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History of Optically Pumped Semiconductor Lasers – VECSELs

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1.1 Introduction

Optically pumped semiconductor lasers (OPSLs) are an old concept that originated in the early days of semiconductor lasers in the 1960s, and that remained a scientific curiosity until the mid-1990s, when its potential capabilities for high power with excellent beam quality were first fully demonstrated, spurring subsequent rapid development of the science and technology of these versatile lasers. Distinguishing features of OPSLs today are light emission normal to the plane of the semiconductor chip, laser cavity external to the chip to stabilize fundamental transverse laser mode and to enable insertion of intracavity functional optical elements, and the use of optical pumping for efficient and high output power operation. A wide range of applications is enabled by additional remarkable properties of this laser family, such as wavelength operation from ultraviolet (UV) to mid-infrared (IR) and even terahertz range, and passively modelocked operation with output pulses shorter than 100 fs. These lasers are also widely known by two other names, descriptive of their geometry: vertical external-cavity surface-emitting lasers (VECSELs) and semiconductor disk lasers (SDLs). Alternatively, VECSELs can also be electrically pumped, but achievable laser output powers are then typically much lower than for the optically pumped version.

OPSL development in the 1990s was spearheaded by Aram Mooradian in Micracor, a small start-up company that spun out technology from Aram's group in the MIT Lincoln Laboratory. I worked with Aram in Micracor to carry out this development. In 2011, the first annual VECSEL conference was held at SPIE Photonics West, with the VECSELs-XI conference scheduled for 2022. The first book about these lasers, *Semiconductor Disk Lasers: Physics and Technology* [1], was published in 2010; it was edited by Oleg Okhotnikov from the Tampere University of Technology in Finland and described the then state of the art in chapters contributed by researchers from around the world. Since the publication of this book, science, technology, and applications of VECSELs have made a significant step forward, and hence the present book to bring VECSELs overview up to date. This chapter

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describes the history of OPSLs, the people that took part in their development, and it's also a personal story of the OPSL development by our team at Micracor. Sadly, both Aram Mooradian and Oleg Okhotnikov, who have contributed so much to the early development of these lasers, have passed away since the publication of the first book. This historical chapter is dedicated to their memory.

1.2 OPS-VECSELs: Concept and History

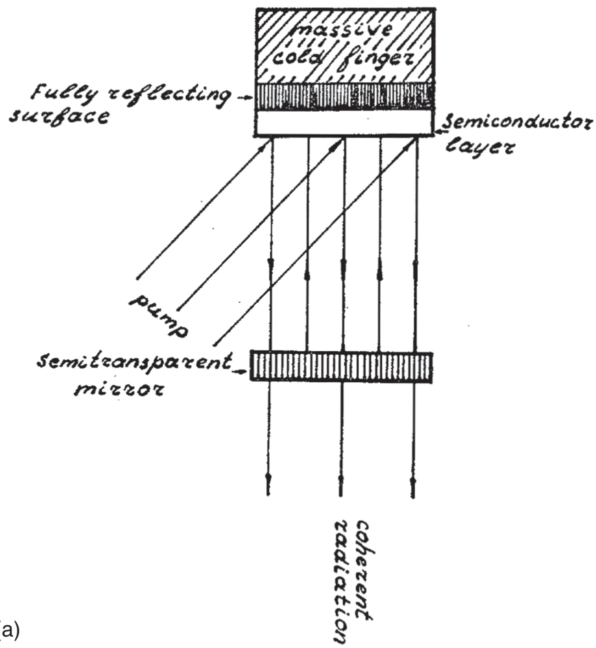
The first laser invented in 1960 was a flashlamp-pumped solid-state ruby laser. Other laser gain media and pumping schemes soon followed, and in 1962 a semiconductor diode laser pumped by current injection in a semiconductor p-n junction was demonstrated [2–6]. Semiconductors offered the possibility of operating at different wavelengths, depending on the material composition – already in 1962, together with the near-IR operation of binary GaAs lasers, ternary alloy GaAsP semiconductor diode laser in the visible was also demonstrated [5]. Electron-hole pairs for laser excitation in semiconductors can be created by various means. Current injection pumping of diode lasers, although requiring more complex device fabrication, is appealing for its simplicity of use and the possibility of direct laser output modulation by current modulation. Yet other schemes for semiconductor laser pumping were also investigated, including optical and electron beam pumping. Semiconductor diode lasers have seen tremendous development from the 1960s to the 1990s, driven primarily by applications in optical fiber communication, CD and DVD optical disk readout, and pumping of solid-state and fiber lasers and amplifiers. One challenge had remained, however. While diode lasers could produce very large, from watts to hundreds of watts, powers, this power was produced with poor beam quality: in highly transverse multimode, high aspect ratio output beams, or from large arrays of lasers. Single transverse mode output, and especially circular Gaussian output beam, could be produced at only much smaller power levels of at most a few hundred milliwatts. Optical pumping had remained an essentially experimental tool to demonstrate lasing capability of the semiconductor gain medium or laser structure, on the way to the ultimately useful diode-current-injection electrical pumping.

Why would semiconductor lasers with high multiwatt output power and beam quality be useful and important? The alternative high-power laser technologies, e.g. solid state, gas, and atomic vapor lasers, rely on discrete atomic transitions and thus are restricted to discrete unique operating wavelengths. Semiconductor lasers, via material composition and bandgap-engineered quantum-confined structures, can produce a very wide range of operating wavelengths, from UV to mid-IR, both directly and using nonlinear optical, including intracavity, conversion. This allows, by design, an essentially continuous coverage of this spectrum and even dual wavelength laser operation. High-power good beam quality semiconductor lasers can offer unique operating parameters not accessible by other types of lasers. If you add to this femtosecond pulse capability with high peak powers, potentially compact size and low fabrication cost, this makes such semiconductor lasers useful, and sometimes possibly unique, for a wide range of applications.

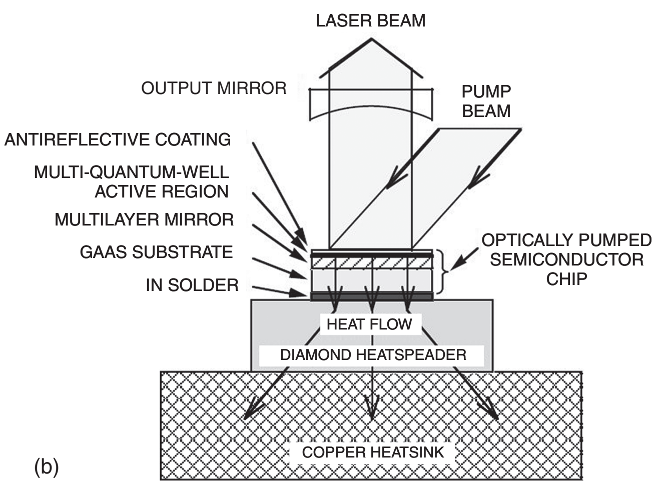
Early semiconductor lasers were edge emitting and emitted light in the plane of the wafer, so that enough gain could be accumulated over the length of the device. Such edge-emitting geometry, both gain and index guided, limits transverse profile beam quality for high powers. Vertical cavity surface-emitting lasers (VCSELs) were first described by Kenichi Iga at the Tokyo Institute of Technology in 1979 [7, 8] and further developed to efficient low threshold operation by Jack Jewell at Bell Laboratories, Holmdel, in 1989 [9–11]. VCSELs surface-emitting geometry, with light emitted normal to the plane of the wafer, because of low gain of the short gain region, requires very high reflectivity semiconductor or dielectric multilayer mirrors. Such vertical cavity geometry allows single transverse mode circular Gaussian beam output, but typically only for milliwatt level powers, limited by the difficulty of heat dissipation from the small mode area of a few microns in diameter.

Optical pumping of semiconductor lasers has a long history; it has been used for various purposes, such as characterization of novel semiconductor laser materials and structures, generation of higher output powers, or short pulse generation. As early as 1965, an OPSL has been demonstrated by Robert Phelan and Robert Rediker at MIT Lincoln Laboratory [12], where an edge-emitting InSb laser was pumped by an edge-emitting GaAs diode laser. Remarkably, both concepts, optical pumping of semiconductors and the use of diode lasers as pumps, are already in use this early in the history of lasers. In 1966, Nikolay Basov's group at the Lebedev Physical Institute in Moscow introduced the concept of a "radiating mirror" [13], Figure 1.1a: a thin semiconductor gain layer placed on top of a mirror and a heatsink, with an external output coupling mirror completing the laser cavity. Both optical and electron beam pumping were envisaged and demonstrated as the possible excitation sources. Large lateral extent of the gain medium, greater than its thickness, would ensure effective heat removal and thus the possibility of high output power. This is essentially the concept of a "disk laser" geometry, which would prove so effective many years later in both solid-state [14, 15] and semiconductor [1] laser configurations. Basov's 1966 "radiating mirror" concept, Figure 1.1a, is remarkably similar to the 1996 Micracor OPSL configuration, Figure 1.1b. In his paper, Basov reported operation of a "radiating mirror" laser with optical pumping of CdSe using two-photon absorption of a Q-switched Nd-doped glass pump laser. So as a concept, SDL had been already introduced and demonstrated in 1966; however, its full potential was yet to be explored and developed.

In the late 1960s, Nick Holonyak's group at the University of Illinois, Urbana, reported several studies of optically pumped CdS, GaAs, and GaAsP semiconductor thin platelet lasers [16], some using GaAsP diode laser pumping, and considered both edge- and surface-emitting laser geometry. Transparent sapphire heatsinking windows had been used to remove heat and help improve power performance of the devices, foreshadowing the future use of such transparent heatspreaders. Optical pumping here is mainly used to explore lasing in different semiconductor materials. In a 1973 publication from Aram Mooradian's MIT Lincoln Lab group, Stephen Chinn demonstrated pulsed operation of optically pumped edge-emitting bulk GaAs semiconductor lasers [17], with the goal of efficient high power generation. Later in 1981, Julian Stone, Jay Wiesenfeld, Andrew Dentai, and coworkers from



(a)



(b)

Figure 1.1 (a) Semiconductor laser with radiating mirrors. *Source*: Reprinted, with permission, from Basov et al. [13], © 1966 IEEE. (b) Optically pumped semiconductor vertical external-cavity surface-emitting laser (OPS-VECSEL), Micracor, 1996.

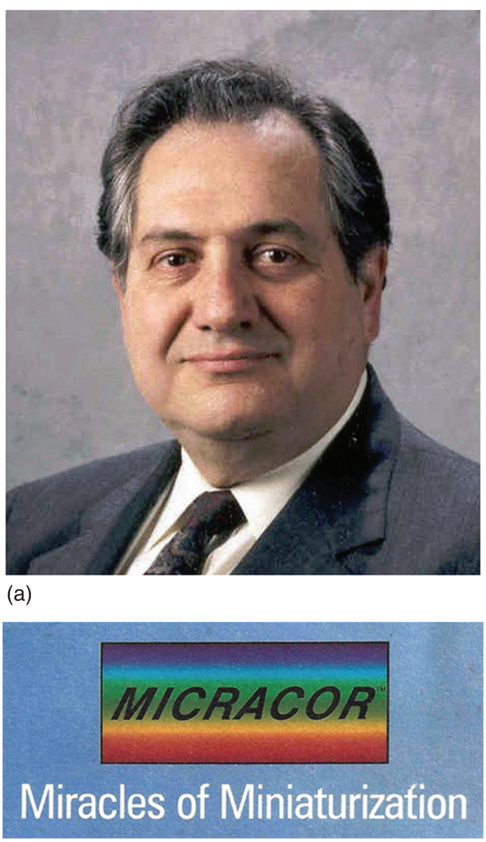
the Bell Laboratories Crawford Hill Lab, used surface-emitting thin-film ultrashort cavity InGaAsP lasers [18] to generate gain-switched picosecond pulses in the 0.83–1.59 mm wavelength range using dye laser pumping. Wavelength versatility of semiconductor materials is explored here, with short pulse generation as the primary goal. Using an external optical cavity for pulse repetition rate and transverse mode control, optically pumped mode locking was demonstrated with a CdS thin platelet laser by Charles Roxlo and Michael Salour at MIT in 1981 [19]. In 1991, Mooradian's group observed high peak power in an external-cavity GaAs platelet laser pumped by a Ti:sapphire laser [20]. Note that the above OPSLs largely used bulk semiconductor material without internal heterostructures. As a result, the performance of these lasers was limited.

When semiconductor heterostructures and quantum wells had been developed, they also had been used for OPSL experiments, e.g. in Holonyak's group [21]. When the first efficient VCSEL semiconductor lasers were demonstrated by Jack Jewell in 1989, early experiments used optical pumping of bulk GaAs [9] and later InGaAs and GaAs quantum well laser structures [10, 11]. On-wafer high reflectivity semiconductor multilayer distributed Bragg reflector (DBR) mirrors were used for these vertical cavity lasers. At this point, the full power of the semiconductor bandstructure engineering was beginning to be applied to OPSLs. But again, optical pumping was used only as an initial characterization of laser structures on the way to eventual diode current-injection pumping [11].

In the 1990s, a series of papers explored optical pumping of semiconductor lasers with the goal of obtaining high power with good beam quality, as well as short pulse generation. A wide variety of laser configurations were explored, both edge and surface emitting, with a range of pump laser options: diode, solid-state, and gas lasers. Using diode laser pumping, low-power 10 mW continuous wave (CW) operation was demonstrated with GaAs VCSEL by Steve Brueck's group at the University of New Mexico [22]; in external cavity, however, such lasers emitted only 20 μW [23, 24]. External resonator was also used with an electrically pumped VCSEL by a group from the University of California, Berkeley, in an attempt to increase its single-transverse-mode output power; however, only 2.4 mW was achieved in CW operation [25]. A diode-laser-pumped surface-emitting optical amplifier was demonstrated at 1.5 μm using InGaAs–InGaAlAs multi-quantum-well structures by Shojiro Kawakami's group at Tohoku University [26]. Using 77 K low temperature operation and a Nd:YAG pump laser, 190 mW continuous output power was obtained from an external-cavity InGaAs–InP surface-emitting laser by Wenbin Jiang in the Yoshihisa Yamamoto's group at the NTT Basic Research Laboratories [27]. The same group used a similar configuration to demonstrate an external-cavity GaAs VCSEL at 77 K with CW output power of 700 mW using a 1.8 W krypton–ion pump laser [28]. Modelocked femtosecond pulse operation was demonstrated with a periodic gain vertical cavity laser in an external cavity by Wenbin Jiang in the John Bowers group at the University of California, Santa Barbara [29]; with synchronous pumping by a modelocked Ti:sapphire laser, 6 mW average output power was obtained. Specially designed edge-emitting InGaAs–GaAs laser structures were used with diode laser pumping to generate as much as 4 W average power by Han Le at MIT Lincoln Laboratory [30, 31]; however, the beams were strongly elongated with aspect ratios between 10 and 50 to 1. To summarize the state of the art by the mid-1990s, semiconductor lasers could emit watt-class power only with poor beam quality from edge-emitting structures; vertical cavity lasers operated with good beams but only with milliwatt class output, external-cavity operation of surface-emitting lasers hadn't produced particularly high powers, and optical pumping remained just a tool for scientific exploration of novel laser configurations.

1.3 Micracor

Micracor (1992–1997) was a small company started by Aram Mooradian, see Figure 1.2, in Acton, a suburb of Boston, to commercialize several technologies from the Quantum Electronics Group at MIT Lincoln Laboratory, where Aram was the group leader for more than 20 years. Micracor's core technologies and nascent products were diode-pumped solid-state microchip lasers, work led by Kevin Wall, and tunable external cavity diode lasers, work led by Ken German. OPSLs were a concept explored previously in Aram's group at MIT Lincoln Lab. Micracor made a quixotic attempt to take this, at the time vague, concept, demonstrate it, and develop and commercialize such devices. The key initial target application was 980 nm pumping of Er-doped fiber amplifiers. Micracor's core technologies weren't very successful commercially, while OPSL development after three and a half years showed tremendous promise. But investors eventually lost patience, and



(b)

Figure 1.2 Aram Mooradian and the Micracor logo.

at the end of 1996 the company was shut down. Luis Spinelli from Coherent Inc. recognized the potential of OPSL technology and drove the purchase of Micracor's assets by Coherent. At this point our group at Micracor published two papers on OPS-VECSELs [32, 33], where the term VECSEL was first introduced. The results of Micracor's more than three-year effort on OPSLs were finally made public. These publications triggered subsequent development and exploration of VECSELs by the scientific community around the world. VECSEL technology was successfully commercialized by Coherent for applications as diverse as entertainment, forensics, life sciences, and medical. If it weren't for OPSLs, Micracor would be forgotten today. A recent Google search on Micracor yielded a puzzled response – "Did you mean: microcar?"

How did I come to Micracor and what was my role there in the development of OPSLs? After Micracor was founded, in 1993 Aram got a Small Business Innovation Research (SBIR) grant from the US Department of Defense to develop high-power OPSLs. However, there was nobody at the company who could actually carry out this work. Phase I money was being spent, but no progress was made. I was hired in August of 1993 to carry the development of what would become OPSLs. Micracor was funded by Rothschild Ventures, and I remember visiting their offices in New York, with Rothschild family portraits on the walls. I came to Micracor after graduate school at MIT with Hermann Haus and Erich Ippen and seven years at Crawford Hill Lab of Bell Laboratories in the department of Ivan Kaminow. Looking back, I was well prepared and had the right background and experience to embark on the risky and challenging development of OPSLs. At Bell Labs, I had worked on electronically tunable quantum well diode lasers, I had both theoretical and experimental experience with semiconductor lasers, and my work has involved extensive modeling and design of edge-emitting semiconductor laser structures, semiconductor device processing, laser fabrication and characterization, as well as device performance analysis. I had also been exposed to earlier work on OPSLs: at MIT, Michael Salour's lab was next door and I had attended multiple talks from the group; at Bell Labs, Julian Stone, Jay Wiesenfeld, and Jack Jewell were colleagues whose work I closely followed. Micracor was a small company of about 20 people working on a variety of projects; to develop OPSLs, I had to rely on myself to get the job done – no grand team to attack the problem; we had limited resources, equipment, and money. Compare this to Novalux, founded by Aram Mooradian several years after closing of Micracor, where $193 million (!) was spent developing electrically pumped VECSELs. Several people at Micracor played crucial roles in the OPSL development: Bob Sutherland (thin semiconductor wafer polishing), Bob Sprague (AR coatings), and Farhad Hakimi (pushing powers higher at the later stages of development). Aram Mooradian was the visionary who initiated the program, guided the program along, and with whom we discussed all aspects and nuances of the work to overcome a continuous string of challenges. Aram had the physical intuition to see OPS laser operation, even when he couldn't tell exactly how to get there. I felt we were "father and mother" team with Aram, nursing and raising our "baby" OPSLs.

Why do I think we succeeded at Micracor? Various groups had worked on OPSLs for several decades, but a common thread was that when they got results good enough for a publication, they were satisfied and stopped at the publication. We were a small company and had to push OPS concept to the commercial performance level to get funding for our work and for the company, both from government program sponsors and from investors. We were fighting for survival as a company, and just a publication was not good enough. And we had persevered, overcoming challenge, after challenge, after challenge, finding a path forward at every step. First, we got some initial miniscule amount of light from the laser. At that point, we had something to work with, and we just kept optimizing and improving, and we never stopped, until the company went out of business. In this process, physical understanding was critical, and fabrication ability was critical. Our work went through multiple iteration cycles: physical modeling and design – device fabrication – characterization of the materials and devices – analysis of the device characteristics – and then finding ways to improve in the next iteration cycle.

Another reason we succeeded at Micracor is the tremendous progress that had been made in the semiconductor technology in the preceding years and that was now available to us. Semiconductor lasers had progressed from simple edge-emitting homojunction GaAs devices grown by liquid-phase epitaxy (LPE) in the 1960s, to the MBE (molecular-beam epitaxy) and MOCVD/MOVPE (metal-organic chemical vapor deposition/vapor-phase epitaxy) grown semiconductor structures with bandgap engineering to manipulate their electronic and optical properties, to strain-engineered and strain-compensated quantum-confined structures, to vertical cavity laser structures with grown multilayer semiconductor DBR mirrors. Such semiconductor materials and structures were now also understood well enough to be grown commercially in companies such as Epitaxial Products International (EPI) PLC (now IQE PLC). These developments enabled diode VCSELs in the late 1980s; we applied these technologies to the optically pumped vertical external-cavity configuration in the early 1990s. Another key enabler was the availability of new multiwatt multitransverse-mode semiconductor diode pump lasers. Such pump lasers had been developed in the 1980s for pumping solid-state lasers, e.g. 808 nm pumps for Nd:YAG lasers.

What were the resources and facilities available to us at Micracor? We had an electron beam evaporator for optical dielectric coatings and a thermal evaporator for chip metallization; we had a polishing facility for thinning the wafers; we also had a spectrophotometer for optical characterization of wafers and coatings. However, we did not have an optical spectrum analyzer (OSA) – commercial OSA was just too expensive. So I made a homemade OSA, converting a grating monochromator to a rudimentary calibrated OSA by rigging a fiber input and a detector output to the input and output slits, driving the grating stepper motor from a computer D/A output and reading the detector output into computer A/D. I periodically calibrated this OSA using a He-Ne laser. To my surprise, coming from Bell Labs, I found that it is possible to do interesting science in a small company environment and with limited resources, of course given the right circumstances.

1.4 OPSL Development at Micracor: First Steps

In August of 1993 when I came to Micracor, it had an SBIR program running, Phase I, on the topic of "High Power Multi-Segmented Semiconductor Lasers." Figure 1.3 shows the device that was promised ultimately to the sponsors, a high-power multiple-bounce optically pumped surface-emitting semiconductor laser. The project was funded by the Department of Defense, U.S. Army Space and Strategic Defense Command, colloquially known then as the "Star Wars" initiative. With not much to show for the program accomplishments at this point, I had two months to finish the project, write the final report, and convince program managers to give us more money for Phase II of the project.

I wrote and submitted the final report for Phase I at the end of September 1993: we had seen no laser light but had done enough experiments to project high hopes for the future; now we just had to sell these hopes to the program managers. We had two semiconductor samples, epigrown DBR stack plus quantum-well gain region on top, to work with, grown and available through Aram's numerous connections: an 850 nm AlGaAs/GaAs wafer from Art D'Asaro at Bell Labs and a 900 nm InGaAs/GaAs wafer grown by Stephen Hersee at the University of New Mexico. Both wafers had major design shortcomings. What had been accomplished in Phase I? I had learned to align pump optics and laser cavity using Si cameras, I imaged and characterized pump and sample spontaneous emission beams, I had demonstrated 1.2 W pump power into ~100 μm diameter spot from a 785 nm 3 W/500 μm-wide stripe diode laser, and I observed strong amplified spontaneous emission (ASE) at 900 nm into the laser mode – but no lasing. I had sketched out a basic OPS laser model, e.g. see Figure 1.4, and determined a set of parameters to make a "single-bounce" OPS surface-emitting laser. Proposed designs had a semiconductor wafer structure with a DBR mirror and a gain region with ~10

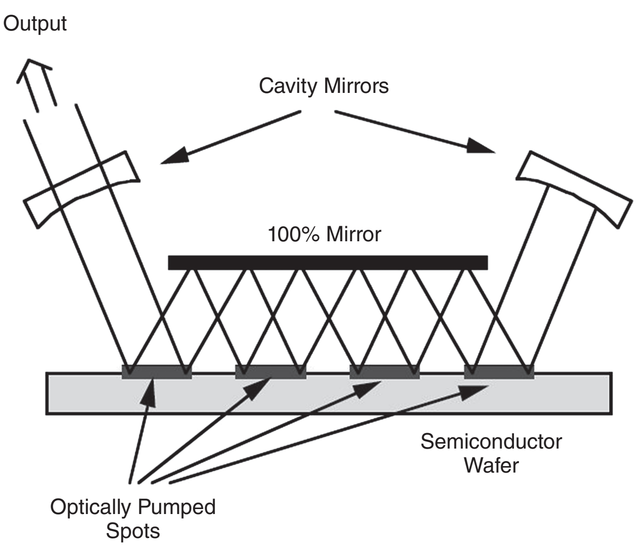


Figure 1.3 Multi-bounce OPS laser Micracor promised in 1993 to make ultimately in its SBIR program "High Power Multi-Segmented Semiconductor Lasers."

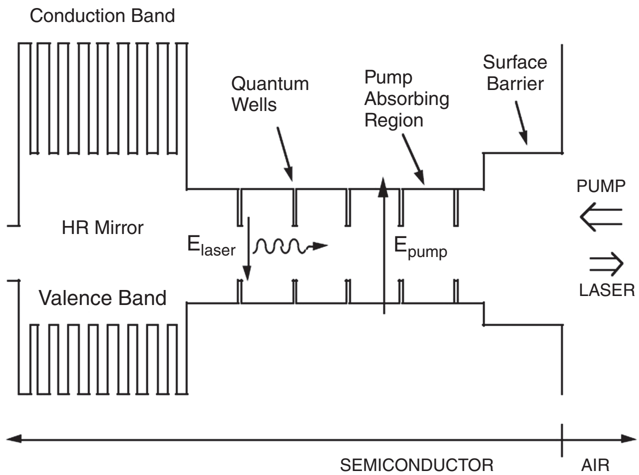


Figure 1.4 Band diagram of the proposed optically pumped surface-emitting semiconductor laser structure in the September 1993 final report for SBIR Phase I. Quantum wells are placed in a resonant periodic gain structure [34].

quantum wells in a resonant periodic gain structure [34], with two specific wafer designs proposed, an external spherical mirror with ~100 mm radius of curvature and a reflectivity $R > 97\%$, and a stable fundamental transverse mode laser cavity with ~1 W threshold pump power for a 100 μm diameter mode. And I had a basic pump optics design with cylindrical lenses. Based on all this, while lacking an actual laser demonstration, we had claimed in the Phase I final report that we had demonstrated the "feasibility" of our optically pumped semiconductor OPS laser approach.

By the time I wrote Phase II SBIR project proposal in April 1994, we had a first major milestone accomplishment – we had seen first laser light at 900 nm with antireflection (AR) coated samples. Only a tiny amount of pulsed light was observed, but we already had something to work with. I wrote a very optimistic proposal, trying to overcome rudimentary results of the first phase, and I described in detail our approach to getting high power operation. Figure 1.5 shows our proposed initial single-bounce OPS laser configuration. We got funding for Phase II.

When we started Phase II of the project in June 1994, we were already characterizing low power pulsed laser light. Our 900 nm InGaAs/GaAs samples had four quantum wells; the chips were AR coated, thinned to 100 μm, metallized, and soldered onto Cu heatsink. With $R > 99\%$ output mirror, and the laser driven with 100 μs pump pulses at 1 kHz, we saw very low power laser light but with an excellent beam profile, see Figure 1.6; chip heating turned the laser off for longer pulses. Thermal impedance of the chip was high; thermal path from active region to heatsink included DBR region and a 100 μm thick residual substrate. But the important thing was that we already had some light to work with, and we started to characterize and optimize our laser.

With money now available to continue the project, in the summer of 1994 we started by designing and growing a new optimized wafer structure based on our

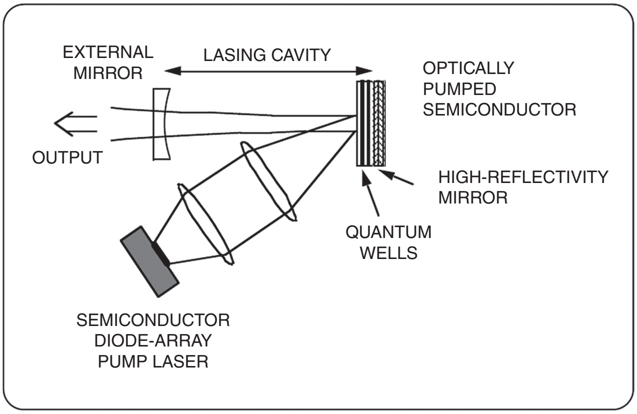
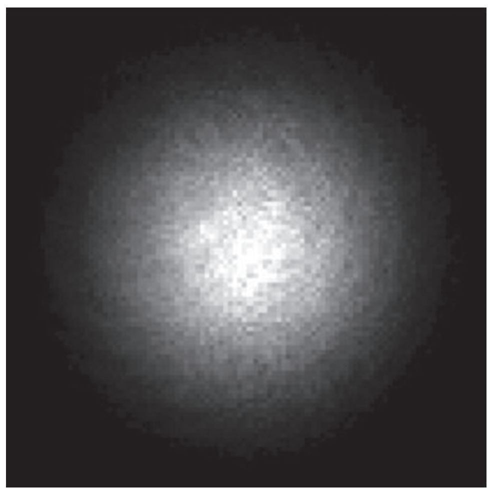


Figure 1.5 Single-bounce OPS laser configuration in the April 1994 SBIR Phase II proposal.

Figure 1.6 Excellent beam profile of the pulsed optically pumped 900 nm InGaAs/GaAs laser, June 1994.



prior analysis and experiments. We targeted operating wavelength of 980 nm for application to pumping Er-doped fiber amplifiers; wafer structures included 10 strained quantum wells in the mature InGaAs/GaAs material system. The structures were designed to be pumped at 808 nm and even included pump-reflecting mirror in the DBR for more efficient double pass pump absorption. The wafers were grown successfully by MOVPE at EPI PLC in Cardiff, United Kingdom. These were fairly complex designs with many DBR and quantum well semiconductor layers; it's impressive that a commercial company at the time could already grow successfully such sophisticated structures. By then, we had developed techniques to characterize the grown OPS wafers with spectrophotometer wafer reflectance spectra, as well as surface and edge photoluminescence; laser power and spectral behavior were also extensively characterized, as well as their temperature dependence. We continued detailed modeling to explain the observed wafer and laser characteristics, both optical and thermal, and had designed several different pump

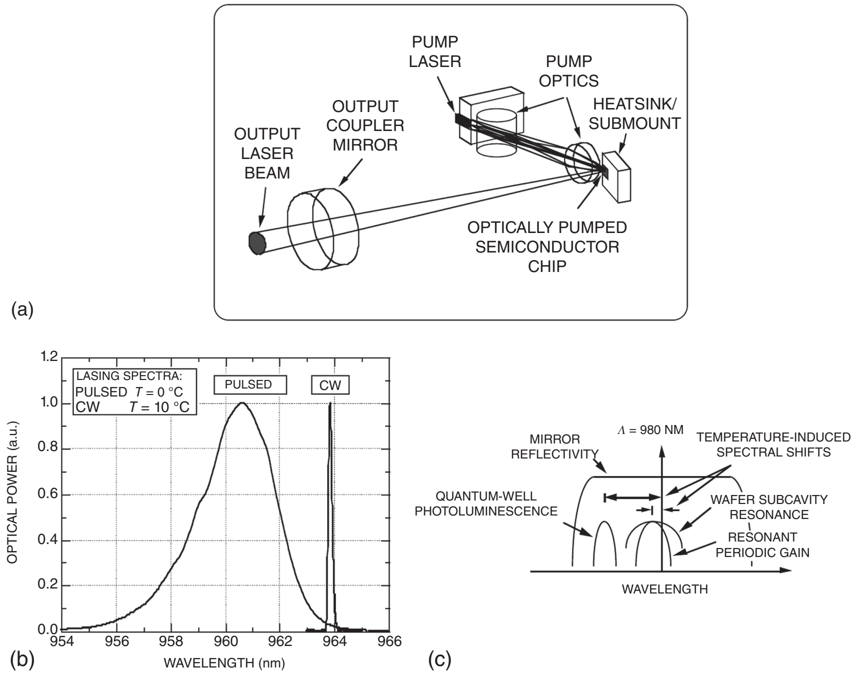


Figure 1.7 Two figures from the Micracor second quarterly report to the sponsor, January 1995: (a) laser and pump configuration, (b) pulsed and CW laser spectra. (c) Figure from the Phase II final report, July 1996: thermal offset design for OPS vertical cavity laser.

optics configurations. In our first Phase II quarterly report in September 1994, we described our accomplishments: the new wafers lased only in the pulsed mode; using $R = 97\%$ output reflecting mirror, threshold was ~400 mW and maximum pulsed output power was only 30 mW, limited by heating.

So a year after the program started, we had learned a lot, but got only 30 mW pulsed – pretty far away from the promised watts of CW power. This was time to get philosophical in the face of challenges, to collect thoughts and to see how to proceed forward. At the time, I was reminded of the quote from Harold Edgerton, MIT professor of the flash photography fame, "We worked and worked, but didn't get anywhere. That's how you know you're doing research." Well, we definitely were doing research. I was also thinking of my work then as a friendly wrestling match with Nature; Nature is a tough opponent, but she is not malicious. I was learning to speak the language of Nature, learning to listen carefully and understand what she says, and trying to speak back to her in her own language; and if I were successful, she would listen and understand me, and do what I asked.

1.5 OPS Development at Micracor: Pushing Forward

In the next quarter we pushed forward, and here are the important advances from the second quarterly report in January of 1995, see Figure 1.7. Laser chips were

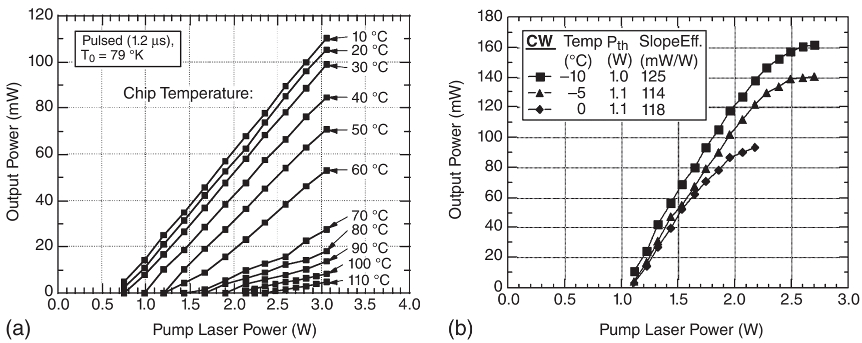


Figure 1.8 (a) Pulsed laser power up to 110 °C with weak temperature dependence, third quarterly report, March 1995. (b) 160 mW CW output power, program extension proposal, May 1995.

thinned to 20–30 μm, to reduce thermal impedance between the quantum well active layer and heatsink, and soldered to Cu submounts – we got 130 mW pulsed output power and, crossing an important barrier, we had ~1 mW CW! (at 0 °C). We had concluded that thermal effects limited our CW output power, and we focused on several approaches to improve further laser power performance. (i) We lowered thermal impedance of on-chip mirror and substrate in order to decrease detrimental temperature rise of the active region. (ii) We made laser threshold less sensitive to temperature. To this end, we improved quantum well design with stronger carrier confinement to prevent carrier escape from the wells at higher temperatures. And finally, (iii) we placed the lasing mode resonance on the long wavelength side of the material gain peak at room temperature. This would compensate the larger temperature shift of the gain spectrum compared to the smaller temperature shift of the resonant wavelength and would align material gain spectral peak and lasing mode wavelength at the increased operating temperature of the laser active region. The key to laser power performance was addressing these thermal issues.

Our understanding and improvement steps proved to be correct. By the time I wrote our Phase II third quarterly report in March of 1995, we had made significant progress. Our second iteration redesigned 980 nm wafer structure was grown – the measured thermal impedance improved by a factor of two to 45 °C/W, in part due to elimination of the pump-reflecting mirror; improved quantum well (QW) carrier confinement resulted in weaker dependence of threshold power on temperature, see Figure 1.8a; CW lasing was now observed at up to 30 °C; and we measured 57 mW CW output power at −5 °C. By May 1995 we had improved performance even further – the chip was now only 17 μm thick and soldered onto diamond heatspreader, which was in turn soldered to a Cu heatsink; CW output power was now 160 mW! See Figure 1.8b. And, based on these results, we got infusion of additional money from the sponsor in the program extension. We could keep going with OPS laser development.

In August of 1995, I had a chance for the first time to attend the Topical Meeting on Semiconductor Lasers in Keystone, Colorado – attending conferences was a luxury not always available in a small company. There I discovered that we had competition – in a poster session, John Sandusky described their work with Steve Brueck at the University of New Mexico on “A CW external-cavity surface-emitting laser” [23]. Their configuration was generically similar to ours, and they reported 20 μW of CW output power using a ring dye laser pump. This was frustrating – at the time we were already measuring 200 mW CW and with a diode laser pump, four orders of magnitude higher power, but we couldn’t report anything at the conference, our work was commercial and proprietary, not for publication. So all I could do is talk to the presenter and comment on their nice work. We did apply for several patents on Micracor work. Once I even had to travel to Washington DC to argue for one of our patent applications in front of a patent examiner – I argued successfully against the objections, and we got that patent. I remember the patent office building, with stacks full of paper copies of old patents, famous patents on display; paper was king then.

As we were increasing OPS output powers, we had discovered serious laser power degradation over time and had found the culprit – under pump illumination, dark line defects were growing in our chips, caused by crystal dislocations due to excessive accumulated strain –thickness product of our multiple-quantum-well (MQW) structures, see Figure 1.9. Moving to a new spot on the chip restored the power, but then it would degrade slowly again. While a single quantum well in our structure was within the strain-thickness stability limits of Matthews and Blakeslee [35], multiple quantum wells violated that limit. In an attempt to address this, by September 1995 in our third iteration wafer design we had reduced the cumulative strain-thickness product and had hoped that large 100 nm separation between wells would also help. We got higher CW output powers – now 200 mW in Transverse Electro-Magnetic (TEM) TEM01 and 140 mW in TEM00 Gaussian beam modes using a 1.2 W fiber-coupled diode laser pump, Figure 1.10. But power degradation and dark line defects were still present.

At this point we were at the threshold of commercially relevant output powers. Aram was already dreaming of optical frequency doubling into the visible. The initial promising application was pumping of Er-doped fiber amplifiers, which required several hundred milliwatts at 980 nm in a single mode fiber. We had contacted several potential customers to inquire how much power was desired. A memorable answer came from Bell Labs: “Too much power is almost enough!” How true. But we still needed to solve the dark line power degradation problem – our devices were useless, if all that power decayed on the scale of hours. We were yet again facing a critical challenge – a fundamental semiconductor materials problem: crystal layer strain in our structures was too high, and attempts to reduce it did not help.

1.6 OPS Development at Micracor: Final Chapter

Reviewing the literature, I had found that strain compensation should solve our problem: thin tensile strain-compensating GaAsP layers to balance the compressively strained InGaAs quantum wells on GaAs. Strain compensation was a

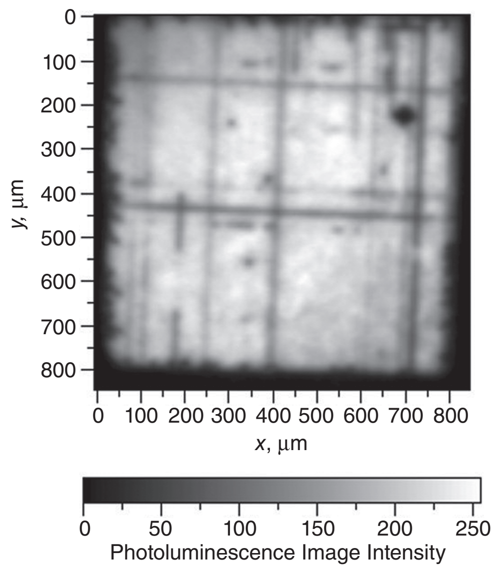


Figure 1.9 Photoluminescence image of the strained multi-quantum-well InGaAs/GaAs OPS chip, 808 nm pump, 980 nm photoluminescence. Dark line defects in the image and a dark spot at the lasing location, caused by dislocation defect lines in the crystal due to excessive crystal strain. Third iteration wafer design, Micracor fifth quarterly report, February 1996.

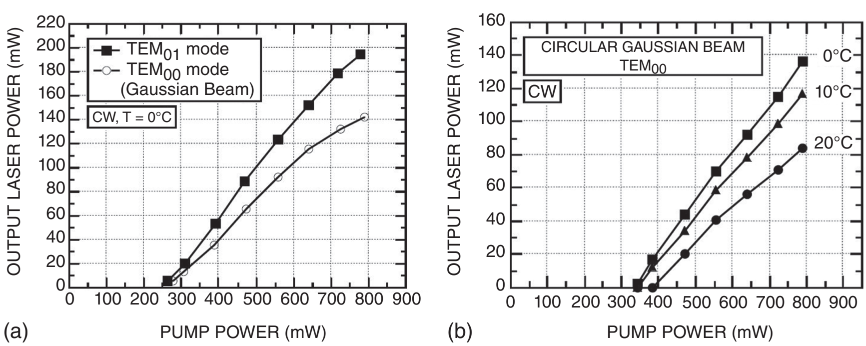


Figure 1.10 (a) OPS CW output power in TEM01 and TEM00 (Gaussian beam) modes, and (b) temperature dependence of TEM00 mode, second iteration wafer design, Micracor fourth quarterly report, September 1995.

relatively new technique at the time, and we hoped that EPI could grow such structures. I had designed the required structure and even calculated its theoretical crystal X-ray diffraction pattern, so that the grower could measure and verify strain balancing. I also calculated tolerance limits of strain compensation, to make sure composition and thickness errors during growth won't destroy crystal strain structural stability. And I verified band edge alignment of the strain-compensating layers in our structure to make sure pump-generated carriers are not blocked on their way to the quantum wells. EPI had accepted the wafer growth order and was learning to do strain compensation.

While EPI was growing our fourth-generation wafer design, now incorporating strain-compensated semiconductor multi-quantum-well structure, I had further

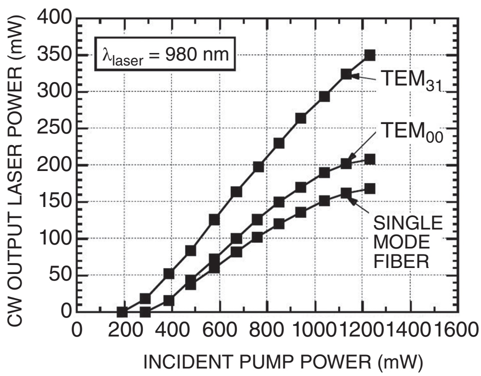


Figure 1.11 OPS CW output power in TEM31, TEM00 (Gaussian beam) modes, and power coupled into single mode fiber, third iteration wafer design, Micracor fifth quarterly report, February 1996.

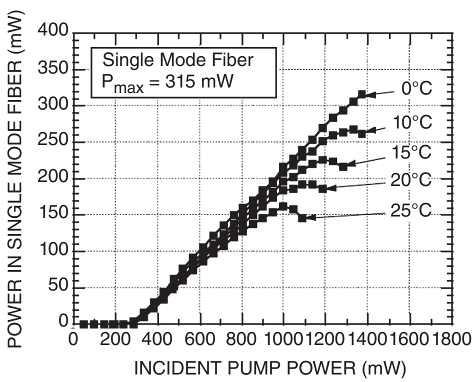


Figure 1.12 OPS power coupled into single mode fiber, fourth generation wafer design, with strain compensation, Phase II Final Report, July 1996. OPS output power now did not degrade with time, wafer was free of photoluminescence dark line defects.

improved our OPS laser performance. I learned how to better thin our chips, experimented with Au/Sn, and thin evaporated indium solders, diamond heatspreaders, etc. By our fifth quarterly report in February 1996, Figure 1.11, using our third iteration wafer design, we had already achieved 350 mW output power, albeit in a higher order transverse mode; fundamental Gaussian beam output was 200 mW; and 160 mW was coupled into single mode fiber.

Wafer growth at EPI was a success, and fourth iteration design with strain compensation worked well – there were no dark lines, and output optical power was not decaying! And we also improved laser performance. In the Phase II program Final Report in July of 1996, OPS power was now 500 mW in TEM01 mode, 425 mW in TEM00 mode, and 315 mW coupled into single mode fiber, see Figure 1.12. At the time, state-of-the-art high power edge-emitting lasers had only ~200 mW in single mode fiber. We started to look into ways of packaging our OPS lasers. We also thought of making our laser tunable and explored using an external mirror on an electrostatically deflectable membrane. The process of device characterization and performance optimization and improvement continued.

In April of 1996 we applied for, and later received, a Small Business Technology Transfer (STTR) program from the Defense Advanced Research Projects Agency (DARPA) of the US Department of Defense to work together with Sandia National Laboratory on the topic of "High-Power Optically-Pumped Vertical Cavity

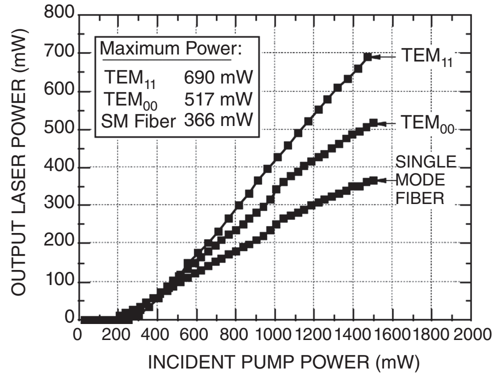


Figure 1.13 OPS power in TEM11 mode, TEM00 fundamental circular Gaussian mode, and coupled into single mode fiber, fifth generation design with inverted wafer structure, DARPA Final Report, December 1996. Output power here is pump power limited.

Semiconductor Lasers with Diffraction-Limited Beams." By then we knew and had announced to the potential sponsor that Micracor had demonstrated a new watt-class high-power optically pumped semiconductor OPS laser technology; and we wanted to push OPS powers even higher to 1 W and beyond. Chip thermal impedance still limited our performance, but we couldn't thin substrate between the DBR and heatspreader any further by polishing. So we applied the "flip-chip" approach to get active region closer to the heatsink. We designed an inverted wafer structure, where the MQW active region was grown on the substrate first, with the DBR region grown on top of it. We then flipped the chip and soldered the DBR mirror directly onto the diamond heatspreader. The substrate, which was now on top of the active region, was then selectively etched away. We had several inverted wafer designs grown at EPI and also by Hong Hou at Sandia Lab. Using this flip-chip approach, we got our OPS thermal impedance down to ~20°K/W, a factor of 2–3 lower than for the non-inverted structure. Laser performance had indeed improved. In our final report to DARPA in December of 1996, OPS laser power was 0.69 W in TEM11 mode, 0.51 W in a fundamental Gaussian TEM00 mode, and 0.36 W coupled into single mode fiber, see Figure 1.13. Output powers for the inverted OPS laser structure were now pump power limited, unlike our earlier lasers, where output power was thermally limited and was saturating and rolling off at the higher pump powers. If we had a more powerful pump, or added a second pump to the laser, laser output power would have been even higher. Indeed, several years later in 2003 a group from Osram Opto Semiconductors used this wafer design, with higher power pump, to demonstrate an OPS laser with 8 W output [36].

So almost three and a half years after the start of the OPS program, we had demonstrated at Micracor the powerful capabilities of the OPS laser approach: watt-class output powers in a circular Gaussian beam, with stable and reliable wafer structure, and multi-transverse-mode diode laser pumps. A path was now open to future developments: yet higher output powers, intracavity optical frequency doubling and visible light generation, modelocking for short pulse generation, new semiconductor materials and new wavelengths, and other yet unknown possibilities. Figure 1.14 shows evolution of Micracor OPS laser power over time: it took us a year to get some pulsed light out of the structures, but after that, continuous improvements in wafer design and chip processing drove the power relentlessly up from the milliwatt scale of the VCSELs to the watt scale of the OPS VECSELs. One thing this chart does not reflect is all the challenges and frustrations that had to be overcome along the way.

But at this point Micracor reached its finale. At the end of 1996 Micracor ran out of money, and investors closed the company. Largely due to the foresight of Luis Spinelli from Coherent Inc., who visited Micracor and realized the potential of OPS technology, Coherent bought the assets of what remained of Micracor, which related to materials and intellectual property of solid-state microchip and OPS lasers. I transferred the OPS laser technology to Coherent and helped to set it up there; Juan Chilla took over the OPS project at Coherent. I was anxious to publish at least some portion of our work, the results of more than three years of our labor. Fortunately, Coherent agreed, we got permission to publish, and in March of 1997 I submitted a short paper on OPS-VECSELs to *IEEE Photonics Technology Letters* (PTL) [32]. At Micracor, from the very beginning we called our technology "OPS lasers," but for the paper Aram came up with the term VECSEL, vertical *external*-cavity surface-emitting laser, to distinguish more clearly the external cavity of our approach from the conventional monolithic short-cavity VCSEL. At this time, the term OPS-VECSEL was born. More than a year later, in November of 1998, when I was already working at MIT Lincoln Laboratory, I wrote a longer and more detailed paper on OPS-VECSELs and our work at Micracor and submitted it to *IEEE Journal of Selected Topics in Quantum Electronics* (JSTQE) [33].

1.7 VECSELs beyond Micracor

I was excited by the results of our work and their publication, but I did not foresee the impact this had on the laser field and the subsequent broad development of VECSEL science and technology in academia and in the commercial world. Following publication of the Micracor OPS papers, after a brief period, VECSEL-related papers started coming out; and I got to review many of them. In 1998 Aram Mooradian started a new company in California, Novalux, to develop electrically pumped VECSELs. Soon, Novalux Extended-Cavity Surface-Emitting Laser (NECSEL) was demonstrated, first in the IR, and then in 2001 Victor Lazarev demonstrated

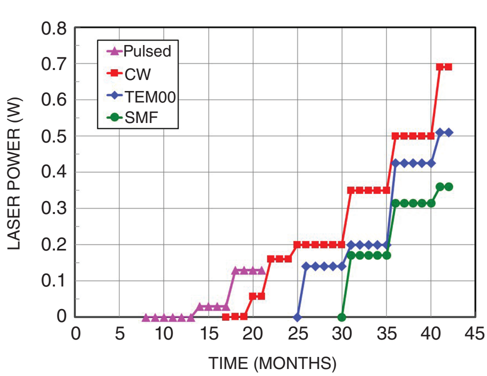


Figure 1.14 Evolution of Micracor OPS laser power over time since the start of the program in August 1993.

intracavity frequency doubling of NECSELs into the blue. Coherent Inc. released commercial products based on OPSL technology, first in the IR (at Optical Fiber Communication (OFC) conference 1999) and later in the visible (Sapphire^{TM} blue laser, 2001). It's interesting that OPS-VECSEL, and NECSEL for that matter, were first developed with 980 nm pumping of Er-fiber amplifiers in mind, and that's one application that never took, either for optically or electrically pumped version. In 1999, Sandia reported OPS-VECSEL intracavity doubled into the blue [37]. In 2000, the first SESAM, semiconductor saturable absorber mirror, passively modelocked picosecond OPS-VECSEL was reported in a joint work between Ann Tropper's group in the University of Southampton in the UK and Ursula Keller's group in the Swiss Federal Institute of Technology ETH in Zurich [38]. Later, VECSEL pulses entered high power femtosecond regime [39] at GHz repetition rates, with promising applications to multiphoton imaging demonstrated by the Ursula Keller's group [40]. The same group developed modelocked integrated external-cavity surface-emitting lasers (MIXSELs), where the gain region and saturable absorber are integrated on a common substrate, with promising applications such as dual-comb spectroscopy [41]. In the following years, CW VECSELs have been demonstrated in a variety of materials and wavelengths, from UV to near-IR, mid-IR, and terahertz (THz) range [1]. Alexei Sirbu and Eli Kapon at École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland, together with the Oleg Okhotnikov group at Tampere University, Finland, demonstrated wafer-fused VECSELs at 1.3 and 1.5 µm [42]. Mid-IR VECSELs were demonstrated by the Hans Zogg group in ETH Zurich [43]. Many originally unexpected applications and features of VECSELs were also demonstrated. Highly sensitive spectroscopic applications of VECSELs, intracavity laser absorption spectroscopy (ICLAS) [44] and cavity ringdown spectroscopy (CRDS) [45], took OPS ideas in new directions, as demonstrated by a collaboration of researchers from several French universities, including Alain Campargue at Université Grenoble and Arnaud Garnache at Université Montpellier. Arnaud Garnache and his group demonstrated a number of VECSEL properties and novel applications, such as spatial vortex beam generation [46]. VECSELs were found to operate in the low noise class-A laser regime and found applications for radio frequency (RF) optical analog links by a group from several French institutions [47]. David Wineland's group at the National Institute of Standards and Technology (NIST) in Boulder, Colorado, in collaboration with Mircea Guina's group from Tampere University in Finland, utilized wavelength versatility, narrow linewidth, power scaling, and intensity stability of VECSELs to demonstrate applications in atomic physics for cooling and trapping of atoms [48] with potential future applications in quantum computing. High power yellow VECSELs in Mircea Guina's group found application for sodium laser guide stars [49]. Jacob Khurgin from the Johns Hopkins University [50] and Mansoor Sheik-Bahae from the University of New Mexico [51] in the US have described the use of VECSELs for optical refrigeration - laser cooling of solids. Benjamin Williams from the University of California Los Angeles has developed terahertz quantum-cascade metasurface-based watt-level and tunable VECSELs [52]. Along the way, the term semiconductor disk laser (SDL) was introduced, by analogy with the similar solid-state disk lasers [14, 15]. *Semiconductor*

Disk Lasers book was published by Oleg Okhotnikov in 2010 [1], and 10 annual conferences focused on VECSELs have been held at SPIE Photonics West in San Francisco. Many researchers, research groups, and commercial companies around the world have contributed to the advancement of VECSELs over the years and have made VECSELs what they are today; they are too numerous for all to be listed here.

From the initial concepts of Nikolay Basov in 1966, and after three decades of advances by many groups working on OPSLs, in 1997 Micracor used modern bandgap-engineered semiconductor structures to demonstrate OPS-VECSELs with watt-class output powers and excellent circular Gaussian beams. By demonstrating feasibility, power, and implementation details of the OPS approach, Micracor work opened the gates for the rapid and broad development of this class of lasers. OPSL – VECSEL – SDL approach combined strengths of semiconductor lasers and diode-pumped solid-state lasers, such combination proving to have unique advantages. Optical pumping and external cavity of VECSELs, which initially appeared as their weaknesses, proved to be instrumental for the rich versatility of these lasers. VECSELs frequently outperform and displace other types of lasers because of their unique combination of properties, such as >100 W output power, femtosecond pulse operation, or output wavelengths from UV to THz. The future of VECSELs lies in further understanding of their physical properties, improvement of their various operational parameters, and broadening the range of their applications, which today range from entertainment to solid-state laser pumping, spectroscopy and atomic physics, fluorescence excitation in biomedicine, retinal photocoagulation therapy, and multiphoton imaging. Yearly VECSEL conferences at SPIE Photonics West bring VECSEL scientists together to exchange their latest results and ideas. This second book on VECSELs reviews their state of the art today. Thanks to the contributions of researchers prior to Micracor, the Micracor work itself, and all the contributions from researchers and engineers since, VECSELs have established their place among the important laser technologies today, with expected rich and multifaceted future.

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