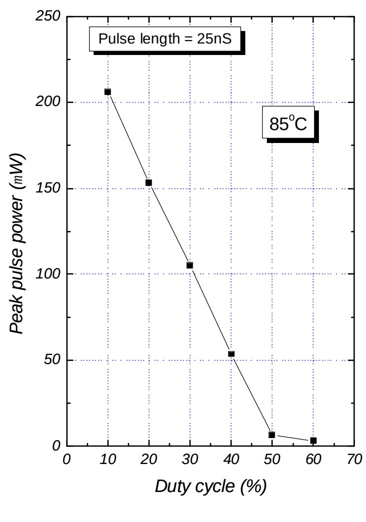


Fig. 14: Pulsed behaviour of a 665nm VCSEL at 85°C, when driven with an electrical pulse of 25ns duration, as a function of the duty cycle.

Its clear from this figure that useful peak powers can still be achieved from a red VCSEL even at 85°C, providing that a short pulse width is used and the duty cycle kept low enough to prevent a rise in the junction temperature. This observation opens up the possibility of transmitting data at gigabit speeds using a red VCSEL in , for example, the harsher environment demanded by automobile applications.

7. SUMMARY

We have reported on the fabrication of high quality, highly reliable visible red VCSEL devices. Single mode devices have a low threshold current of <1.5mA and the maximum, room temperature, output power is about 1mW. When operating at powers within the Class 1, eye-safe limit the devices are single mode with a SMSR of ~20db and discrimination between the polarization states of also ~20dB.

Ageing tests allow us to infer a 1% time-to-failure of >200,000h at an ambient operating temperature of 40°C, which to the best of our knowledge is the longest reported lifetime for a visible, red VCSEL. This demonstrated reliability makes the red VCSEL ready for use in consumer-type applications.

The cw performance of the VCSEL is limited to temperatures of ~60°C, but still makes the VCSEL suitable for applications such as gigabit Ethernet communications within the home environment and in mass market position sensing applications. Finally, when operated in appropriate pulsed mode conditions, we have shown that useful powers can still be attained from the VCSEL even at 85°C, making in a contender for use in Gb communications in a harsher environment.

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