VCSEL Proliferation

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ABSTRACT

Since the commercialization of Vertical Cavity Surface Emitting Lasers (VCSELs) in 1996, Finisar's Advanced Optical Components Division has shipped well over 50 Million VCSELs. The vast majority of these were shipped into the data communications industry, which was essentially the only volume application until 2005. The driver for VCSEL manufacturing might well shift to the increasingly popular laser based optical mouse. The advantages of the laser based mouse over traditional LED mice include operation on a wider range of surfaces, higher resolution, and increased battery lifetime. What is the next application that will drive growth in VCSELs? This paper will offer a historical perspective on the emergence of VCSELs from the laboratory to reality, and the companies that have played key roles in VCSEL commercialization. Furthermore, a perspective on the market needs of future VCSEL development and applications is described.

Keywords: VCSEL, Data Communications, Sensors

1. INTRODUCTION

There is an ancient curse that goes something like "May you live in interesting times." This has been particularly close to the heart for many VCSEL companies. The commercial introduction of VCSELs brought companies such as Motorola (now disbanded) Honeywell (now Finisar), Hewlett Packard (now Avago Technologies), Mitel (now Zarlink), and Vixel (now defunct) out from under the cloak of development and into the spotlight in the race to deliver this new laser source to the emerging data communications market place. The need for VCSELs became apparent as the market desire for highly reliable low cost, high data rate optical interconnects was being fueled by the rapid expansion of the then infant internet. Little did the players realize that the perfect storm was brewing. Easy access to venture capital quickly swelled the number of companies in the VCSEL market space to in excess of 30, which was noted in 2003 to be too many to support in this one application segment [1]. True to this statement, a significant contraction and consolidation in the number of VCSEL suppliers has occurred, and today, there are only a handful of viable companies remaining. Today, viability of VCSEL companies has become synonymous with product diversification.

2. VCSELs IN DATA COMMUNICATIONS

There may be different opinions as to the real success attributes of the VCSEL, but it is this author's opinion that if edge emitting lasers (EELs) used in compact disc players had been widely available with reliability sufficient for data communications, VCSELs may never have emerged (or at least would have been delayed) from the laboratory. The datacom market was at a crossroads, and needed a new low cost alternative to 1310nm lasers and single mode fiber technology to meet the burgeoning requirements of data in the face of the internet expansion. In 1990 Finisar was one of the first companies to propose the use of multimode fiber optics to the Fibre Channel Standards Organization (ANSI X3.T11), which was the protocol that was being deployed in the massively expanding data storage environment. Early demonstrations from companies such as IBM's transceiver division (now JDSU), Fujikura (now Sigma Links), Finisar, and others demonstrated that low cost EELs could meet the technical requirements for short distance communications on less expensive multimode optical fiber, and deployment of Gigabit Link Modules (GLMs) began in earnest. Until

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Vertical-Cavity Surface-Emitting Lasers XI, edited by Kent D. Choquette, James K. Guenter,
Proc. of SPIE Vol. 6484, 648403, (2007) · 0277-786X/07/$18 · doi: 10.1117/12.715082

1996, VCSELs had been primarily laboratory curiosities, but a hallmark reliability paper published by Honeywell in 1996 began to pique interest in this new device [2]. Simultaneously, VCSELs were in a battle to be included into the new networking standard IEEE 802.3z, more popularly known today as Gigabit Ethernet [3]. A myriad of technical issues, including optical fiber modal bandwidth, an unproven manufacturing infrastructure, and political chicanery were conspiring to remove short wavelength multimode optical fiber solutions from inclusion into the standard. However, sufficient market attractiveness of a lower cost solution ultimately prevailed and the multimode fiber solution utilizing short wavelength lasers was included. With both Ethernet and Fibre Channel now supporting short wavelength lasers and multimode optical fibers, the pressure was on the VCSEL industry to deliver. Today, multimode transceivers represent as much as 90% of the total volume shipped for GBE and FC applications [4]. With the widespread strong growth in demand being experienced, Venture Capitalists (VCs) were hard at work funding infant companies and rapidly swelling the number of optical transceiver suppliers to in excess of 30 [1]. It was truly an interesting time to be an optical engineer.

While the market forces of expansion were solidly at work, the technical understanding of VCSEL dynamic properties, reliability, commercialization and manufacturing expansion was also growing rapidly. Significant improvements in reliability, producability, and fundamental physical properties were being achieved seemingly on a daily basis [5,6]. Chief among the advances was the development of so called oxide isolated VCSELs, which were seen as necessary to increase the fundamental speed of the VCSEL to keep up with the next Fiber Channel data rate, 2Gbps. The inclusion of a non lattice matched, non-thermally matched insulating material inside a semiconductor laser cavity was indeed a heroic engineering effort. The oxidation layer brought new reliability failure mechanisms, and the need to further the theoretical understanding of the physical properties of this structure. Two papers were published at the 2002 Electronic Components and Technology Conference were among the first to describe the reliability aspects of oxide isolated VCSELs [7,8]. It was truly an interesting time.

The perfect storm, resulting from tremendous market interest in a new device in a booming economy, had been whipped into a frenzy and it finally released its fury in 2003. The number of VCSEL companies was cut in half in less than a year, and the number of companies supplying VCSEL based transceivers was similarly reduced. Consolidation was the word of the day, and larger companies began to gobble up competitors and in the span a less than 2 years, the number of viable VCSEL suppliers could be counted on one hand. While the VCSEL industry was damaged by the storm, the hardest hit were the telecommunications suppliers, and in particularly those supplying pump lasers for Erbium Doped Fiber Amplifiers (EDFAs) where shipping volumes are still yet to return to levels prior to 2003. It was truly an interesting time.

Figures 1 (a) and (b) below demonstrate the rapid consolidation that has happened. Figure 1(a) is a plot of the number of VCSEL suppliers and VCSEL based transceiver vendors by year. In the last several years, only 850nm VCSEL suppliers with data communications as a major company focus are included. Figure 1(b) is a plot of the total VCSEL

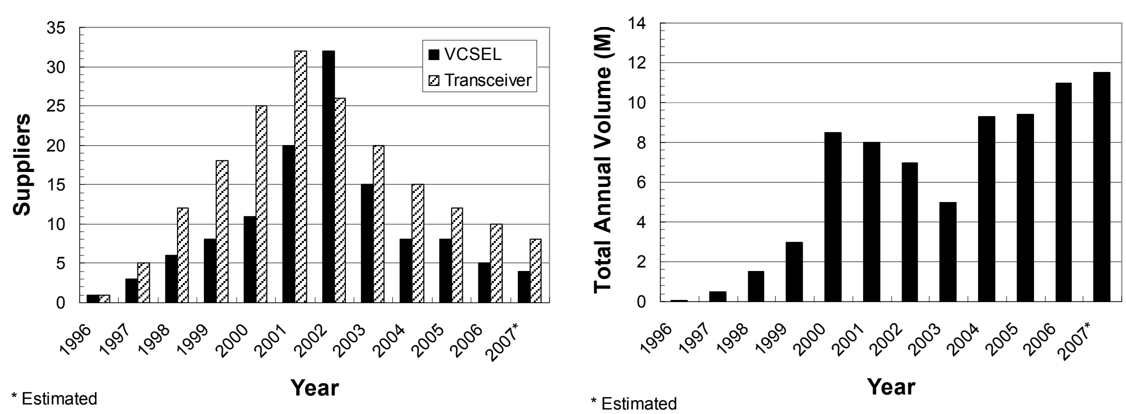

Fig. 1. (a) Historical perspective of the evolution of the number of VCSEL suppliers and transceiver suppliers. (b) Total annual volume of VCSELs in data communication networks.

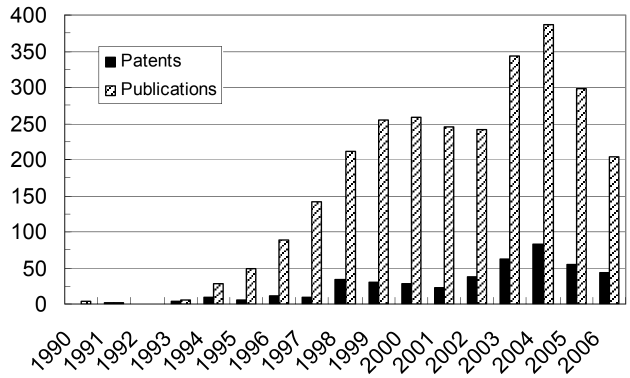

Fig. 2. Number of patents published with the term VCSEL in the abstract, and the number of papers published with VCSEL in the title.

market as a function of year. The eye of the storm is clearly evident in 2003 in both figures. Please note that this figure was compiled from various market reports and industry surveys, and is intended to only roughly scale the entire market. Figure 2 is a plot of the number of issued patents with the term VCSEL in the abstract, and the number of papers published with the term VCSEL in the title. The patents were determined from the United States Patent and Trademark Office website search [9], and the papers were determined using the Scholarly search feature at Google^{TM} [10]. These numbers should not be taken as exact, but as a relative indicator of the number of patents and publications during the time periods. Unfortunately, both the patents and publications are trailing indicators instead of leading economic indicators.

Figure 1 also demonstrates the resiliency of the VCSEL and VCSEL based transceivers in the data communications market place, and the bullishness of the author with respect to the datacom market. To be sure, the market has changed, and the evolution is rapidly pushing devices to higher speeds, such as 10Gbs and even now 100Gbps for Ethernet, and 8 and 17Gbps for Fiber Channel. The market is not only moving up in speed but also spatially as VCSEL arrays are resurgent after being nearly obliterated in 2003. The primary growth factors in data communications continue to be the desire to increase the size of Storage Area Networks (SANs) and driving more bandwidth to the user in Local Area Networks (LANs). There are still significant technical challenges ahead for the VCSEL in data communications, including increasing the modulation bandwidth per device to in excess of 20Gbps, and maintaining excellent reliability, both of which will be fueled by the demand for more bandwidth to the user. There is often talk about what is the next “killer application” for networking. Today, the demand for video over internet protocol (IP) networks appears to be that. As more service providers push video content to the user, such as television on your mobile handset (it really is not just a cell phone anymore) the need for data and networking infrastructure will continue to blossom. Another application for VCSELs that will began to emerge is more data links *inside the box;* the bandwidth bottleneck of copper interconnects is rapidly becoming the limitation to continuation of Moore’s Law. Research being led by Intel into the use of so-called Silicon Photonics highlights the need for fatter data pipes inside the equipment boxes. It will continue to be interesting times.

No discussion of VCSELs in datacom applications would be complete without at least a mention of devices for the first and second telecom windows (1310nm and 1550nm). Several companies continue to chase the elusive market for long wavelength (LW) VCSELs (e.g., Finisar, Picolight, Vertilas) while others have withered from the fray (Infineon, Cielo). The market drivers for LW VCSELs are a not as immediately compelling as for 850nm devices. Lasers exist in both the first and second window that are relative modest in cost, are produced in high volume, and certainly are reliable enough. So the market differentiation is less clear. Pundits cite the ability to reduce the electrical power requirements and make higher density parallel interconnects. However, market expectation that significant cost reduction with VCSELs is achievable may not be the case for LW VCSELs as a significantly larger portion of the overall cost is allocated to packaging the devices. Another potential barrier to widespread adoption of LW VCSELs is the very modest power levels achievable from current devices, which severely limits their usefulness in Passive Optical Networks (PONs) and Fiber to the home (FTTH) applications. The jury is still out on the ultimate success of LW VCSELs in this marketplace.

3. BEYOND DATA COMMUNICATIONS

The tumultuous nature of the VCSEL business over the last 10 years has led many companies to seek safe harbor by developing both VCSELs and applications targeted outside the data communications market. This section will examine some of these markets and comment on some emerging market potentials for VCSELs.

3.1. Why VCSELs

A survey of VCSELs in applications outside of the data communications arena was presented at the Sensors Expo Conference in 2005 [11]. The primary advantages realized by using VCSELs are the enhanced battery lifetime, high optical beam quality, and extremely high degree of coherence. Battery lifetime is a significant issue when one considers the use of optical components in some consumer electronics applications. Figure 3 is a plot of CW operating lifetime (defined as emitting 1mW of optical power into a cone angle of 30 degrees) of various optical sources as a function of battery rating. Note that several commonly used battery types are indicated on the graph as well. Using a VCSEL source can increase battery lifetime by nearly an order of magnitude, which is a significant concern to the end user. Note that the two lines shown for VCSELs are for a Single mode (top line) and multimode VCSEL.

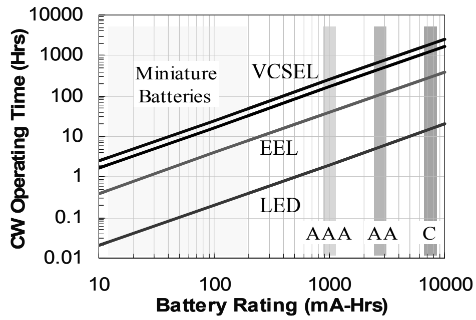

Figure 3 Operation of several optical sources as a function of battery rating.

For applications where coherence and/or a specific wavelength of laser emission are important, VCSELs offer significant advantages over other light sources such as LEDs and EELs. Figure 4 is a plot of the optical spectrum of a VCSEL, an LED and an EEL showing the differences in spectral purity of the optical source. This is particularly important when one is looking sensing coherent effects such as laser speckle, or using the laser source as a wavelength sensitive optical sensor. Table 1 summarizes some of the traits of various light sources that may be important in developing non-data communication applications.

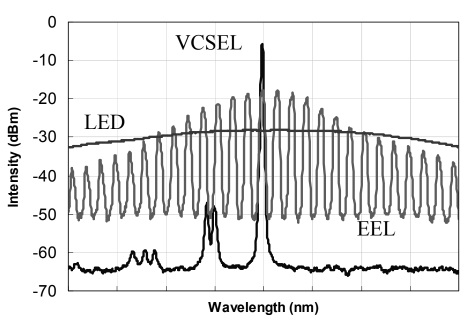

Figure 4 Optical spectrums of a VCSEL, LED and EEL

Attribute	Symbol	Units	SM VCSEL	MM VCSEL	EE Laser	LED
Electrical Power	P_{elec}	mW	5	20	60	60
Optical Power	P_{opt}	mW	1	5	10	1
Efficiency at Popt=1mW	η	%	20	10	5	2*
Wavelength	λ	nm	760-860	670-870	630-1300	400-1300
Spectral Width	$\Delta\lambda$	nm	0.01	0.5	2	50
Spectral Tuning (Temperature)	$\Delta\lambda/\Delta T$	nm/°C	0.06	0.06	0.3	0.3
Spectral Tuning (Current)	$\Delta\lambda/\Delta I$	nm/mA	0.25	0.09		
Beam Angle (full width at half of maximum value)	$\angle$	°	<15	~15	15 par. 35 perp	120

Table 1 Summary of relevant optical characteristics for several sources for sensing applications.

3.2. A better mouse

Video killed the radio star, so the song goes; are LEDs, and now VCSELs the demise of the trackball mouse? Containing no moving parts, ability to go cordless, and inexpensive to manufacture, the Holy Grail seemed to have been discovered in optical computer mice. Now, enter the VCSEL, to take optical mice to a new level of euphoria, with the ability to work on practically any surface, operate on a single AA battery for many months (depending on use), and provide the user with better resolution and higher speed of movement. In 2004 Agilent technologies (now Avago Technologies) introduced a line of VCSEL based mouse engines that delivered as promised. Today, in an informal survey of retailers, fully half of the mice sold aftermarket are VCSEL based. Estimations of the computer mouse market place the total annual volume in the 100's of millions per year. (In 2006, Agilent announced cumulative shipments in excess of 500 Million LED based devices [11]) Most of the mice sold by Original Equipment Manufacturers (OEMs) continue to be LED or trackball based, but the majority of aftermarket devices are now laser based. Following quickly on the success of Agilent in the VCSEL market were Truelight, Avalon Photonics (now Bookham) and Ulm Photonics (now Philips). Removed were many of the hurdles required to supply VCSELs to the datacom market, and cost truly began to rule the day. The traditional TO can used in packaging VCSELs was also being replaced with plastic encapsulated packages, and in some cases, no package. Like video and radio, it would appear that both LED and VCSEL based mice can happily coexist in the once strong domain of the trackball.

Modern optical mice are essentially a camera and an image correlator. The surface is illuminated, and a picture of the surface reflection is taken, and compared to the previous image every few milliseconds. The autocorrelation function of the two images is used to determine direction of motion. The LED illuminator was a good choice for most surfaces, but not for surfaces such as glass, repetitively patterned surfaces, and black surfaces. The primary advantage of laser light illumination is the coherent emission, which allows more light to be presented to the camera, enhances surface imperfections, and allows the cameras to image in the partially developed speckle plane, all of which improved the contrast ratio of the pixels in the camera. The primary disadvantage of the VCSEL was that manufacturers now had to consider labeling products with eye safety warnings. It was found that the mouse worked best if the VCSEL was single mode, polarized, and very low power consumption, attributes that were not harmonious with the requirements for data communications, forcing manufacturers to customize the laser for the application.

In 2005, Finisar and Philips introduced a new laser navigation system that uses the principles of intensity modulation as a result of external feedback to determine direction and velocity of movement [13]. This new navigation system has the potential to significant reduce the physical size requirements of optical navigation systems, and may be extremely useful in other handheld devices such as Personal Digital Assistants (PDAs), mobile phones, and entertainment devices. This new navigation sensor was awarded the best of Sensors+Test show in 2006 [14].

It is widely held that the VCSEL is here to stay in computer mice applications, and that the annual volume of VCSELs in this application will far outpace that of the datacom market.

3.3. VCSELs on wheels

The 2006 SPIE conference on VCSELs included several papers on the emergence of VCSELs in automotive networks such as the Media Oriented System Transport MOST™ protocol [15]. VCSELs are an attractive optical source for automotive applications because (1) ability to operate at temperatures up to and beyond 125°C, (2) high speed modulation, (3) and excellent coupling efficiency to Polymer Clad Silica (PCS) optical fiber. Actual system integration may be realized with the adoption of the advanced physical layer MOST standard now under development. Other industry groups such as the AMI in Japan are also considering the use of VCSELs in automotive infotainment networks. Significant traction for the POF system still exists because of the low cost potential, and more importantly, it is easier for technicians to service systems when there is visible light at the end of the fiber. The MOST protocol is now being deployed in the many millions per year, and volumes are projected to surpass more than 10M nodes per year [16].

Video networks that contain real time images, such as those in backup cameras and other collision avoidance systems require significantly more bandwidth to operate, and may represent a more attractive market potential for VCSELs in automobiles. These are often dedicated systems as the user can not tolerate the potential latency of running over the infotainment network. Other applications for VCSELs in automobiles may emerge in dynamic collision avoidance and other safety systems. These applications are based on LIDAR and will require the development of high power VCSEL arrays.

3.4. Can you see the light?

The continued widespread adoption of High Definition Television (HDTV) has pointed to some deficiencies in the light sources employed. Several companies are now developing VCSEL like structures that are frequency doubled in external cavities to produce visible light [17]. The color gamut achievable using lasers as the illumination source is roughly 30% larger than that of traditional sources [18]. In addition, the efficacy of the emitted light compared to other sources results in dramatically brighter displays and is likely to improve the lifetime of the optical source. One issue often raised with laser illumination is speckle caused by the coherence of the laser source. Researchers have been able to mitigate these effects by utilizing VCSEL arrays that lase at slightly different wavelengths thereby minimizing the apparent speckle. With an estimated 1 Billion television sets in the United States alone, the manufacturing of televisions is going to continue to increase over the next several years as these are replaced with high definition capable devices. Other more mundane applications have emerged where VCSELs are used in a fiber optic link from the set top box to the display, where more than 5Gbps of data are required to render a full HDTV frame.

3.5. What's that gas?

VCSELs can be made that lase in a single wavelength with polarization controlled outputs. They offer a lower cost alternative to other single mode laser sources such as Distributed Feedback (DFB) lasers. Limited tuning of the wavelength can be done with both current and temperature. As such, they are gaining interest in spectroscopic applications such as oxymetry, homeland security and atomic clocks [19]. Each of these spectroscopic applications require specific laser wavelengths (e.g 763nm, 894nm, etc). Unfortunately most gases of interest tend to have stronger absorption cross sections in the 1 to 3µm range, and few VCSEL companies are actively developing such lasers. While volumes in the gas sensing market tend to be modest (10-100k per year), the selling prices can be quite handsome [20].

4. FINAL THOUGHTS

Semiconductor lasers are found in many common consumer electronics CD players, DVD Players, pointers, printers, saws, levels, security systems, safety shields, mice, automobiles, fiber optics, and many more. A recent survey of the author's home revealed no less than 20 lasers (including several VCSELs) in various consumer appliances. That number is likely to increase as scientist and engineers continue to push optical technology to the user.

ACKNOWLEDGEMENTS

The list is too long to put into a single section, and invariably would omit many significant contributors to the success of VCSELs. Scientists, engineers, and businessmen (even venture capitalists) conspired to make the VCSEL a success in the market. Significant technical advancement, tremendous infrastructure investment and manufacturing expansion were, and continue to be, key forces working to shape the future of VCSELs in a wide variety of applications.

REFERENCES

1. J. A. Tatum and J. K. Guenter, "The VCSELs are Coming," *Vertical-Cavity Surface-Emitting LasersVII*. C. Lei and S. Kilcoyne, editors Proc. SPIE vol. 4994, pp. 1-11 , SPIE, Bellingham, WA, 2003.
2. J. K. Guenter, R. A. Hawthorne, D. N. Granville, M. K. Hibbs-Brenner and R.A. Morgan, "Reliability of Proton-Implanted VCSELs for Data Communications," *Vertical-Cavity Surface-Emitting Lasers,* Ed. By M. Fallahi and S. Wang, Proc. SPIE vol. 2683, SPIE, Bellingham, WA, 1996.
3. Gigabit Ethernet Networking, D. Cunningham and W. Lane, Macmillan Technology Publishing, Indianapolis, IN, 1999.
4. "Semiconductor Laser Market Review," Lasers and Optoelectronics Marketplace Seminar, January 27, 2003.
5. J.A. Tatum, A. Clark, J.K. Guenter, R.A. Hawthorne, and R.H. Johnson, "Commercialization of Honeywell's VCSEL technology," *Vertical-Cavity Surface-Emitting Lasers IV*, K.D. Choquette and C. Lei, editors, Proceedings of the SPIE, vol. 3946, pp. 2-13, SPIE, Bellingham, WA, 2000
6. J. K. Guenter, J.A. Tatum, A. Clark, R.S. Penner, R.H. Johnson, R.A. Hawthorne, J.R. Biard, Y. Liu., "Commercialization of Honeywell's VCSEL technology: further developments," *Vertical-Cavity Surface-Emitting Lasers V*, K.D. Choquette and C. Lei, editors, Proceedings of the SPIE Vol. 4286, pp. 1-14, SPIE, Bellingham, WA, 2001
7. R.W. Herrick, "Reliability of Fiber Optic Datacom Modules at Agilent Technologies," *Proceedings of the 52nd Electronic Components and Technology Conference*, pp. 532-539, IEEE, Piscataway, NJ, 2002
8. B.M. Hawkins, R.A. Hawthorne III, J.K. Guenter, J.A. Tatum, J.R. Biard, "Reliability of Various Size Oxide Aperture VCSELs," *Proceedings of the 52nd Electronic Components and Technology Conference*, pp. 540-550, IEEE, Piscataway, NJ, 2002
9. United States Patent and Trademark Office at www.uspto.gov
10. Scholarly search at www.google.com

11. J. A. Tatum, "VCSELs in Various Sensor Applications," Sensors Expo 2005.
12. Press release issued January 9, 2006, available at www.avagotech.com
13. R. Duijve, *et al,* "A compact laser based optical scrolling device," SID Digest, P-50.5L, 2000.
14. SENSOR innovation award 2006, SENSORS+TEST exhibition, 2006. Press release issued May 31, 2006,
15. See for example, *Vertical Cavity Surface Emitting Lasers IX*, Proc. SPIE vol. 6132, Ed. By C. Lei and K Choquette, 2006
16. Market estimations can be found at www.mostcooperation.com
17. M. Jansen, B. D. Cantos, G. P. Carey, R. Dato, R. Carico, A. M. Earman, M. J. Finander, G. Giaretta, S. Hallstein, W. R. Hitchens, J. H. Hofler, C. P. Kocot, S. Lim, A. Mooradian, G. T. Niven, Y. Okuno, F. G. Patterson, A. Tandon, A. Umbrasas, "Visible Laser Sources for Projection Displays," in *Projection Displays XII*, Ed. by M. Wu and H. Lin, Proc. SPIE 6489, 2007.
18. "Laser-Based displays will deliver superior images," by Andrew Masters, *Laser Focus World*, pp. S9-S11, November 2006.
19. D. K. Serkland, G. M. Peake, K. M. Geib, R. Lutwak, M. Garvey, M. Varghese, and M. Mescher, "VCSELs for Atomic Clocks," in *Vertical Cavity Surface Emitting Lasers IX*, Proc. SPIE vol. 6132, Ed. By C. Lei and K Choquette, 2006.
20. R. Steele, "LASER MARKETPLACE 2006: Diode doldrums," *Laser Focus World*, February, 2006.