JDS Uniphase (formerly SDL, Inc.) and Xerox Corporation

Monolithic Array of Laser Diodes Expand Laser Applications

Since the invention of the first optical laser in 1960 and the subsequent development of low-cost lasers for widespread applications by the 1980s, the potential of laser technology has sparked an intense pursuit of higher powered laser diodes. Applications as diverse as supermarket bar code scanners and photodynamic cancer therapies have spurred the search for better technology. Funding was not available to advance laser research, because it was too high risk and long term for investors. In 1991, SDL, Inc., in cooperation with Xerox Corporation and Stanford University, submitted a proposal to the Advanced Technology Program (ATP) to expand the laser applications base by developing a monolithic array of laser diodes that could be individually activated and emit light at predetermined wavelengths ranging from infrared to blue.

With the ATP award, the research team successfully developed high-performance, multibeam red laser diodes; two alternative methods for monolithic integrations of red, infrared, and blue emitters; and several valuable intermediary technologies. From these successes, the ATP-funded project built a strong U.S. technology base for multiple laser applications. Eighty-four inventions have been commercialized into numerous products. SDL (currently a part of JDS Uniphase) sells laser products for several markets, including high-speed color reprographics, optical data storage, displays, medical therapy, and telecommunications. Xerox used these technologies to enable a new generation of high-performance, high-speed printers and multifunction office product systems that are on the market today. These products enable companies to fulfill their printing requirements, such as one-to-one marketing and on-demand book printing, in minutes instead of days.

COMPOSITE PERFORMANCE SCORE
(based on a four star rating)
* * * *

Research and data for Status Report 91-01-0176 were collected during October - December 2001 and June 2003.

Laser Diodes Could Outshine Existing Technologies

By the 1990s, researchers understood the basics of optical lasers and were ready to exploit this technology. They imagined far-reaching applications for optical lasers, but many of the anticipated uses required that researchers move from infrared to blue lasers by developing shorter wavelength, higher powered laser diodes. SDL, Inc. and Xerox Corporation sought ATP funding to pursue single-mode laser diodes of previously unattained wavelengths and power levels. Although the research team outlined several worthwhile intermediary technologies, they ultimately hoped to build a single semiconductor device with an array of lasers tuned to different frequencies, resulting in a monolithic array of diodes that would operate at predetermined wavelengths in blue, green, red, and infrared.

The plan involved technically aggressive milestones, and success would have a significant impact on several industries, such as colors, compact color projection displays, high-density optical storage systems, high-resolution spectroscopes, medical devices, gas laser replacement markets, and medical therapy.

Proposal Highlights Impact to Multiple U.S. Markets

The companies' proposal to ATP highlighted the role of advanced laser technology in the growth of multiple industries over the next decade. For example, when this ATP-funded project commenced, the color printing and systems reprographics market promised lucrative opportunities for laser technology innovators. The U.S. xerographic marks-on-paper industry, valued at $48 billion in 1990, was expected to increase to $125 billion by 2000. Most of this increase would come from color printing systems and from replacing light-lens copiers with digital systems, if they were available. The reprographic industry needed the technology to develop compact printing engines capable of producing color graphics simply, quickly, and cost effectively.

At the time, existing high-speed printing systems were either limited in speed or needed to utilize complex multilaser optical systems. Limitations such as these also restricted the speed of color copier systems, which needed to print digitally in order to produce good print quality. SDL and Xerox proposed that monolithic multibeam lasers would enable print speeds to be increased, with a relatively small cost to the rest of the system. They further proposed that multiwavelength devices could enable new architectures in which single laser arrays would be able to address different photoreceptor layers.

The reprographic industry needed the technology to develop compact printing engines.

Thus, the SDL and Xerox team hoped to stimulate the expected growth of the color reprographic industry by providing the necessary technology for U.S. companies, including Xerox, Kodak, IBM, and 3M, to develop cutting-edge compact xerographic systems architecture.

Other possible applications of the ATP-funded research included:

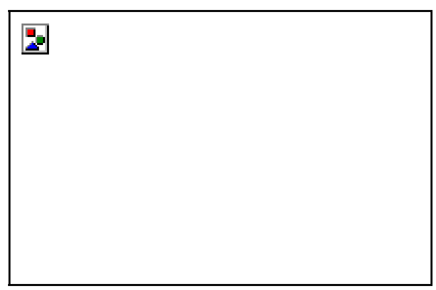
- Compact color projection displays that are better than cathode ray tube (CRT) or liquid crystal display (LCD) technology, because the brightness of a multiwavelength laser diode array greatly exceeds the brightness available for a CRT or an LCD.

- Optical data storage systems that can scan, store, and rapidly retrieve copious amounts of data from the small space of a compact disc. Because increased data density requires shorter laser wavelength emissions, the team's goal of developing laser diodes with wavelengths as low as 430 nm held high promise to increase data storage density by as much as 230 percent. This early effort in blue-laser development was a precursor to later efforts using cyan lasers for DVDs.

- Retail bar code scanners would be more reliable and cost significantly less if they were based on a 630-nm laser diode instead of the existing gas laser technology.

- Photodynamic therapy (PDT) was a laser-powered alternative to chemotherapy that uses laser light in combination with photoactive drugs called photosensitizers that target and destroy diseased cells while limiting damage to surrounding healthy tissue.

- Noninvasive glucose monitoring would allow more than 20 million diabetics in the United States alone to manage their blood sugar levels with laser technology rather than using needles.



Applications of the JDS Uniphase single-mode laser diode, which was developed in this project, include image recording, printing, spectral analysis, optical data storage, and point-to-point communications.

Aggressive Technology Goals Target Development of High-Power Lasers

Through its ATP-supported research and development (R&D) efforts, the research team wanted to combine the features of high-power, single-mode output, wide-range wavelength accessibility, and close-aperture spacing in a compact and manufacturable laser diode. The researchers hoped to develop several contributing technologies, including the following:

- High-power visible laser diodes operating at greater than 100 mW with continuous wavelengths between 630 nm and 680 nm

- High-power, single-mode laser diodes operating between 700 nm and 780 nm

- Monolithic integration of multiwavelength laser diodes operating between 630 nm and 1.1 mm

- High-power, frequency-doubled laser diodes with wavelengths between 430 nm and 550 nm in hybrid format

- Epitaxial format (a single crystal layer growth of ferroelectric materials)

The research team expected to expand the U.S. knowledge base in key technologies, including visible laser growth capabilities; high-power, single-mode device design; epitaxial growth of ferroelectric materials; and frequency-doubling techniques.

ATP Funding Needed to Jump-Start Research

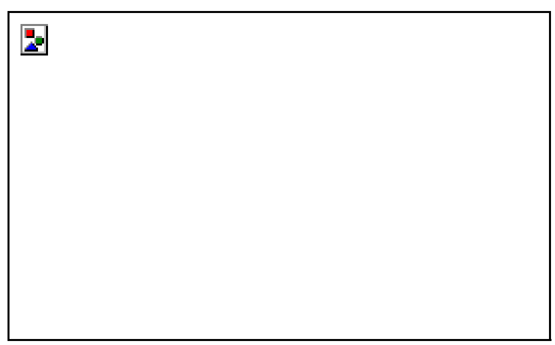
Before the ATP-funded project, laser technology presented a wide field of opportunity that was simultaneously enticing and intimidating to companies in various industries. The sheer magnitude of possibilities for laser technology made it difficult for any one company to take on the expense or risk of generic research. Venture capital firms shunned investment in laser technology for the same reason: initial research was high risk, broad based, and unlikely to yield a quick turnaround from technology to profitable products. Other sources of government funding, such as the Defense Advanced Research Projects Agency (DARPA), required that laser research produce technology for a specific application, such as missile defense or data storage.

ATP provided the jump-start by supporting the productive partnership between Xerox, a company interested in lasers specifically for xerographic applications; SDL, a company aiming to supply laser products to multiple industries; and Stanford University, which provided research support in modeling the frequency-doubling waveguides for the short wavelength devices. The project established broad laser capabilities and stimulated subsequent investment in application-specific research.

For example, SDL and Xerox joined Hewlett-Packard and others in an $8 million research program co-funded by DARPA to develop blue semiconductor lasers and light-emitting diodes (LEDs). Because of this ATP-funded project's success, Xerox's Palo Alto Research Center received approximately $8 million in internal R&D funds over four years for blue-laser-diode research to advance its xerographic products. SDL later channeled its knowledge into the telecommunications industry, where multiple lasers traveling on one fiber-optic cable allow faster Internet communication.

Technical Successes Lead to Commercial Impact

The R&D work of scientists from SDL, Xerox, and Stanford became a prolific source of new laser technologies. Donald Scifres, president of SDL at the time of the project, pointed out that without ATP, development of these technologies would have taken much longer, in an industry where time is critical. The ATP research team achieved several breakthroughs, including demonstrations of red lasers with powers up to 120 mW in single mode, lasing in the previously unattained 700- to 755-nm range, and green and blue lasers by frequency doubling. By the end of the project, SDL offered some of the lowest threshold laser devices available. Because low-threshold lasers produce less heat, which translates directly to higher data densities, SDL used these devices to produce competitive printing and data storage laser products. After it became clear that these devices were ideal for reprographic and printing applications, researchers also developed two alternative methods for monolithically integrated red, infrared, and blue emitters.



The JDS Uniphase 2600 Series of 98-nm pump modules for optical amplifiers are built on the monolithic multiwavelength laser technology developed in this project.

The transformation of the laser industry from gas tube lasers to semiconductor optoelectronic integrated circuits (OEICs) created a huge global market. "We were the first company in the world to successfully commercialize the integration of multiple lasers on a single OEIC device," said Scifres. This resulted from developing high-performance, multibeam red and infrared lasers by the end of the project in 1997. These multibeam lasers enabled a new generation of high-performance printers and multifunction office product systems later introduced by Xerox. Today, these machines continue to generate a large percentage of Xerox's total revenue and to create economic spillover for companies whose short-run office needs were met previously by lithographic printers that required several days to fill orders. These companies can now fulfill their printing requirements in just minutes, thereby increasing business efficiency.

The R&D work of scientists from SDL, Xerox, and Stanford became a prolific source of new laser technologies.

Digital printing capabilities that improved as a result of the ATP-funded project also enabled Xerox to tap the emerging "print-on-demand" market, which boasted a retail value of $21 billion in 2000. Xerox now sells print-on-demand machines that can print, cover, and glue a 300-page book in just over a minute, enabling rapid production for internal corporate and government publications departments and commercial print shops. These machines allow retailers to produce a customized sales brochure for each customer's model and color specifications, called one-to-one marketing.

The research team also completed significant work with gallium nitride (GaN)-based blue laser diodes, an area that began as a small focus of the project but became an increasingly attractive prospect during the research. After a breakthrough demonstration of long-lived blue LEDs in the GaN materials family by Nichia Chemical of Japan, SDL and Xerox decided to concentrate greater effort on blue laser diodes. They made this decision because of the diodes' appealing lower cost, higher efficiency, and smaller size compared with small gas lasers or frequency-doubled, diode-pumped solid-state lasers that require high power to double the frequency of red light. By shifting their focus to blue laser diodes, the researchers established epitaxial growth capability, fabricated high-quality LEDs, and demonstrated pulsed blue laser diodes.

The main application for blue laser diodes was in high-density optical storage. Since the end of the project, Xerox has continued to develop these devices, although to date they have not been introduced in Xerox products. SDL's smaller applications that take advantage of blue diodes include color printing (using blue diodes to expose commercial printing plates), biotechnology (DNA sequencing and cytometry), and measurement and inspection.

The transformation of the laser industry from gas tube lasers to semiconductor optoelectronic integrated circuits (OEICs) created a huge global market.

PDT technology has benefited significantly from the project's 635-nm single-mode laser diode. In the United States, PDT is currently used for treating cancer and a wide variety of other medical disorders. The combination of fiber delivery and the efficient laser diode source allow production of hand-held, portable machines that are highly reliable and moderately priced. Moreover, they consume less power and provide flexible energy delivery to the target. Previous PDT systems utilizing this wavelength relied on gas lasers and were unreliable, large, and expensive. The new laser flexibility allowed the development of new medications for treatment, with fewer side effects. SDL won the "Photonics Circle of Excellence Award" in 1999 for this work. In early 2000, the Food and Drug Administration approved the use of PDT for treating wet macular degeneration, a retina disorder (see illustration below).

The development of these technologies has enabled SDL to deliver laser products for applications ranging from optical storage to medical therapy, a laser diode for printing and data storage, and fiber-coupled laser bars for medical systems and displays. SDL revenue leveraged from the 84 technologies developed during the course of the ATP-funded project, particularly from red laser diode technologies, totaled $18.25 million from 1993 to 1997. The company grew from 200 employees in 1992 to 1,700 in 2000, prior to the merger with JDS Uniphase.

Broad Laser Capabilities and Bright Futures for SDL and Xerox

By 1998, SDL had attracted top researchers and had established broad capabilities in laser technology, in part because of the accomplishments of the ATP-funded project. With a solid track record in developing and commercializing innovative products, SDL felt confident in enlarging its strategic focus into the dynamic telecommunications industry, applying some of the laser technologies developed in this project directly to the new focus area. After making successful strides in this direction, SDL drew the attention of telecommunications leader JDS Uniphase. Evolving technology and fierce global competition were leading to consolidation in the high-tech industry, and, in 2000, JDS Uniphase acquired SDL for $41 billion.

Today, JDS Uniphase focuses mainly on laser technology for fiber-optic telecommunications, using wavelengths of light from multiple lasers to travel simultaneously on one fiber-optic cable; this technology helps to reduce congestion on the Internet. A small division of the company remains committed to discovering applications for viable blue laser diodes. Some SDL components, such as the Laser Diode Driver, are being manufactured by third parties.

Xerox's customers continue to benefit from the ATP-funded technology, because the project's multibeam red lasers now enhance the majority of Xerox's xerographic systems. Moreover, the company is continuing its blue laser diode R&D to further enhance its products.

Conclusion

During this ATP-funded project, the SDL and Xerox research team, in conjunction with Stanford University, developed high-performance, multibeam red laser diodes; two alternative methods for monolithic integrations of red, infrared, and blue emitters; and several valuable intermediary technologies. These successes helped to build a strong U.S. technology base for multiple laser diode applications, allowed Xerox to manufacture best-in-class xerographic systems, and propelled SDL to the forefront of laser technology for the telecommunications industry. This ATP-funded project has also resulted in the filing of 29 patents of which 27 were granted.

PROJECT HIGHLIGHTS
JDS Uniphase (formerly SDL, Inc.) and Xerox Corporation

Project Title: Monolithic Array of Laser Diodes Expand Laser Applications (Monolithic Multiwavelength Laser Diode Array Spanning 430 to 1100 nm)

Project: To develop a monolithic process to produce multiwavelength arrays of individually selectable, high-powered laser diodes emitting infrared, red, green, and blue light.

Duration: 10/1/1992-9/30/1997
ATP Number: 91-01-0176

Funding (in thousands):

ATP Final Cost	$ 8,925	50%
Participant Final Cost	9,102	50%
Total	$18,027	

Accomplishments: The SDL, Xerox, and Stanford University research team successfully demonstrated the first integration of multiple-wavelength laser diodes on a single semiconductor device. In the course of this work, the team established several intermediary technologies and accomplished important research in the field of gallium nitride (GaN)-based blue laser diodes. Demonstrated technologies include two alternative methods for monolithic integrations of red, infrared, and blue emitters; red laser diodes with powers of up to 120 mW single mode; lasers in the 700- to 755-nm range; green and blue lasers with frequency doubling; and the lasing of blue GaN diodes at room temperature.

The project generated 84 inventions. The team filed 29 patent applications, with the following 27 patents granted to Xerox as a direct result of the ATP-funded project:

- "Stacked active region laser array for multicolor emissions"
  (No. 5,386,428: filed November 2, 1993; granted January 31, 1995)

- "Method of fabricating a stacked active region laser array"
  (No. 5,436,193: filed November 2, 1993; granted July 25, 1995)

- "Index guided semiconductor laser diode with shallow selective IILD"
  (No. 5,832,019: filed November 28, 1994; granted November 3, 1998)

- "Semiconductor laser or array formed by layer intermixing"
  (No. 5,708,674: filed January 3, 1995; granted January 13, 1998)

- "Index guided semiconductor laser diode with reduced shunt leakage currents"
  (No. 5,717,707: filed January 3, 1995; granted Febraury 10, 1998)

- "Thermally processed, phosphorus- or arsenic-containing semiconductor laser with selective IILD"
  (No. 5,766,981: filed January 4, 1995; granted June 16, 1998)

- "Method for replicating periodic nonlinear coefficient patterning during and after growth of epitaxial ferroelectric oxide films"
  (No. 5,654,229: filed April 26, 1995; granted August 5, 1997)

- "Alternative doping for AlGaInP laser diodes fabricated by impurity-induced layer disordering (IILD)"
  (No. 5,745,517: filed December 29, 1995; granted April 28, 1998)

- "Loss-guided semiconductor lasers"
  (No. 5,812,576: filed August 26, 1996; granted September 22, 1998)

- "Transversely injected multiple wavelength diode laser array formed by layer disordering"
  (No. 5,764,676: filed September 26, 1996; granted June 9, 1998)

- "Polarization mode selection by distributed Bragg reflector in a quantum well laser"
  (No. 5,784,399: filed December 19, 1996; granted July 21, 1998)

- "Semiconductor devices constructed from crystallites"
  (No. 5,977,612: filed December 20, 1996; granted November 2, 1999)

- "Edge-emitting semiconductor lasers"
  (No. 5,886,370: filed May 29, 1997; granted March 23, 1999)

PROJECT HIGHLIGHTS
JDS Uniphase (formerly SDL, Inc.) and Xerox Corporation

- "Deep native oxide confined ridge waveguide semiconductor lasers"
  (No. 6,044,098: filed August 29, 1997; granted March 28, 2000)

- "Independently addressable laser array with native oxide for optical confinement and electrical isolation"
  (No. 6,052,399: filed August 29, 1997; granted April 18, 2000)

- "In-situ acceptor activation in group III-v nitride compound semiconductors"
  (No. 5,926,726: filed September 12, 1997; granted July 20, 1999)

- "Independently addressable semiconductor laser arrays with buried selectively oxidized native oxide apertures"
  (No. 5,917,847: filed September 26, 1997; granted June 29, 1999)

- "Monolithic red/ir side by side laser fabricated from a stacked dual laser structure by ion implantation channel"
  (No. 5,999,553: filed November 25,1997; granted December 7, 1999)

- "Monolithic independently addressable Red/IR side by side laser"
  (No. 6,058,124: filed November 25, 1997; granted May 2, 2000)

- "Method of manufacturing vertical cavity surface emitting semiconductor lasers using intermixing and oxidation"
  (No. 5,915,165: filed December 15, 1997; granted June 22, 1999)

- "Red and blue stacked laser diode array by wafer fusion"
  (No. 5,920,766: filed January 7, 1998; granted July 6, 1999)

- "Infrared and blue stacked laser diode array by wafer fusion"
  (No. 6,104,740: filed January 7, 1998; granted August 15, 2000)

- "Red, infrared, and blue stacked laser diode array by wafer fusion"
  (No. 6,144,683: filed January 7, 1998; granted November 7, 2000)

- "Multiple wavelength laser arrays by flip-chip bonding"
  (No. 6,136,623: filed May 6, 1998; granted October 24, 2000)

- "Fabrication of group III-V nitrides on mesas"
  (No. 6,163,557: filed May 21, 1998; granted December 19, 2000)

- "AlGaInN LED and laser diode structures for pure blue or green emission"
  (No. 6,233,265: filed July 31, 1998; granted May 15, 2001)

- "Structure and method for self-aligned, index-guided, buried heterostructure AlGalnN laser diodes"
  (No. 6,567,443: filed September 29, 1999; granted May 20, 2003)

In 1999, SDL won the "Photonics Circle of Excellence Award" for its development of the 3-W, 630-nm Photodynamic Therapy (PDT) Laser, which resulted from the project.

Commercialization Status: After the ATP-funded project, SDL commercialized several laser products that were based on technologies developed in the course of the project, including the following:

- SDL-7511-30-mW, 650-nm single-mode laser using facet passivation technology (used in the early development of high-density optical storage systems; the technology has been discontinued).

- SDL-7311-30-mW, 680-nm single-mode laser (for PDT applications). Some of the second-generation PDT drugs were activated in the 680-nm range. PDT systems typically needed more power than 30 mW, so higher power multimode versions of this single-mode laser were typically supplied to PDT customers.

- SDL-7601-2-mW to 10-mW, 680-nm dual-spot single-mode laser (applications include data storage, printing, displays, and alignment). This monolithic multichannel device provided higher speed and lower cost.

PROJECT HIGHLIGHTS
JDS Uniphase (formerly SDL, Inc.) and Xerox Corporation

- SDL-7400-500-mW, 680-nm multimode laser (the high-power multimode cousin of the SDL-7311 for the PDT market).
- SDL-7470-3-W fiber-coupled laser bars at 665 nm to 690 nm (for solid state pump lasers, medical systems, and displays in niche applications).
- SDL-5700-up to 150-mW, 852-nm distributed Bragg reflector laser (applications include frequency doubling, interferometry, atomic clocks, and spectroscopy).

SDL, currently known as JDS Uniphase, continues to apply the broad knowledge gained in this project to the fiber-optic communications and commercial laser industries. The company is developing and supplying high-power semiconductor lasers for many applications. They are the leading supplier of high-power 980-nm pump lasers for optical amplifiers. They are also a leading supplier of single-mode and multimode lasers in ranges of 810 nm to 850 nm and 910 nm to 980 nm, which are used for pumping, printing, materials processing, inspecting, testing, and other applications. JDS Uniphase continues to market the SDL-7311 and the SDL-7400 for PDT applications, the SDL-7601 for data storage and other applications, the SDL-7470 for pump lasers and other applications, and the SDL-5700 for frequency doubling and other applications.

Third parties have purchased the rights and continue to produce SDL's Laser Diode Driver, Laser Diode Heatsink, and semiconductor lasers, as well as its pulsed laser diodes and its green, blue, red and infrared modules.

Xerox incorporated the multibeam red laser technology from the ATP-funded project that has enabled a new generation of high-performance, high-speed printers and multifunction office product systems.

Outlook: In 2001, SDL's success in developing and commercializing semiconductor laser technology prompted the company's merger with fiber-optics giant JDS Uniphase. Since this merger, SDL (now JDS Uniphase) has applied its knowledge mainly to the fiber-optic communications industry, with 86 percent of its revenues derived in this area. Some of the laser technologies from this ATP-funded project are used in this new focus area. JDS Uniphase continues to develop and supply high-power semiconductor lasers for many applications.

Xerox's customers continue to benefit from the ATP-funded technology, because the project's multibeam red lasers are used in Xerox's high-speed, high-performance xerographic systems. Moreover, the company is continuing its blue laser diode research and development to further enhance its products.

Composite Performance Score: * * * *

Number of Employees: 200 in October 1992 (SDL); 1,700 as of July 2000 (SDL, prior to the merger with JDS Uniphase).

Companies:

JDS Uniphase Corporation
1768 Automation Parkway
San Jose, CA 95131

Contact: Gordon Mitchard
Phone: (408) 546-5000

Xerox Palo Alto Research Center
3333 Coyote Hill Road
Palo Alto, CA 94304

Contact: Dr. Ross Bringans
Phone: (650) 812-4000

Subcontractors:

- Stanford University
  Stanford, CA

Research and data for Status Report 91-01-0176 were collected during October - December 2001 and June 2003.