Evolution of VCSELs

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ABSTRACT

Over the last 20 years, nearly 1 billion VCSELs have been shipped, the vast majority of them emitting at 850nm using GaAs active regions, and primarily used in data communications and optical tracking applications. Looking to the future, the ever increasing speed of data communications is driving the VCSEL to evolve with more complex active regions, optical mode control, and alternate wavelengths to meet the more stringent requirements. We will discuss the current state of VCSELs for 28Gbps, and higher speeds, focusing on evolution to more complex active regions and alternate wavelength approaches, particularly as the market evolves to more active optical cables. Other high volume applications for VCSELs are driving improvements in single mode and optical power characteristics. We will present several evolving market trends and applications, and the specific VCSEL requirements that are imposed. The ubiquitous 850nm, GaAs active region VCSEL is evolving in multiple ways, and will continue to be a viable optical source well in to the future.

Keywords: VCSEL, Fiber Optic, Optical Networking

1. INTRODUCTION

The first paper to discuss the Vertical Cavity Surface Emitting Laser (VCSEL) market segment in detail was presented in 2003 [1] and then reinvestigated in 2007. [2] This was on the tail end of the significant market decline in the optical industry, and it was forecasted at that time that significant consolidation of both the VCSEL and transceiver industry would need to happen for a sustainable ecosystem to emerge. Since 2003, there have been a large number of mergers, acquisitions, and other events that have dramatically changed the VCSEL and transceiver landscape. Figure one is a plot of the VCSEL and transceiver companies showing the evolution over time. The data through 2007 is replicated from [2] and 2013 is an author estimate of actual shipping companies. Note that that in the last 10 years the number of VCSEL and transceiver companies has been cut in half. Of those remaining companies, the volume is really split among three or four major transceiver companies. The number of VCSEL companies has actually increased slightly, however the high volume is split by application, with two or three having the majority of data communications VCSELs, and two or three having the majority of single mode (optical guidance) VCSELs. The remaining VCSEL companies are primarily focused on other specialty or emerging applications with significantly lower shipping volume at this time.

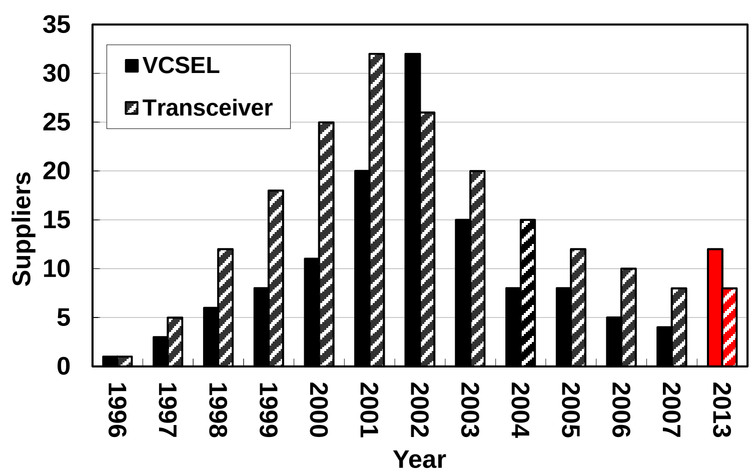

Figure 1. Number of VCSEL and transceiver companies since shipments began in 2013. Data up to 2007 is from [2] and 2013 is an estimate from the author.

2. DATA COMMUNCATIONS

2.1 Market Overview

VCSELs were first commercially introduced by Honeywell in 1996 for the data communications industry. [3] The first devices were based on GaAs quantum well active regions and utilized proton implants to direct current into the quantum wells. The first commercial application was ushered in with the ratification of the IEEE 802.3z standard widely known as gigabit Ethernet. These devices were proven to be highly reliable [4] and quickly supplanted more traditional Fabry-Perot type edge emitting lasers. As the speed of the optical networks increased to 2 and 4Gbps with the introduction of the ANSI X3.T11 (Fibre Channel) standard, the proton isolated VCSEL had trouble robustly meeting the speed requirements and required more complex electrical signals to improve the optical output. A new class of VCSELs was now available that replaced the proton isolation with a native oxide that could be formed directly in the Distributed Bragg Reflector (DBR) layers. The oxide layer also added index guiding to the structure and significantly improved the dynamic performance of the VCSEL by improving the overlap of the carriers and the optical modes. There was significant angst within the VCSEL community about the reliability of the oxide confined VCSEL stemming from the significant mechanical and thermal mismatch of the oxidized layer and the surrounding semiconductor material. Ultimately, these lasers were made as reliable, and even more reliable, than the original proton implanted VCSELs. [5] Oxide VCSELs have now become essentially the only type of commercially available VCSEL today. Optical networking speeds continued to increase with the adoption of IEEE 802.3ae (10Gbps Ethernet) and Fibre Channel introducing an 8Gbps variant. Today, these two speeds are by far the largest shipping volume of datacom VCSELs. The seemingly insatiable appetite for data continues to drive network bandwidth resulting in the standardization of 14Gps optical links in Fibre channel. Up to this point, GaAs active regions have been sufficient and have certainly proven to be highly reliable. The next generation of optical standards will require data transmission of 25Gbps (Ethernet) and 28Gbps (Fibre Chanel) and are requiring the advent of a higher speed active region. With approximately double the differential gain, InGaAs is a very attractive choice. Once again, there was significant angst in the VCSEL user community about the reliability of this active region. There have been reliability reports published previously [6],[7], and an invited paper to be presented at OFC 2014. [8]

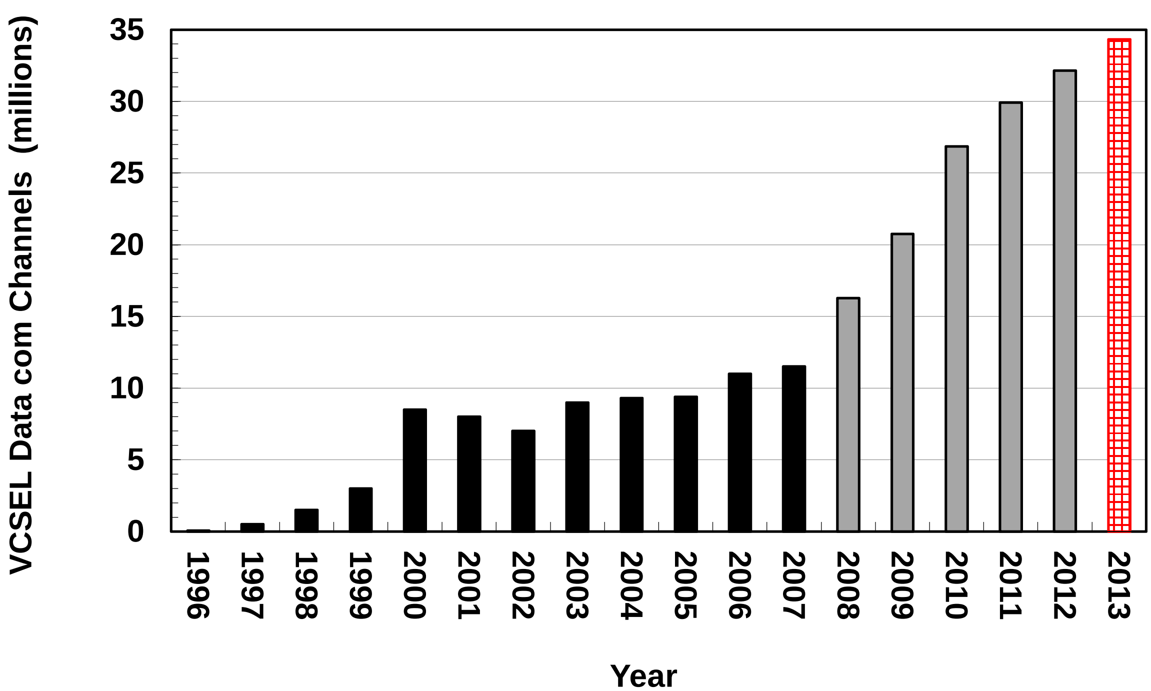

Figure 2. Number of VCSEL data ports shipped by year. Data up to 2007 is from [2] and 2008-2013 is adapted from Light Counting Marketing reports, with 2013 being an estimate. [10]

While the speed of serial optical channels has been increasing, so has the number of channels. Parallel optical interconnects now make up more than one third of the VCSEL based optical links by total channel count. Parallel transceivers have become popular because of the increased faceplate density attainable in a common 19 inch equipment rack. Figure two is a plot of the annual VCSEL shipping volume of VCSEL channels in data communications. In this chart, we have counted each of the channels in a parallel application. It should be noted that like any market report, the annual volume figures are a best estimate and should be indicative of the overall market but may not represent the absolute volume. Figure three is a breakdown of the total VCSEL datacom channels by type. Here we have again counted each channel in parallel applications. The 1x4 and 1x12 parallel applications, as well as the active optical cable applications are a mix of speeds ranging from 2.5 to 12.7Gbps, with the largest volume being at 10Gbps. For calculations we have assumed that they are all running 10Gbps. When the total 2013 shipping volume and speed per channel is included, the industry is delivering approximately 30Mbps of bandwidth for every person on the earth every year. This is equivalent to streaming 40 high definition movies simultaneously to every person on the planet.

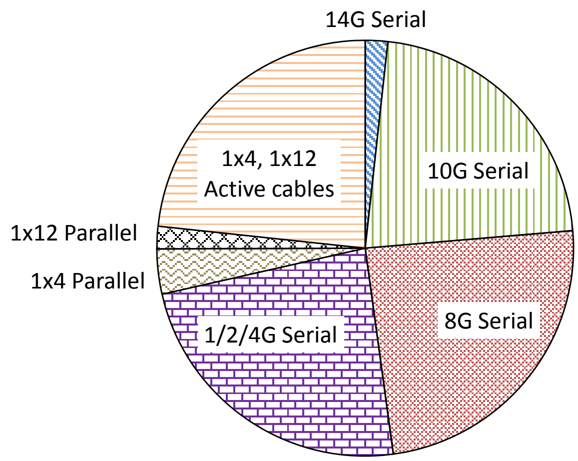

Figure 3. VCSEL data ports shipped by type shipped in 2013. Data adapted from Light Counting Marketing reports. [10]

2.2 Technical challenges for VCSELs for 28Gbps and beyond

There are several papers contributed to the VCSEL conference that cover the operation of VCSELs at 28Gbps and the commercial viability of these products. Optical transceivers operating at 100G Ethernet (4x25Gbps) and 32G Fiber Channel (28Gbps) will be commercial available in 2014. These sources are directly modulated VCSELs using InGaAs active regions. Reliability of these high indium content lasers is still an open industry question, though it has been stated that the lasers will have reliability similar to 10G GaAs based devices. [9]

As the data rates have continued to increase, the achievable fiber link distance has declined. At 1Gbps, the link coverage was up to 550m, and now at 28Gpbs, the maximum link length is set at 100m. Improvements in optical fiber bandwidth from 500Mhz/km to 4000MHz/km have helped to keep the link distances up, but the continued scaling of fiber bandwidth while maintaining backwards compatibility is becoming increasingly difficult. While there has been a loss of distance coverage, still over 90% of deployed multimode fiber links are less than 100m. [11] The 25/28G market is expected to be very large even with the reduced link length coverage as optical interconnects move to displace more and more copper cables in the short distance interconnect market. The advantages of the optical interconnects at this speed include superior cable management (the copper wires are bulky and inflexible) and a significant improvement in the energy per bit requirement to transmit the data. [12] Taking the total bandwidth produced by the industry in 2013 and using 1pJ per bit as the figure of merit, the energy consumed in just the optical part of data communications is equivalent to power 60,000 typical US homes. [13] With the considerable focus on more “green photonics” recently, state of the art VCSELs can transmit at energies as low as 50fJ/bit [12], making them even more compelling in very high density interconnects, even driving to on board links. In the copper market the link length distribution is shorter. Figure 4 is a plot reproduced from [14] that shows the distribution of copper cables in a study of several data centers indicating that 95% of links are covered by 70m or less. Link distances for 25G and 28G standards are currently specified to 100m. To achieve this distance, the Fibre Channel standard now requires the use of Forward Error Correction (FEC), clock and data recovery circuits (CDR) in both the transmitter and receiver, and the receiver may have some other form of dispersion compensation in order to meet all the of the requirements.

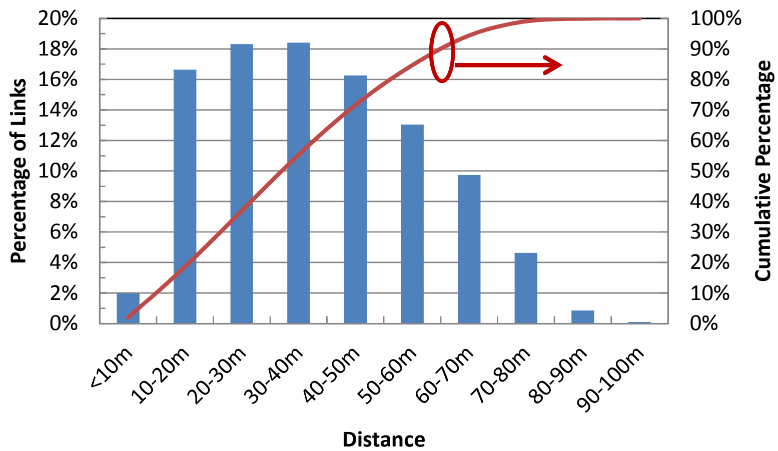

Figure 4. Distribution of Copper interconnects in data centers. Data has been reproduced from [14].

Looking forward, serial operation of VCSELs at 40Gbps and even 56Gbps is being pulled by industry as the next logical serial data rate. Making devices with sufficient bandwidth and reliability will be a technical challenge, but already devices have been shown to have closed optical links at those speeds using devices designed for 28Gbps by using electronic equalization techniques. [9] Serial operation at these higher speeds is not a foregone conclusion and there are multiple obstacles to overcome to make viable commercial links. With the doubling of the data rate, to a first approximation, the link length will be reduced by the same factor of two. There have been a couple of proposed methods to continue to hold the link length, or to possibly extend it. The first is to use near single mode VCSELs to combat the chromatic dispersion in the optical fiber. Figure 5 shows the calculated link length as a function of the laser spectral bandwidth for 28G Fibre Channel conditions on 4000MHz/km (OM4) optical fiber. Up to 70% increase in link length can be obtained by reducing the spectral bandwidth. However this does not come for free. Single mode or nearly single mode lasers will be much more susceptible to optical feedback from the link that could increase the Relative Intensity Noise (RIN) of the laser. Near single mode lasers have been demonstrated to transmit up to 500m in an optical fiber at 25Gbps [15]. Another approach utilizes digital signal processing techniques such as Feed Forward Equalization (FFE) and/or Decision Forward equalization (DFE) or other Continuous Time Linear Equalization (CTLE) techniques to recover the signal integrity loss due to the limited overall bandwidth of the laser, fiber and detector [10],[16]. Collectively these techniques could be used to keep link distances for multimode fiber above 100m for 40 and possibly 56Gbps application. These techniques can also be used to extend 28Gbps links to 300m. Pulse Amplitude Modulation (PAM) is another method that can be used to increase the laser data rate without necessarily increasing the laser bandwidth. In this technique, the laser intensity level is used to encode the data and has been shown to operate links up to 60Gbps [17]. It may also be possible to borrow phase encoding techniques from the telecommunications industry to increase the data carrying capacity, but operation in multimode fiber may limit the practicality of this approach. [18] Other methods to meet the 40 and 56Gbps requirements such as Wavelength Division Multiplexing (WDM) and mutlitcore optical fibers are also under consideration and are attractive to the VCSEL community because they may not require an increase in the laser bandwidth. Serial data links at these speeds are not expected to be required until 2017.

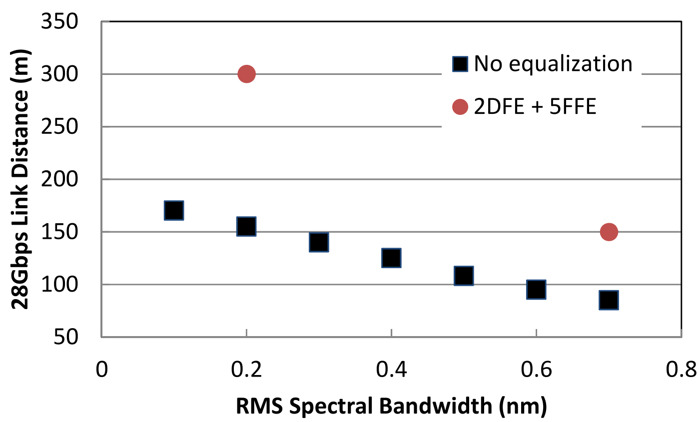

Figure 5. Achievable link lengths for 28Gbps Fibre channel specifications as a function of spectral bandwidth with and without equalization.

Without the use of equalization, the 3dB optical bandwidth required to operate a 56Gbps is approximately 40GHz. Making VCSELs that are capable in direct modulation is a technical challenge considering that state of the industry is less than 30GHz [19]. There has been effort to modulate the loss in the VCSEL with a coupled cavity resonator that has shown promise, but these techniques often are plagued with low modulation amplitudes and extinction ratios. [20] One potential that is being explored is moving to longer wavelengths such as 980nm where the differential gain in the quantum wells can be made larger by adding more Indium. These VCSELs may be particularly well suited for active optical cables and very short reach (<10m) interconnects where communications standards may not be suited to cover.

3. SINGLE MODE VCSELS

3.1 Market Overview

Single mode VCSELs have been primarily used in optical mice or other such applications. The requirements for the VCSELs are significantly different than the data communications VCSELs. These VCSELs are required to have single polarization with Gaussian like beams that do not contain speckle. These features are critical to preventing jumps in the position of the input device. Like datacom devices, early VCSELs were based on proton implantation with the addition of a mechanical stress feature to force polarization locking.[21] As the industry evolved the oxide VCSEL structure, it has since moved in to the single mode realm, and either mechanical stress or optical gratings are used to insure polarization locking.[22] The required apertures are typically less than five microns in diameter, which does present some challenges to manufacturing. The sections below will describe two production applications of single mode VCSELs. While there are certainly other applications that can be classified as being in mature production, these two were chosen to illustrate the extremes of the market, one driven by high volume and low cost, the other driven more by device performance with a smaller emphasis on cost.

3.2 Optical Guidance

VCSELs used in optical mice first appeared in 2000 and were based on measuring complex speckle patterns [23]. Later versions used laser self-mixing [24], and ultimately with the advent of good single mode VCSELs and very low cost CMOS cameras, they evolved to simply replacing the LED used in image correlation based devices as this ultimately provided the lowest cost and highly manufacturable sensor. The primary advantages to the VCSEL over the LED are improved operation on a wider range of surfaces and ability to handle higher speed movements. The market grew to almost 100M devices per year, but has been in retreat for the last several years with the increased popularity of the touchscreen devices. The annual shipping volume for the optical guidance market is shown in figure six. As stated previously, the absolute numbers are likely not fully accurate but are representative of the overall market condition.

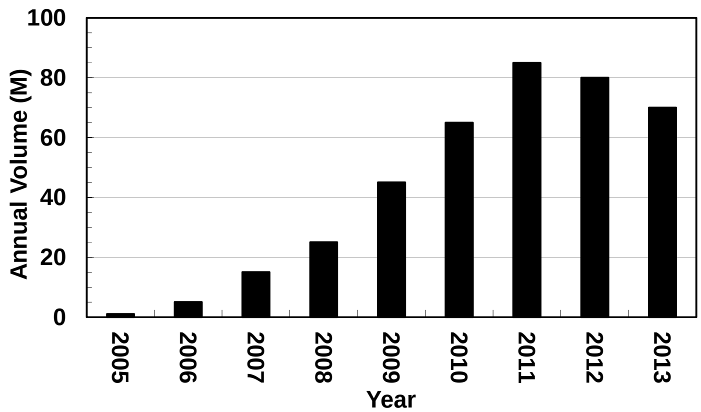

Figure 6. Annual VCSEL volume in the optical guidance market.

3.3 Atomic Clocks

Single mode VCSELs have been used in making atomic clocks with both Cesium and Rubidium atoms. [25] The wavelengths required are 795nm for Rubidium and either 852.1nm or 894.6nm for Cesium. In addition to the previous requirements on single mode VCSELs of polarization stability and beam profiles, the clock function and accuracy is controlled by the laser linewidth. For practical devices, linewidths under 100MHz are a requirement, and typical devices are under 50MHz with careful design. The other difficulty is the requirement for the VCSEL to operate at high temperatures, typically more than 90°C, because of the need to volatize the Cs or Rb atoms. Volumes in this market are very modest (thousands, not millions, per year).

3.4 Technical challenges for single mode VCSELs

Looking forward there are two areas of research and development that are important for single mode VCSELs. The first is the maturation of a broadly tunable wavelength source. There have been many reports of devices with more than 80nm using several methods. [26] Widely tunable sources across a range of infrared wavelengths would be very attractive for Frequency Domain Optical Coherence Tomography (FD-OCT) that could be widely adopted in the medical field. Volumes would be modest with a premium on performance. Secondly, the development of single mode devices with up to 100mW of optical power would make an attractive source for Heat Assisted Magnetic Recording (HAMR, sometimes called LAMR). Here the requirement is to focus enough energy through a single mode waveguide and a plasmonic or other near field optical element enough energy to locally heat the magnetic media. The single mode definition is a little ambiguous here, more driven by the beam quality than single wavelength, and is driven by the need to deliver enough power in to a single mode waveguide. The volumes in the disk drive industry are enormous, hundreds of millions per year, and HAMR is widely believed to be required to the next step in density of up to 10Tb/in^2 in the magnetic media. [27]

4. HIGH POWER VCSELS

4.1 Market Overview

The ability to scale VCSELs to higher emission powers comes in two forms. The first is scaling the active region to larger diameters, typically 100μm or larger. The disadvantage is that the thermal lensing in the material tends to limit the optical output power and significantly deteriorate the optical beam profile. This has been overcome by using an external cavity to create what is commonly referred to as a VECSEL or Vertical External Cavity Surface Emitting Laser. VECSELs can be made to emit several watts of near single mode power. [28] The second method to increase the total optical output power is to make 2 dimensional arrays of emitters. Several companies now provide VCSEL arrays with up to one kilowatt of total optical power, and have even achieved power emission density of more than 1kW/cm^2. [29] Given that each VCSEL element is operating near 10mW, the total number of VCSELs in the arrays can be tens of thousands. The principle disadvantage to VCSELs in the high power operation has been the relatively low wallplug efficiency that results from a higher electrical and thermal resistance necessitated by the DBR mirror structure when compared to edge emitting lasers. The principle advantages are wavelength stability, circular beams with low divergence, and high reliability that primarily comes from the elimination of catastrophic optical damage to the laser facets and the fact that there are thousands of individual emitters that make failure of a few lasers inconsequential to the overall power output.

4.2 Illumination

The first commercial application of high power VCSELs was in the area of terrain illumination for night vision equipment. Several manufacturers have developed devices with multiple kilowatts of total optical power and have shown the benefits of these illuminators in multiple aerospace and military applications. [29] The overall market size is modest, but a very high premium is paid in these industries for quality, reliability and performance.

4.3 Gesture recognition

Since the introduction of gesture recognition in the Microsoft Kinect system, more than 24M have been sold through 2013 [30], and now that the Kinect system is bundled directly with the XBOX system, even higher sales are expected. Since Kinect's introduction, there have been numerous other gesture recognition systems introduced, most of which are not laser based. There has been a tremendous amount of hype around the entire field of gesture recognition but as yet the penetration into consumer applications has been limited. The overall technology is beginning to emerge from the "Trough of Disillusionment" and beginning to climb the "Slope of Enlightenment" in the Gartner hype cycle of emerging technologies. [31] VCSELs do offers some compelling benefits for the application such as low divergence beams, 2D array of emitters, and reliability.

5. WAVELENGTHS OTHER THAN 850NM

This paper has been primarily focused on the 850nm VCSEL opportunities in the previous sections (except atomic clocks). Here we will present the relative opportunities for VCSELs operating outside of the 850nm window. The table below summarizes the various applications by wavelength. The table was compiled from various publications, websites and conference exhibits and is not completely comprehensive, but is intended to represent the range of commercially advertised wavelengths and applications.

Table 1. Summary of VCSEL applications and market status for wavelengths outside of 850nm.

Wavelength	Application	Status	Annual Market size
670nm	Datacom on Plastic Optical Fiber (POF)	Development	10M
763nm	Oxygen sensing, blood oxymetry	Emerging	10k
780nm	Laser printing	Production	100k
	Coarse Wavelength Division Multiplexing (CWDM) on Multimode Fiber (MMF) for video.	Production	10k
795nm	Rb atomic clocks	Production	10k
800nm	CWDM on MMF for video	Production	10k
808nm	Solid state laser pumping	Production	1k
825nm	CWDM on MMF for video	Production	10k
852nm	Cs atomic clocks	Production	10k
894nm	Cs atomic clocks	Production	10k
910nm	CWDM on MMF for video	Production	10k
975nm	Illumination	Production	100k
980nm	CWDM on MMF for video	Production	10k
1060nm	Short distance datacom	Development	TBD

Wavelength	Application	Status	Annual Market size
1064nm	Solid state laser pumping	Production	10k
	Frequency doubling for green lasers	Production	10k
1310nm	Fiber optic communications	Development	10M
1550nm	Fiber optic communications	Development	1M
	Optical Coherence Tomography	Development	TBD
1860nm	Optical Coherence Tomography	Development	TBD
>2000nm	Gas sensing (CO, CO_2, etc.)	Emerging	10k

The definitions used in the status column are coarsely defined as follows; Development means the VCSELs have been demonstrated, and perhaps used in an application but the commercial viability is not known; Emerging indicates that there is market acceptance and at least one company has offered the end product for sale or use outside of an R&D environment; Production describes a VCSEL and an end product that is readily available in the market. The annual market size is an estimate based on published data and various technical and non-technical articles accumulated over the last 20 years and are intended to only give a sense of market scale and not be definitive. One thing to take away from this table is that most of the applications that require specialized wavelengths are generally modest sized markets. The highest potential volume markets are still in data communications, whether in short wavelength POF, or in the telecom windows. Both of these wavelengths have been under extensive development by several companies, but have yet to deliver on the full market potential.

6. CONCLUSIONS

The VCSELs that are available in the commercial market today are considerably different than those that first appeared in 1996. They can be 28× faster, oxide isolated, polarization controlled, single mode, tunable, very high power, and possibly emitting at wavelengths from 650nm to more than 2μm. The future for VCSELs in the datacom industry is favorably competing for short distance interconnects, those less than 100m. VCSELs will continue to be the lowest cost and lowest energy consuming data links available. Applications for single mode and high power VCSELs will continue to proliferate into more consumer applications that will drive the overall VCSEL demand.

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