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ADVISORY GROUP ON ELECTRON DEVICES
WORKING GROUP C (ELECTRO-OPTICS)

SPECIAL TECHNOLOGY AREA REVIEW

ON

LOW COST, MASS PRODUCIBLE, SOLID-STATE LASERS

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FOREWORD

Periodically, the Advisory Group on Electron Devices (AGED) conducts Special Technology Area Reviews (STARs) to better evaluate the status of an electron device technology for defense application. STARs strive to elicit the applicable military requirements for a particular technology while relating the present technology status to those requirements. The STAR culminates in a report that provides a set of findings and recommendations, which the Office of the Secretary of Defense can utilize for strategic planning. Since each electron device technology that falls under AGED's purview resides at a different level of maturity, and thus, varying requirements, the content of each STAR is tailored to extract the appropriate data through preparation of "Terms of Reference."

The STAR on Low Cost, Mass Producible, Solid-State Lasers was conducted on 14-15 September 1999, by AGED Working Group C (Electro-Optics) at the Palisades Institute for Research Services, Arlington, VA. The goal of the STAR was to assess the status of advanced solid-state laser technology and to provide recommendations concerning technical direction. As a consequence of the STAR, an innovative program for reliable laser technology has been proposed, one that will bring optical manufacturing closer to the automated processes characteristic of the electronics industry.

Presentations were made by a distinguished panel of experts from industry, government, and academia. Industrial representatives included manufacturers of semiconductor lasers and laser arrays, manufacturers of advanced solid-state lasers, and systems manufacturers. Working Group C members are experts in electro-optical technology. The group includes representatives from the Army, Navy, Air Force and the Defense Advanced Research Projects Agency as well as consultants from industry and academia.

On behalf of Working Group C, I would like to take this opportunity to express my sincere appreciation to all of the people who took part in this study – listed in the following section – for their valuable contributions. This applies particularly to Dr. Susan Turnbach, OUSD (A&T)/DDR&E/SE&BE[1], whose support and encouragement were essential for the successful completion of this effort. I would also like to extend my thanks to Dr. Clifford Muller formerly of the Air Force Research Laboratory for conceiving this STAR topic and recommending expert speakers. Dr. Paul Kelley of Tufts University is also thanked and commended for significant contributions to this study.

Dr. Andrew Yang
Chairman, Working Group C

[1] Subsequent to the STAR, the name of this office changed to USD (AT&L)/DDR&E/DUSD/S&T/SS: Office of the Undersecretary of Defense for Acquisition, Technology and Logistics, Director of Defense Research and Engineering, Deputy Under Secretary of Defense for Science and Technology, Sensor Systems.

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REPORT OF SPECIAL TECHNOLOGY AREA REVIEW HELD 14-15 SEPTEMBER 1999 ON LOW COST, MASS PRODUCIBLE, SOLID-STATE LASERS

EXECUTIVE SUMMARY

This STAR proposes an innovative program in laser technology, one that will bring optical manufacturing closer to the automated processes characteristic of the electronics industry. The basic goals will be to obtain higher efficiency, lower cost, and more reliable lasers. If this effort is successful, it should be possible to make well integrated, monolithic, inexpensive laser systems that are also rugged, stable and long-lived.

Many current Department of Defense (DoD) mission areas require battlespace sensors and directed energy solutions. Vital military laser applications include range finders, illuminators, beam riders, and designators, and laser radar. Recent DoD studies (such as LASSOS: Lasers and Space Optical Systems and DE-ATAC: Directed Energy Advanced Tactical Airborne Combat) describe the key enabling laser technologies needed in the future as a) agile multi-wavelength lasers and b) high efficiency electric lasers. Important mission areas include countermeasures, chemical warfare agent detection and identification, nighttime imaging, tunnel and underground structure detection, and tactical directed energy weapons. These laser systems need to be efficient, compact, lightweight, inexpensive, easily transportable and maintainable, rugged, reliable, and capable of operation in widely diverse environments. Unfortunately, current lasers often do not meet many of these requirements. To meet these requirements, a new generation of solid-state laser technology is necessary.

The basic goal of a successful program in military solid-state lasers should be the improvement, over the next five years, of a factor of three or more in many of the parameters that define the operational capability of these systems. Significant advancements have been made over the last few years in solid-state laser capabilities such as wavelength coverage and output power, but these sources have experienced limited deployment in operational systems due to cost, reliability, and packaging issues. The higher power solid-state lasers for DEW will require at least an order of magnitude decrease in cost to be price competitive with chemical and gas laser sources.

A close and early teaming relationship between DoD and industry is needed if low-cost, mass producible, solid-state laser products are to become a reality. An order of magnitude decrease in system cost will require more than just manufacturing technology advancement. New component technologies (e.g., fiber lasers, slab lasers and high performance diode pumps) and novel system-level solutions will be needed.

Strong Science and Technology (S&T) programs are needed to develop the new technologies required for low cost, mass producible, solid-state lasers. These technologies include high-performance, high-temperature diode pump lasers, dual-clad fiber lasers, edge-pumped slab lasers, and high performance optical sensors and beam directors. These S&T activities must be closely coordinated with specific DoD missions and applications. A DoD investment of $25M per year over the next five years is needed to develop the important laser products for the DoD. Technology development at telecommunications companies such as Lucent, Alcatel, JDS Uniphase, SDL, and Nortel should be leveraged when feasible. Cooperative arrangements with these companies should be explored. Additional "Killer Commercial Applications" should to be found to fully realize the $10-$100M parallel commercial development expense needed for these technologies. Examples of "killer applications" include material processing and fabrication, medical lasers, Doppler radar for commercial aviation, and laser projection displays.

Reliability concerns are critical to all military laser systems. Therefore, system designers will need to elevate reliability to a dominant requirement. They will need to demand statistical validity, and keep in mind that good statistics always require large numbers of samples. As a result, DoD systems designers should not qualify unique devices. Instead, where possible, they should qualify commercial products with a wider variety of applications and experience. They should focus on commonality of packages and specifications. Standards in diode-pump solid-state laser (DPSSL) pump packages will allow better technical focus, better prices, and higher reliability. Packaging will remain a significant concern for all applications. DoD should leverage from packaging technologies developed for commercial products. Synergy with electronics packaging technology should be exploited.

REPORT OF SPECIAL TECHNOLOGY AREA REVIEW HELD 14-15 SEPTEMBER 1999 ON LOW COST, MASS PRODUCIBLE, SOLID-STATE LASERS

INTRODUCTION AND OVERVIEW

Vision

This STAR proposes an innovative program in laser technology, one that will bring optical manufacturing closer to the automated processes characteristic of the electronics industry. The basic goals will be to obtain higher efficiency, lower cost, and more reliable lasers. If this effort is successful, it should be possible to make well integrated, monolithic, inexpensive laser systems that are also rugged, stable and long-lived. Mass produced, standardized electronic components have been important in the development of affordable, high-performance sensor and weapons systems. Manufacturing of optical systems, most particularly lasers, unfortunately involves piecework, manual finishing, and time-consuming adjustment. The program proposed here should overcome these difficulties.

Reliable technologies must be an important consequence of this program. In the area of pump diode arrays, lifetimes under conditions close to those expected in military operation are of the order of hundreds of hours. The problem appears to lie in inadequate thermo-mechanical materials and package design. Unless appropriate solutions are found, individual diodes or small diode array pumps will need to be used. In this case, to achieve the power levels required, the radiation from a large number of discrete diodes or small diode arrays will have to be combined in a complex fiber delivery system.

In order to make this effort viable, there must be a clear need. DoD spends about $100M/yr on laser designators and beam riders. With a change in designator modulation format, dramatic reductions in system cost could be achieved using diode-pumped solid-state lasers. Other applications that will benefit from advances in low-cost, producible lasers are rangefinders, illuminators, and anti-sensor weapons. Applications that have not yet established themselves as clear DoD requirements could also be enabled by the success of this technology development.

The program discussed in this report leverages on the development of new devices and automated manufacturing in the optical communications industry. There is a direct overlap between the low cost, mass producible solid-state laser (LCMPSSL) technology proposed here and systems under development for multi-wavelength telecommunications systems. Examples of other commercial applications with strong technology overlap include material processing and fabrication, medical lasers, Doppler radar for commercial aviation, and laser projection displays.

Applications and Technology Goals

Laser sources (continuous wave {CW} and pulsed) are required to achieve many National Defense requirements including: range finders; beam riders; illuminators; mid-infrared (mid-IR) sources for infrared countermeasures (IRCM); and solid state optical radars for range gated imaging, autonomous piloting, targeting and guidance. A list of mission applications is given in Table I.

Significant advancements have been made over the last few years in laser capabilities such as wavelength coverage and output power, but these sources are rarely deployed in operational systems due to three separate problems. The two primary problems that have precluded the use of lasers for many defense as well as commercial applications are cost and reliability. These problems are severe with costs running many times larger than what is economically reasonable for government and commercial systems. Further, many lasers today are simply not capable of reliable operation. Therefore, an important goal is to find manufacturing techniques that effectively reduce the cost and improve reliability. The third problem is laser efficiency. Mission applications generally require high efficiency to achieve high power levels within power availability limitations and to limit waste heat levels. The proposed program aims at achieving overall electrical to optical system efficiencies greater than 20%.

Table I: Mission applications that require efficient, reliable, low cost lasers (both CW and pulsed). This table includes both current and envisioned applications.

Tactical	Space
Directed Energy Weapons IRCM Autonomous Guidance Radar, Designators, Trackers, Illuminators Remote Sensing, and Imaging Displays	Directed Energy Weapons UAV Control Battlefield Illumination and Covert Search and Rescue Remote Sensing and Imaging Detection of Underground Facilities Target Designation for Fire and Forget Laser Communications

Military applications of lasers include IR countermeasures (spoof and jam as well as potential damage and destroy), ladar (vibrometry, polarization, 1, 2, and 3-D imaging, and hyperspectral contrast enhancement), target designation, directed energy weapons (DEW), communication and navigation. Commercial aerospace applications include wind shear detection, vortex detection, microburst monitoring, clear air turbulence warning, optimal altitude (headwind) selection and climatological/meterological/pollution wind and species monitoring. The laser requirements for these mission areas include frequency and wavelength agility, ultra narrow bandwidth, and scalable modules for high-energy applications (a flow down to common or re-useable modules is needed).

Manufacturing Technology Issues

Many DoD mission applications will not benefit from the advantages that laser sources bring unless their cost is lowered and the reliability improved. One goal of this Special Technology Area Review is to determine the important issues related to the development of low cost, reliable, high efficiency laser source. An example of current costs is given in Table II.

Current laser manufacturing techniques are similar to the approach used to manufacture TVs in the 1950s. There are many very expensive, individually machined, precision components with three dimensional micrometer positioning and adjustment accuracy required. Sadly, they bear very little resemblance to modern manufacturing technologies such as those used in integrated circuits today.

Laser diodes in the near-IR are typically 50% efficient. Order of magnitude scaling of solid-state laser average power has been demonstrated based on the match between diode emission wavelengths and solid-state absorption bands. Diodes are now available with emission wavelengths ranging from the blue to the mid-IR. However, the most extensively developed diodes emit in the 0.8 to 1.5-micron wavelength region. Many packages, some complete with cooling chambers, are available. Certain packages have demonstrated lifetimes of thousands of hours in laboratory tests but have not demonstrated the required reliability in field tests.

Table II: Key component costs for a 10 W CW solid-state laser pumped by two diode laser bars. Diode laser pump bars are a major cost driver for "small" and "moderate" production quantities.

	Small Quantities ($)	Moderate > 100/yr ($)	Large > 10,000/yr ($)
Diode bars	2,000	800	
Laser medium (w/coatings)	1,800	700	TBD
Refrigerator/Chiller	850	400	
Power Supply	1,200	600	No manufacturers work
Q-switch	2,500	1,200	at these volumes today.
Labor (assembly, testing and alignment)	5,000	4,000	
Cost of Goods Sold	13,350	7,700	

High temperature diodes and diode bars take a burden off the cooling requirements and make certain fielded applications feasible. A number of one-of-a-kind diode-pumped solid-state laser systems have performed satisfactorily on aircraft platforms and satellites but the cost is far too high. In spite of the outstanding promise of diodes, greater general utilization is limited by cost and reliability issues.

Historical Issues

Laser diodes are an enabling technology for efficient, high power solid-state lasers. Laser diode pumped solid-state lasers became a feasible laser technology following the first demonstration of a 1 cm long, 1 W diode array in 1978 by Scifres, Burnham and Streifer at Xerox PARC. By 1990 the same 1 cm laser diode array was generating more than 120 W of CW output power in a research laboratory. The first commercial laser diode array was introduced in 1982 with 5 W of output power. By 1999 60 W arrays were commercially available with 100 W arrays on the horizon. In less than one decade the cost per Watt had decreased from $3000 to less than $100 with the prospect of $1 per watt by the year 2004. This trend will continue if the market volume for laser diode pumped solid-state lasers increases. increases. A market volume of $1 million dollars per month for a particular laser diode array configuration may be required to sustain a cost of $1 per watt.

Over the same decade, studies of advanced solid-state lasers showed that scaling to weapons power levels with good beam quality appeared to be possible. Recent progress in edge pumped slab lasers and double-clad fiber lasers has allowed laser diode pumped solid-state lasers to operated at high slope[2] efficiency with >100 W of output power and at a gain adequate for master-oscillator power-amplifier (MOPA) configurations. Power scaling in Yb-doped materials is particularly favorable with electrical efficiencies above 20% predicted for room temperature laser diode pump sources. Mass production of these solid-state laser sources will greatly reduce their costs and allow their use in many DoD weapons applications.

Questions for Briefers

1. **Cost: What determines the lifetime cost of lasers and how can we greatly reduce the cost?**

   a) Identify the cost constraints related to the manufacture of current generation diode-pumped solid-state lasers. Most solid-state lasers cost $1000-$2000 per diffraction limited watt. Why are these lasers so expensive? Is there any paradigm shift in manufacturing technologies that can reduce the cost of lasers by 10X or 20X?

   b) No manufacturer makes 1000 lasers/year unless it is gas (e.g. HeNe) or diode lasers. Is it possible to reduce the cost significantly even with relatively low production volumes. Can better implementation of manufacturing methodologies (design for manufacture, just-in-time, lean manufacturing) bring significant cost reduction?

   c) What factors determine the cost of diode pump bars? Diode laser bars continue to drop in price at about 30% per year.[3] But they are still very expensive. At what volume will the price be $10 per watt CW in the near term ($1 per watt in the longer term)? At what

[2] This is the efficiency determined from the rate of change of power output with respect to power input.

[3] Subsequent to the STAR the Army reported conflicting information. Their experience has shown that quasi-CW bars have averaged about $9/W for the last decade.

volume will the current price hold and can we expect a price reduction to $1 per W in the long term? Who is the customer for this volume, the government or the commercial sector?

d) The US has a strong industrial base in solid-state materials, nonlinear optical materials, diode lasers and semiconductor fabrication. Are we applying these capabilities adequately to solving the need for lower cost lasers? Does the rapidly developing MOEMS technology base provide us with an example of how to reduce laser costs?

e) Do we understand how to determine the lifetime cost of military or commercial laser systems?

f) Is there a recommended solid-state laser material and design for low cost lasers? Is there a recommended packaging configuration for low cost lasers? Can we simulate, with our modeling codes, the cost, reliability, and efficiency of proposed laser systems? Do we have a testing methodology that is relevant to low cost, high efficiency laser manufacturing?

2. Reliability: What are the reasons for reduced/low reliability in today's solid-state laser systems.

a) Are laser failures due to coatings, diode bars, electronics, mechanical alignment, etc.? What is the real cost of repairs or failures in military and commercial lasers? Why is it possible for very complex components like Pentium chips, with millions of transistors, to virtually never fail?

b) Is the large number of components in typical diode pumped solid-state lasers a key factor in failures? If so, how can we minimize the number of components? Are there paradigm shifts we can apply to greatly increase the reliability of lasers?

3. Manufacturing Technologies: How can we leverage from the electronics and telecommunications industrial base in the US?[4]

Many companies like Intel package complex electronics with basically zero failure rates once the product is on the street. Companies like Lucent have been manufacturing high data rate lasers for telecommunications for many years and their products have virtually no failures. If their assembly techniques were applied to the manufacture of solid-state lasers, would the reliability improve?

Agenda of Presentations

The agenda of presentations can be found in Appendix A.

[4] For a view of the commercial optoelectronics market see Appendix D.

SUMMARY OF PRESENTATIONS

Synopsis of Presentations

In general, there was surprising unanimity regarding the problems that have been encountered and the types of solutions that can be used in achieving low-cost solid-state lasers. Only the highlights of the presentations are discussed here.

1. Robert Byer of Stanford made the point that low cost diode arrays will produce important changes in solid-state laser design and manufacturing. These changes include:

    a) Redundancy in design for manufacturing.
    b) Automated assembly.
    c) The ability to make repairs while the laser is operating.
    d) The feasibility of multi-element, parallel designs.

2. Tim Albrecht of Litton pointed out that his company has a $60M per year military laser business that he expects to grow to $100M per year. Applications include mine detection, IRCM, target designators, and eye-safe rangefinders. Litton's production rates are hundreds of high peak-pulse tactical laser system units per year, as follows: Laser Designators - $100-200K/100-200mJ, Laser Rangefinders - $10-20K/10-20mJ.

    He also pointed out that the microlaser represents a big technological advance. These lasers have only a few standardized parts that can be used in many different laser designs. The microlasers are compact and simple to align.

3. TRW described two approaches for power scaling with excellent beam quality, using either conduction-cooled zigzag slabs or fiber laser amplifiers. The former allows the use of fewer, higher power modules. Alternatively, fiber lasers offer higher efficiency and facilitated cooling due to large surface to volume ratio. Fiber lasers may minimize labor-intensive manufacture and repair making use of telecom industry components and technologies. TRW suggested that fiber lasers might be scaled via a phased array architecture employing MEMS technology. The validity of the scaling has been demonstrated by several groups.

4. Bob Byren and Rob Baltimore from Raytheon discussed the extensive experience of the company in manufacturing a wide variety of laser rangefinders and target designators. They feel that high duty factor coherent waveforms, fiber lasers, low cost diode packaging, and drop-in optical alignment using a moldable optical bench will bring significant cost reduction to laser manufacturing. Reusable designs and common interface specifications in an open architecture are important strategies for achieving low cost. They are developing a multifunction laser that is aimed at meeting the goals described above.

    Raytheon has participated with Spectrolab in the technology transfer of Lawrence Livermore National Laboratories' diode laser manufacturing. They indicate that for pump diodes, a cost of $2-4 per watt is feasible with present device technology, and less than $1 per watt should be possible long term. They also pointed to the problems of low production volumes and frequent re-competitions and program cancellations. Finally, they noted that erosion of the military optics and lasers supplier base to the more lucrative telecommunications industry has become a serious and growing concern.

5. Robert Lang of SDL gave the perspective of a major pump diode array manufacturer.[5] He pointed to the basic problems of semiconductor based optical devices, namely, the use of minority carriers, the high current densities, and the light driven defect migration.[6] On the positive side, the power per chip is rising at 60% per year and a cost of $1 per watt is projected by 2005. SDL has a new approach to reliability involving process and device model qualification, burn-in to reduce infant deaths, and the production of larger batches with better statistics.

   Lang pointed to a number of evolutionary improvements in technology. He also stressed the need to rely on advances in telecommunication device technology and suggested the DoD qualify commercial products where possible.

6. In his presentation for Aculight, Chuck Miyake stressed their innovative approach to low cost solid-state laser technology. The principal approaches involve scalable bulk fabrication, monolithic structures, high power pumps, and tooling to reduce recurring parts cost. Low cost fabrication based on processes used in the semiconductor industries can eliminate machining, reduce parts counts, and produce self-registering structures. These processes can also be used to fabricate optical mounting components that can improve the temperature stability and vibration resistance of the laser.

7. Ken Walker of Lucent presented the viewpoint of a high volume laser manufacturer. They use $4x10^5$ pump lasers per year in addition to large number of well-controlled diode lasers for synchronous optical network transceivers. They are developing novel cladding pumped fiber systems in a 20-member technical staff program. Lucent is using tapered and fused fiber bundles to introduce pump radiation from multiple discrete diodes. Non-circular cladding is used to efficiently couple the pump radiation into the fiber core. Scalability to powers of over 100 W has been achieved. Lucent predicts that either wavelength or phase combining will lead to powers in the kilowatt range. They recognize the limitations on power imposed by stimulated scattering and are carrying out research to reduce its effect.

8. Jeff Kmetec of Lightwave Electronics gave a presentation on their diode-pumped solid-state laser-manufacturing program. Commercial applications include inspection and imaging, DRAM yield enhancement, ophthalmic lasers, thermal reprographics, and via drilling. Kmetec gave an extensive discussion of the Lightwave business model. About half the cost is material purchased and the other half is internal labor. The external material cost also consists mostly of the cost of labor, due to relatively low volumes. They see problems with

[5] After the STAR presentations, it was reported that SDL plans to exit the pump array business.

[6] Since the STAR was conducted, it was reported by Cliff Muller that the migration problem was apparently no longer a concern.

variable government funding, thin profit margins, and insufficient income for cost reduction programs.

10. Duane Smith of Coherent Technologies discussed their development of lasers for remote sensing. Since active remote sensing often involves coherent detection, the laser design is more difficult. They have been primarily in the military market but have expanded into the commercial aviation market for wind, clear air turbulence, and wake vortex detection. They see an important role in the future for guided wave lasers. Since stimulated Brillouin scattering, Raman scattering and other nonlinear processes are challenging at high intensities in waveguides, CTI would like to develop innovative planar waveguide technology that addresses these challenges and is compatible with integrated optics manufacturing. CTI feels that cost reduction is difficult in part because suppliers do not sense that component redesign will lead to significant benefits for their businesses. They predict that low cost transmit/receive modules and phased array technology will be developed as a cost-reduction measure and to enhance performance, mimicking the evolution of electronic integrated circuits. The similarity of DoD operational requirements to the needs of commercial aviation is a valuable synergy that has yet to be fully exploited.

Issues Identified and Addressed by the Presenters

1. Solid-state lasers that meet the requirements of military applications are currently not cheap relative to other lasers, but they have significant advantages in terms of weight and operation in desirable wavelength regions.

2. There is a clear need to develop less expensive ways to manufacture solid-state lasers.

3. About 70% of the cost of the laser is for components supplied by vendors to the laser manufacturer. The remaining cost is primarily manufacturer’s labor including design, fabrication, alignment, and testing. In the case of components supplied by vendors, most of the cost is the labor required to fabricate components using today’s state-of-the-art methods.

4. Great precision is required for optical component manufacture and system assembly. These requirements include axial distance accuracies of micrometers and smaller over transverse distances of centimeters and angular accuracies of milliradians and smaller.

5. The sales volume of laser systems at military power levels is small.

6. Partly as a consequence of the last two items, the manufacture of lasers, and optical systems in general, involves non-automated fabrication of laser assemblies, tedious alignment and re-alignment, and extensive testing. This is the major cost driver.

7. A number of changes in solid-state laser manufacturing have either occurred or can emerge quickly with modest investment that should dramatically improve the somewhat bleak picture presented above.

8. Given the advantages of quasi-CW diode pumped solid-state lasers over lamp pumped systems, attention should be given to changing the modulation format of designators and rangefinders.

9. To achieve the critical mass required for the introduction of cost reducing technologies, DoD program managers should coordinate their procurements where possible. An effort should also be made by manufacturers to set common standards for optical components. Both the DoD community and manufacturers should encourage modular and scaleable designs.

10. The use of microelectronics methods and materials for the manufacture of optical components should allow reproducible fabrication of components and devices with submicrometer tolerances. These techniques should also be applicable to the fabrication of optics assembly platforms using both Si and SiO_2. With 2-D photolithography and etching, 3-D structures could be fabricated with sufficient accuracy to allow precision component registration and make further manual alignment unnecessary.

FINDINGS AND RESULTS

Cost and Manufacturing Technologies

1. Low-cost solid-state lasers can be obtained only by leveraging the commercial market to the maximum extent possible. Some feel that the $1.6 billion telecommunications market is the best leverage source, while others feel the commercial aviation market best matches the environments expected for DoD applications. 10X to 20X cost reduction will require more than manufacturing process/technology advancement. New component technologies (e.g., fiber lasers) developed in forward-looking S&T programs and different system-level solutions will be needed.

2. Production experience shows that component costs for military laser systems represent as much as 70% of the total manufacturing cost and to a large extent commercial and military manufacturers use the same supplier base. The major elements of cost reduction strategy are:

    a) reduce the materials costs by elimination of high cost components and precision machined parts,
    b) reduce diode laser cost (largest cost element) by minimizing the number of pump diodes, using the highest power density diode laser technology available, and increasing the laser efficiency and reliability,
    c) reduce assembly labor costs by reducing the number of parts and by using novel packaging techniques similar to those used in electronics industry,
    d) reduce component replacement costs by increasing reliability of the laser diodes and the solid-state laser materials (including optics).
    e) require early involvement of suppliers in concurrent engineering,
    f) develop standards,
    g) design-for-reuse strategies,

h) use multi-year procurement practices that increase the quantities for individual purchases and encourage suppliers to invest in higher-rate tooling and test equipment, and
i) use of third-party agreements to extend purchasing power up and down the supply chain.

3. It is not possible to design lasers that have zero failure rate, but it is possible to design lasers that can be repaired while in operation, are low cost and can be scheduled for replacement prior to expected lifetime limits.

4. One strategy to accelerating the cost decline at a given performance is to purchase lasers for less demanding tasks thus increasing volume while keeping design requirements simple. For example, laser surface cleaning of stealth coatings, laser de-painting, and laser assisted painting of aircraft require high average power at low beam quality and serve many Air Force needs. Lasers purchased to meet widespread service tasks will increase market size and production run volumes thus leading to lower costs for future high performance laser devices.

5. A 30% per year rate of cost reduction in laser diode arrays will force a change in the design approach of laser diode pumped solid-state lasers over the next few years. This change will be from an approach that favors using the least number of laser diode bars to an approach that favors using the least time to assemble and test the final product. This in turn will allow the application of well-known mass production techniques. Further, increase in laser power will continue under the cost ceiling already imposed by customers of laser diode pumped solid-state lasers. These trends are already evident in manufacturing practices of laser diode pumped solid-state laser companies that increasingly are using the best practices of integrated circuit manufacturing and assembly.

6. Despite the fact that high pulse energy lasers appear to be optimal for some military DE applications, CW diode-pumped lasers with quasi-CW pulse formats can satisfy many DoD directed energy needs including DEW and <u>are far less costly per watt</u>. Military DE functions that require high pulse energies will benefit from the cost-volume leveraging obtained by developing quasi-CW solid-state lasers.

7. It is clear that the diode-pumped laser systems provide the greatest efficiency. Today, the laser diode cost makes up a large percentage of the total cost for medium to high power laser systems. In the last decade, this cost has been dramatically reduced thereby making laser systems more affordable. Surveys of the diode manufacturers further indicate that their manufacturing cost is also being reduced as a result of more efficient manufacturing techniques and of course the increased demand. It is projected that, with advanced packaging technology, affordable laser diode pricing may be achievable. The cycle of cost reduction and increased demand is expected to increase well into the new millennium with expectations at $1 per watt (peak).

Commercial Applications and the Prospects for DoD Cost Reduction

The rapid development and deployment of fiber optical communications systems can have significant impact on LCMPSSL technology. High power semiconductor diode lasers and diode laser arrays have been developed for pumping crystalline materials and glass fibers doped with rare earths. Methods of combining incoherent pump beams as well as coherent output beams have been demonstrated. Telecommunications equipment manufacturers such as Lucent have achieved nearly 100 W of single transverse mode power from a double clad fiber laser. The use of wavelength division multiplexing (WDM) with more than one hundred channels mandates high pump powers. Communications systems must be protected from failure with recovery times in the tens of milliseconds and should be long-lived and require little servicing. Together with this explosion in technology comes the commercial need for cost reduction and automated manufacturing techniques. In addition to the application to communications systems, there is increasing use of diode-pumped solid-state lasers for printing and materials processing. Because of the overlap with commercial technology, military systems will benefit from common underlying characteristics as well as the advances in the commercial sector aimed at higher output powers, reduced manufacturing costs, and high reliability.

Reliability

1. Test data from diode pump laser manufacturers indicate lifetimes exceeding billions of shots. However, many diode pumped lasers have failures in the laser diode arrays after a few million shots:

   a) DAPKL – >20% of bars failed and others are degrading,

   b) Lightweight Laser – Arrays refurbished,

   c) Comanche Laser – Arrays failed during temperature cycling,

   d) Celrap Laser – One bar failed open during test, and

   e) ATLAS Laser – Many bars failed while operating.

   In a similar vein, Lucent has also come to the conclusion that diode laser pump bars using current technology are simply not reliable enough to use in telecommunications applications. [Note: At the 18 May 2000 AGED Working Group C meeting, Steve Post reported that the Air Force has given an assessment of their in-house tests on commercial arrays. The dominant source of failure appears to be in the bar packaging, not the semiconductor material. They conclude that better thermo-mechanical designs, both in terms of materials used and package configurations, are needed. Operation in CW or at quasi-CW mode would reduce the stress of thermal cycling. Information provided by the Air Force indicates that diode tests by vendors are often run in ultra clean laboratories using carefully filtered powers supplies. In these tests, the lasers are left on for long times. However, in tests conducted for military applications, in which diode arrays were repeatedly turned on and off show that significant failures frequently occur as a result of the packages used.]

2. The properties of GaAs and Indium-based materials are very different from Silicon. For example, the migration of defects may preclude the use of these materials over long periods of time or at high power levels.[7] Nevertheless, the data support certain scaling laws for CW diode pumps, including a 60% per year scaling in power (with 1 kW achievable in 2005) and also a 60% per year reduction in cost (to $1 per W in 2005). This assumes the market grows to make these scaling laws continue to hold. Diffraction limited power has a 35% increase to a projected 90 W in 2005. At the critical 980 nm wavelength, SDL sees 30% growth in power, with a power level at 1000 W in about 2001. They pointed out that the 30% per year number yields a Moore's law time span (2x improvement) of 24 months. But that does assume volume production with increasing volume. There is a 3-way trade in power, reliability, and cost. They showed one set of results that had performance levels of 50 FIT, which means that these devices have a 2000-year half-life.[8]

3. Reliability is a critical requirement on solid-state lasers (SSL), especially on the diode pump arrays. Therefore, reliability should be built into the laser specification at the beginning. DoD program managers cannot assume that reliability is a given just because it is a "solid-state" laser.

Availability of Pump Arrays

Since the STAR was held in September 1999 several business changes have occurred which have significant impact on the commercial availability of pump diode arrays. SDL has announced that it will no longer sell pump arrays. SDL has played a major role in cost reduction and reliability and their exit from the military business will have a severe adverse impact. In addition, OptoPower, a division of Spectra, will only produce arrays for internal use. This leaves Siemens and two smaller, untested companies as sources for diode arrays.

RECOMMENDATIONS

Summary

An innovative program in laser technology is recommended, one that will bring optical manufacturing closer to the automated processes characteristic of the electronics industry. The basic goals will be to obtain higher efficiency, lower cost, and more reliable lasers. If this effort is successful, it should be possible to make well integrated, monolithic, inexpensive laser systems that are also rugged, stable and long-lived. Developing a limited number of broadly applicable laser modules would further facilitate the following recommendations.

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[7] Since the Star presentations, Cliff Muller reported that new data indicates defect migration may not be a problem.

[8] SDL has an interesting way to judge reliability, using a figure of merit called Failure In Time (FIT), which is used in telecommunication applications and seems to mean failures in 10^9 device hours

A close and early teaming relationship between DoD and industry is needed if low-cost, mass producible, solid-state laser products are to become a reality. An order of magnitude decrease in system cost will require more than just manufacturing technology advancement. New component technologies (e.g., fiber lasers, slab lasers and high performance diode pumps) and different system-level solutions will be required. The telecommunications, material working, medical, and commercial aviation markets represent the best source of leverage The technology goals of Lucent, Alcatel, JDS Uniphase, SDL, and Nortel overlap to a degree with those of the DoD and they will be carrying out development programs that could reduce DoD cost. High-volume technologies that can be adapted to military use (e.g., fiber lasers and their pumping technologies will be very important to the military) should be identified. System designers should focus on designs that are easily manufacturable and cost effective. These designs will likely include but not be limited to high duty factor diodes, fiber lasers, and integrated optics.

1. Strong S&T programs in laser development are needed to develop the new technologies required for low cost, mass producible, solid-state lasers. These technologies include high performance, high temperature diode pump lasers, double-clad fiber lasers, and high performance optical sensors and beam directors. These S&T activities must be closely coordinated with specific DoD missions and applications. Technology development at telecommunications companies such as Lucent, Alcatel, JDS Uniphase, SDL, and Nortel will need to be leveraged to the maximum extent possible. Other "Killer Commercial Applications" must exist or be identified to justify the $10-$100M parallel commercial development expense needed for these technologies. Examples of "killer applications" include material processing and fabrication, medical lasers, Doppler radar for commercial aviation, and laser projection displays.

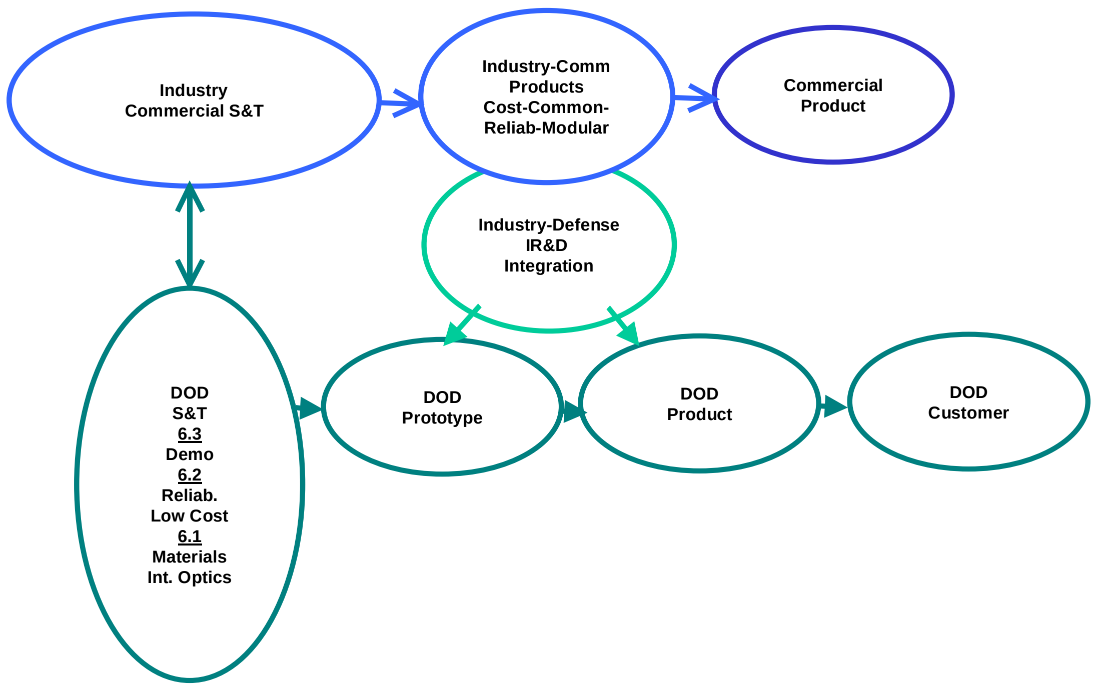
2. Reliability is a critical requirement on SSL, especially on the diode pumps. If reliability is truly important for the application, then it must be made a dominant specification. DoD program managers must demand statistical validity, while keeping in mind that good statistics always require large numbers of samples. They should not qualify unique devices, but instead qualify commercial products while focusing on commonality of packages and specifications.

3. Packaging remains a significant concern for all applications. Standards in DPSSL pump packages that encourage high volume production of fewer varieties will allow better technical focus, better prices, and higher reliability. Novel approaches to thermo-mechanical design and packaging should be investigated. Any synergy with electronics packaging technology should be exploited. For example, pick and place packaging machinery operates at or close to the precision needed for automated assembly of solid-state lasers.

Military and Commercial/Defense Industry Teaming Considerations

1. Involve commercial and defense industry early in product design.
2. Utilize multi-year procurements.
3. Coordinate DoD users in diverse areas such as IRCM, DE Weapons, and Imaging.
4. Utilize open system architectures with standard interfaces and reuse of common modules.

Figure I: Potential Teaming Structure



High Visibility DoD Applications Appropriate for Driving S&T Programs.

1. Infrared countermeasures (Disrupt and Jam, See IRCM Laser STAR).
2. Remote sensing (Coherent and incoherent CW detection).
3. Low to medium power lasers for imaging, designation, discrimination, and ranging.
4. DE Weapons (10 kW illuminators and >100 kW weapons).

S&T Focus Areas

1. **Develop modules –** A preliminary set of parameters for a solid-state laser module is given in Table III.

Table III: Low Cost, Mass Producible, Solid-State Laser Module Goals for diffraction limited output power.

Parameter	Value	Comment
Lifetime cost reduction factor	10 to 20	Estimate < $100 per watt
Lifetime	> 10,000 hours	
Wall plug efficiency	> 25%	All inclusive
Wavelength	Near 1 μm	Will consider other useful values
Laser output power density	>100 W / kg	Laser head only
Average power, laser module	>10-100 W	Application dependant
Scaling mechanism	Coherent/Incoherent > 1 kW, Strehl > 0.9	Multiple modules

2. **High Efficiency Solid-State Lasers (Wall plug >20%)**
   a) Laser materials with broad absorption bands.
   b) Monolithic, edge-pumped slab designs.
   c) Double-clad fiber lasers.

3. **High Performance Diode Pump Lasers**
   a) High temperature, air-cooled diodes and diode bars (> 70 C)
   b) Temperature insensitive wavelength coverage (<< 0.1 nm per degree C).
   c) Low cost, monolithic package technologies (<$1 per CW watt).
   d) Improved reliability through threshold reduction and power de-rating.
   e) Greater than 10,000 hr reliability under operating conditions expected in military systems.
   f) High efficiency (> 50%) fiber-coupled diode pumps.

4. **Coherent Array Technologies for Scaling**
   a) Phase conjugation and adaptive optics.
   b) MOPAs.
   c) Wavelength multiplexing.

5. **Manufacturing Technologies**
   a) Traceable to commercial mass production technologies.
   b) Standardization of diode packages and pump geometries.
   c) Stress technologies that separate thermal and optical processes. For example, deliver pump energy with fibers.
   d) Heat removal scalable to > 1 kW per cm^2.
   e) Drop-in optical alignment

6. **Ancillary High Impact Technologies**
   a) Electronic beam steering [e.g., DARPA Steering Agile Beams (STAB)].
   b) High gain, low noise photo-detectors (e.g., APDs).
   c) High sensitivity near-IR FPAs.

APPENDIX A

REPORT OF SPECIAL TECHNOLOGY AREA REVIEW
ON
LOW COST, MASS PRODUCIBLE, SOLID-STATE LASERS

AGENDA

TUESDAY, 14 SEPTEMBER 1999

	0800-0830	Check-In	All	
OP	0830-0930	Overview of Low Cost Lasers STAR	Cliff Muller	Air Force
OP	0930-1000	Low Cost Lasers for Army Applications	Ward Trussell	Army
OP	1000-1030	DARPA Optical Technologies for Military Systems	Bob Leheny	DARPA
	1030-1045	Break		
IP	1045-1130	Low Cost Laser Design/Manufacturing at Raytheon-SES	Bob Byren	Raytheon
IP	1130-1215	Cost, Reliability, and Technology Trades	Tim Albrecht	Litton
	1215-1300	Lunch		
IP	1300-1345	Can Spectroscopy Save the Day?	Evan Chicklis	Sanders
IP	1345-1430	Scalable High-Brightness Solid-State Laser Architectures	Len Marabella	TRW
	1430-1445	Break		
IP	1445-1530	Paradigm Shifts in Low Cost Solid-State Laser Technologies	Bob Rice	Boeing
IP	1530-1615	Volume Manufacturing of High-Reliability, Low-Cost Semiconductor Lasers	Jim Harrison	Opto Power
IP	1615-1700	Fiber Laser Technology at Spectran	Arthur Rhea	Spectran-Specialty
IP	1700-1745	Low Cost Diode Laser Arrays For Display Applications	Bill Bischel	Gemfire

AGENDA (continued)

WEDNESDAY, 15 SEPTEMBER 1999

	0800-0830	Check-In	All	
IP	0830-0915	Optical Fiber Lasers and Amplifiers for Telecom Applications and Scalability to High Power Applications	Ken Walker	Lucent
IP	0915-1000	Laser Diodes for Low-Cost, Mass-Producible Solid-State Lasers	Robert Lang	SDL
IP	1000-1045	Low Cost Diode Pumped Solid-State Laser Technologies	Chuck Miyake	Aculight
	1045-1100	Break		
IP	1100-1145	Some DPSSL Perspectives from Lightwave Electronics	Jeff Kmetec	Lightwave
IP	1145-1230	New Architectures and Paradigms for Solid-State Lasers Envisioned for Next-Generation Sensors and Directed Energy Applications	Duane Smith	Coherent
	1230-1330	Lunch		
OP	1330-1415	Advanced Solid-State Lasers - Power Scaling With Cost Reduction	Bob Byer	Stanford U.
	1415-1430	Break		
OP	1430-1630	Roundtable Discussion		See Below**

**Participants in Roundtable Discussion:	Byer (Stanford)	Leheny (DARPA)	Rice (Boeing)
	Trussell (Army)	Miyake (Aculight)	Smith (Coherent)
	Lang (SDL)	Muller (Air Force)	Trussell (Army)

APPENDIX B

REPORT OF SPECIAL TECHNOLOGY AREA REVIEW
ON
LOW COST, MASS PRODUCIBLE, SOLID-STATE LASERS

TERMS OF REFERENCE

DEPARTMENT OF DEFENSE
ADVISORY GROUP ON ELECTRON DEVICES (AGED)
WORKING GROUP C (ELECTRO-OPTICS)

SPECIAL TECHNOLOGY AREA REVIEW

Low Cost, Mass Producible, Solid-State Lasers

I. Applications and Technology Goals

Laser sources (CW and pulsed) are required to achieve many National Defense requirements including: range finders; illuminators; mid-IR sources for countermeasures (IRCM); and solid state optical radars for range gated imaging, autonomous piloting, targeting and guidance. Significant advancements have been made over the last few years in laser capability such as wavelength coverage and output power, but these sources are rarely deployed in operational systems due to three separate problems. The two primary problems that have precluded the use of lasers for many defense as well as commercial applications are <u>cost and reliability</u>. These problems are severe with costs running many times larger than what is economically viable for government and commercial systems. Further, many lasers today are simply not capable of reliable operation. Finding manufacturing techniques that effectively reduce the cost and improve reliability will provide a huge value to the application user while meeting a range of needs from medical treatment to protecting aircraft from attack. Mission applications generally require <u>high efficiency</u> to achieve high power levels within power availability limitations and to limit waste heat levels.

Table I: Mission applications that require efficient, reliable, low cost lasers (both CW and pulsed)

Tactical	Space
IRCM Autonomous Guidance Radar, Designators, Trackers, Illuminators Remote Sensing and Imaging Displays Directed Energy Weapons	High Energy Lasers UAV Control Battlefield Illumination and Covert Search and Rescue Remote Sensing and Imaging Detection of Underground Facilities Target Designation for Fire and Forget. Laser Communications

II. Manufacturing Technology Issues

Many DoD mission applications will not benefit from the advantages that laser sources bring unless their cost is lowered and the reliability improved. One goal of this Special Technology Area Review is to determine the important issues related to the development of low cost, reliable, high efficiency laser source.

Current laser manufacturing techniques are similar to the approach used to manufacture TVs in the 1950s. There are many very expensive, individually machined, precision components with three-dimensional positioning and adjustment required. Sadly, they bear very little resemblance to modern manufacturing technologies such as those used in integrated circuits today.

Table II: Key component costs for a solid-state laser pumped by two diode lasers. Diode laser pump bars are a major cost driver for "small" and "moderate" production quantities.

	Small Quantities ($)	Moderate > 100/Yr ($)	Large > 10,000/yr ($)
Diode bars	2,000	800	TBD No manufacturers work at these volumes today.
Laser medium(w/coat)	1,800	700	
Refrigerator/Chiller	850	400	
Power Supply	1,200	600	
Q-switch	2,500	1,200	
Labor (assembly, test-ing and alignment)	5,000	4,000	
Cost of Goods Sold	13,350	7,700	

Laser diodes in the near-IR are commonly 50% efficient. Order of magnitude scaling of solid-state laser average power has been demonstrated based on the match between diode emission wavelengths and solid-state absorption bands. Diodes are now available with emission wavelengths ranging from the blue to the mid-IR. Many packages, some complete with cooling chambers are available. Certain packages have demonstrated lifetimes of thousands of hours in laboratory tests but have not demonstrated the required reliability in field tests.

High temperature diodes take a burden off the cooling requirements and make certain fielded applications feasible. A number of one-of-a-kind diode-pumped solid-state laser systems have performed satisfactorily on aircraft platforms and satellites but the cost is far too high.

In spite of the outstanding promise of diodes, greater general utilization is limited by cost and reliability issues.

SPECIAL TECHNOLOGY AREA REVIEW
Low Cost, Mass Producible, Solid-State Lasers

TERMS OF REFERENCE

Table III: Laser Module Development Goals (with diffraction limited output power)

Parameter	Value	Comment
Lifetime cost reduction factor	10 to 20	Estimate < $100 per watt
Lifetime	> 10,000 hours	
Wall plug efficiency	> 25%	All inclusive
Wavelength	Near 1 μm	Will consider other useful values
Laser output power density	>100 W / kg	Laser head only
Average power, laser module	>10-100 W	Application dependant
Scaling mechanism	Coherent/Incoherent > 1 kW, Strehl > 0.9	Multiple modules

I. Cost: What determines the lifetime cost of lasers and how can we greatly reduce the cost?

A. Identify the cost constraints related to the manufacture of current generation diode-pumped solid-state lasers. Most solid-state lasers cost $1000-$2000 per diffraction limited watt. Why are these lasers so expensive? Is there any paradigm shift in manufacturing technologies that can reduce the cost of lasers by 10X or 20X?

B. No manufacturer makes 1000 lasers/year unless it is gas (HeNe, Ar^+, etc.) or diode lasers. Is it possible to reduce the cost significantly even with relatively low production volumes. Can better implementation of manufacturing methodologies (design for manufacture, just-in-time, lean manufacturing) bring significant cost reduction?

C. What factors determine the cost of diode pump bars? Diode laser bars continue to drop in price at about 30%/year. But, they are still very expensive. At what volume will the price be $10.00 /Watt CW in the near term ($1.00/Watt in the longer term)? Who is the customer for this volume, the government or industry?

D. The US has a strong industrial base in solid-state materials, nonlinear optical materials, diode lasers and semiconductor fabrication. Are we applying these capabilities adequately to solving the need for lower cost lasers? Does the rapidly developing MOEMS technology base provide us with an example of how to reduce laser costs?

E. Do we understand how to determine the lifetime cost of military or commercial laser systems?

F. Is there a recommended solid-state laser material and design for low cost lasers? Is there a recommended packaging configuration for low cost lasers? Can we simulate, with our modeling codes, the cost, reliability, and efficiency of proposed laser systems? Do we have a testing methodology that is relevant to low cost, high efficiency laser manufacturing?

II. Reliability: What are the reasons for reduced/low reliability in today's solid-state laser systems.

A. Are laser failures due to coatings, diode bars, electronics, mechanical alignment, etc.? What is the real cost of repairs or failures in military and commercial lasers? Why is it possible for very complex components like Pentium Chips, with millions of transistors, to virtually never fail?

B. Is the large number of components in typical diode pumped solid-state lasers a key factor in failures? If so, how can we minimize the number of components? Are there paradigm shifts we can apply to greatly increase the reliability of lasers?

III. Manufacturing Technologies: How can we leverage from the electronics and telecommunications industrial base in the US?

Many companies like Intel package complex electronics with basically zero failure rates once the product is on the street. Companies like Lucent have been manufacturing high data rate lasers for telecommunications for many years and their products have virtually no failure rates. If their assembly techniques were applied to the manufacture of solid-state lasers, would the reliability improve?

IV. Low Cost, High Efficiency Solid-State Lasers: STAR Output

The STAR output will be a technical approach for developing low cost laser manufacturing technologies for DoD applications.

APPENDIX C

REPORT OF SPECIAL TECHNOLOGY AREA REVIEW ON LOW COST, MASS PRODUCIBLE, SOLID-STATE LASERS

ACRONYMS, ABBREVIATIONS AND DEFINITIONS

AGED	Advisory Group on Electron Devices
APD	High Pulse Repetition Frequency
CW	Continuous Wave
DAPKL	DARPA/Army Diode Pumped Laser
DE	Directed Energy
DE-ATAC	Directed Energy Advanced Tactical Airborne Combat
DEW	Directed Energy Weapon
DoD	Department of Defense
DPSSL	Diode Pump Solid-State Laser
FPA	Focal Plane Array
GaAs	Gallium Arsenide
IR	Infrared
IRCM	Infrared Countermeasures
LASSOS	Lasers and Space Optical Systems
LCMPSSL	Low Cost, Mass Producible, Solid-State Laser
Mid-IR	Mid Infrared
MEMS	MicroElectroMechanical Systems
MOEMS	MicroOptoElectroMechanical Systems
MOPA	Master-Oscillator Power-Amplifier
NIR	Near Infrared
OUSD (A&T)/DDR&E/SE&BE	Office of the Undersecretary of Defense for Acquisition and Technology/Director of Defense Research and Engineering/Sensors, Electronics and Battlefield Environment
S&T	Science and Technology
STAR	Special Technology Area Review

SSL .... Solid-State Laser
UAV .... Unmanned Aerial Vehicle
WDM... Wave Division Multiplexing

Future Opportunities for Optoelectronic Components

ARPAD BERGH
President, Optoelectronics Industry Development Association
Washington, DC

Presented at the Key Conference on Compound Semiconductors
Key West, Florida
March 13-14, 2000

Optoelectronics can be viewed as the meeting place of electronics and optics, where electrons and photons are used simultaneously. Anchored firmly between a $12 billion optics market and the $150 billion electronics market, the $50 billion market for optoelectronic components is probably the fastest growing of these three areas. It is important to realize that optoelectronics is not an industry, but consists of many technologies, ranging from lasers to image sensors, with all these technologies supporting a whole variety of industries. These can be characterized within four broad categories: communications, storage, displays and imaging, each of which represent multibillion dollar markets as shown in Figure 1. In addition to these broad categories, LEDs and solar cells should also be noted as important optoelectronics markets, much smaller in size than the other four categories, but growing quickly.

The Optoelectronics Industry Development Association (OIDA) is in the process of developing roadmaps for these various segments. OIDA's objective is to not only help the North American optoelectronics industry to improve its competitiveness, but in general to promote the technology and try to enlarge the optoelectronics industry. This is accomplished in a number of ways, ranging from technology roadmapping to carrying out optoelectronic market surveys to serving as a voice for industry to the government in Washington.

Projections

When trying to see where markets will be in the future, technologists usually project the performance of components up to ten to twenty years in the future and then place them in today's markets. But this is a flawed methodology, usually leading to big surprises when demand comes much faster than anticipated. Instead, we should try to determine what the market will be ten years from now for the devices we will have ten years from now.

At first this may sound like a daunting task, because most of the things that we will have ten to twenty years from now are already here. Usually it takes twenty years for a new technology to become an overnight success.

The Internet is a perfect example of this phenomenon. Although first developed in 1975, the Internet did not really take off in any commercial sense until 1995. Since then, its growth has been explosive - and it is the catalyst for the future growth of

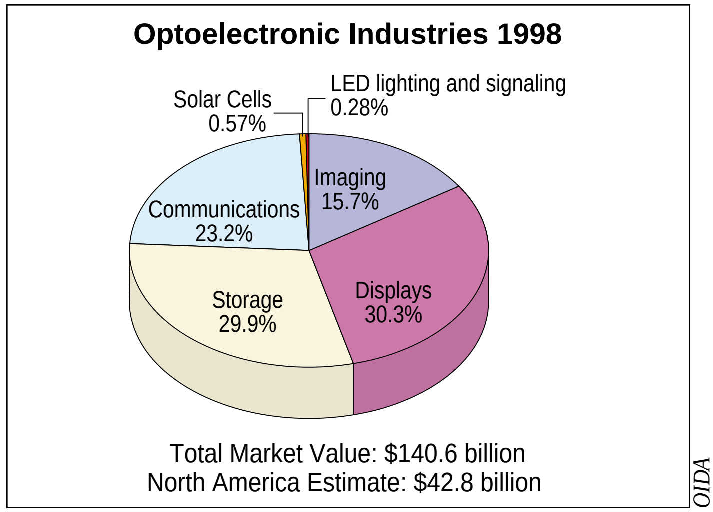


Figure 1. The four main industries that utilize optoelectronic components - communication, storage, displays and imaging - each represent multibillion-dollar markets.

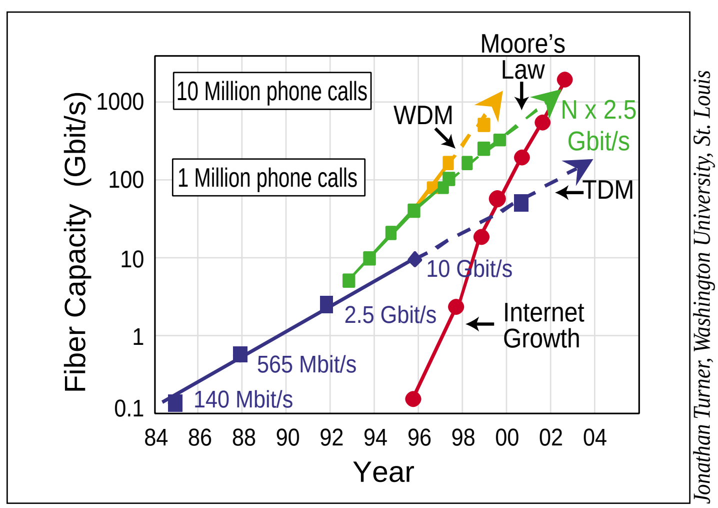


Figure 2. WDM technology is now allowing fiber capacity to grow faster than Moore's Law (which states that the number of transistors per square inch doubles every 18 months). If the fiber network had remained dependent solely on TDM technology, Internet demand would quickly have swamped the existing fiber capacity.

optoelectronics. The ability of the Internet to drive the optoelectronics marketplace has already made itself felt. As shown in Figure 2, the fiber capacity required to handle Internet traffic is doubling every 3-12 months. When Internet growth began to take off around five years ago, time division multiplexing (TDM) was only able to double transmission capacity every 24 months. If the fiber network had remained dependent solely on TDM technology, Internet demand would quickly have swamped the existing fiber capacity.

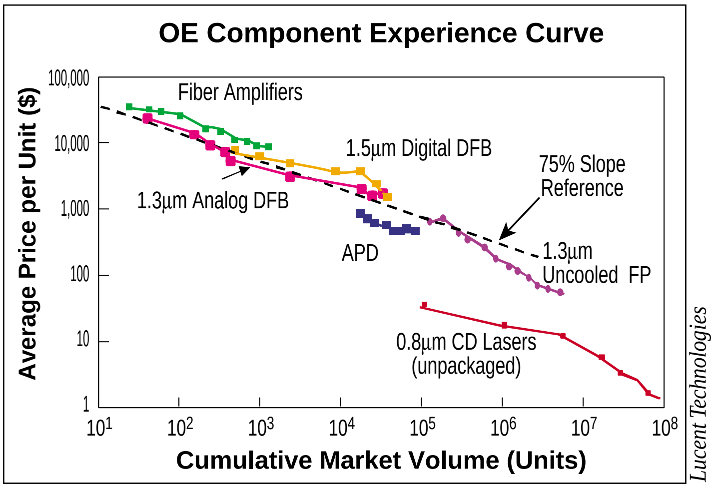


Figure 3. The cost of almost any optoelectronic component decreases at a rate of 75% as the market volume increases.

But fortunately, wavelength division multiplexing (WDM) techniques came into play. WDM technology has been able to double fiber capacity every 10-15 months, with a slope in Figure 2 much closer to that of Internet growth, and helped avoid a tremendous bottleneck which would have existed had fiber capacity been constrained by reliance on TDM technologies alone.

Thus one characteristic of our industry is its tremendous growth rate as exemplified by improved performance and an increase in capacity. The other important characteristic is the continuous, relentless decrease of cost. Almost any optoelectronic component, whether it is something as basic as a CD laser or as sophisticated as a high cost fiber amplifier, will have an experience curve which exhibits a 75% slope in cost. This is shown in Figure 3. Costs drop with increasing volume of production while performance improves. This recipe has fueled the explosive growth of the silicon IC industry and is doing the same to the optoelectronics communication market.

In making predictions of where optoelectronics technologies are heading, it is not only important to keep in mind how the silicon IC industry has evolved, but to also realize that a major paradigm shift is occurring in the telecommunications industry. The location of the intelligence in the network is shifting. Formerly, intelligence was located in a central office. But today it has spread outward, distributed throughout the network, and the form of communication has shifted from analog audio to digital multimedia, with the added complexity of mobility thrown into the mix.

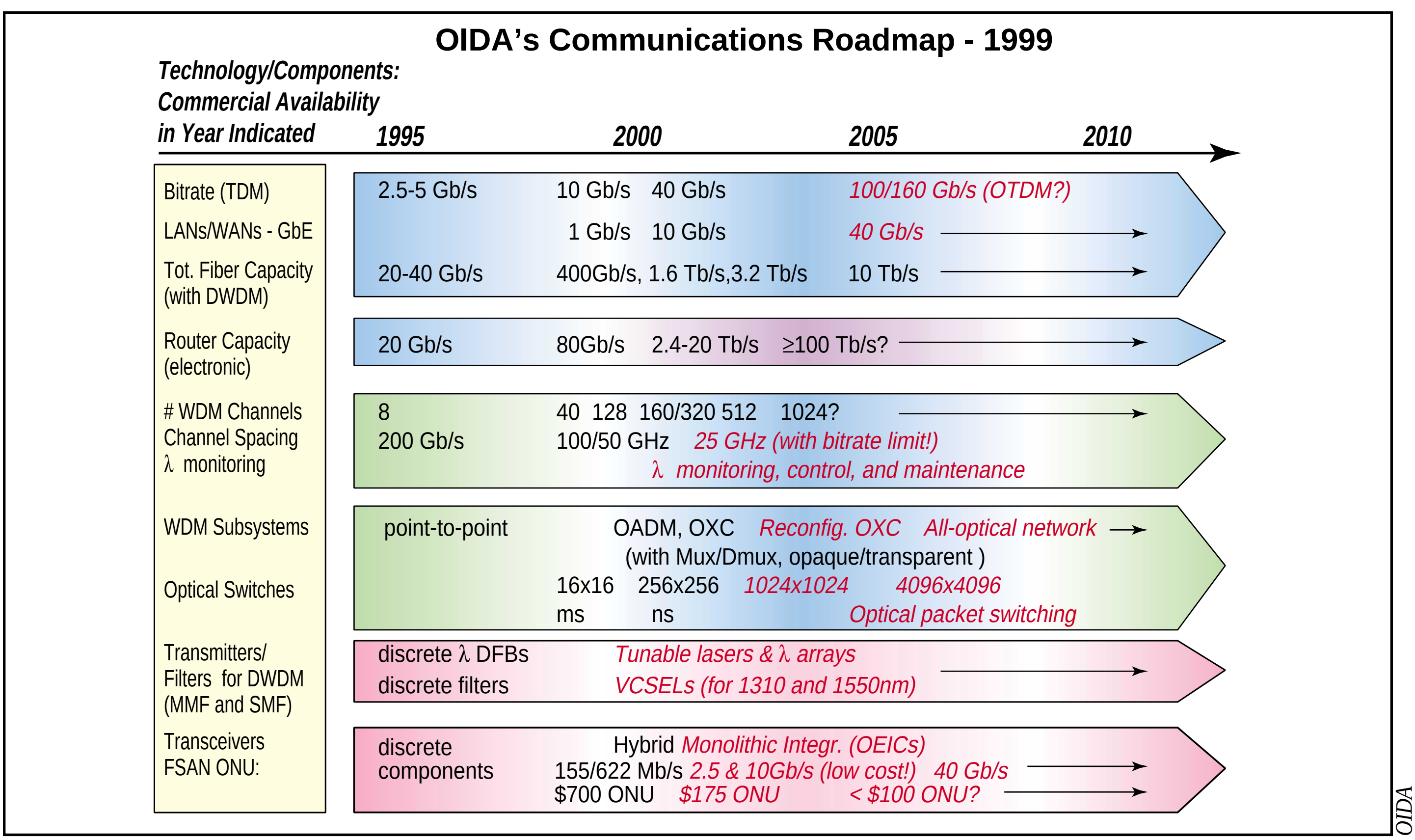


Figure 4. OIDA's roadmap for the commercial introduction of optoelectronic components in the communications industry. Red italics indicates that major industry efforts are required to achieve commercialization.

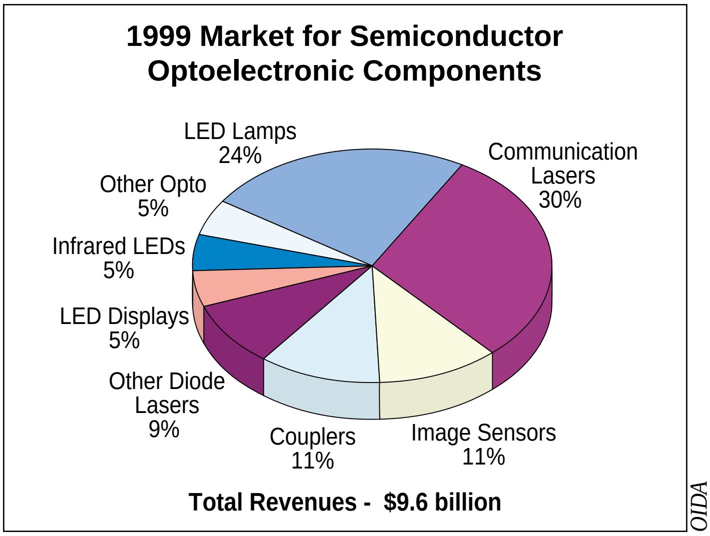


Figure 5. OIDA estimates that the total market for semiconductor optoelectronic components reached $9.6 billion in 1999.

Laser Diode Markets

	Laser Revenues		Unit Sales of Lasers	
Application	Market share (%)	Revenue ($ million)	Market Share (%)	Unit Sales (million)
Communication	71	2691	2	7.2
Storage	22	834	84	300.7
Image Recording	2	76	3	10.7
Laser Pointers	2	76	10	35.8
Materials Processing	1	38	-	-
Medical	1	38	-	-
All Other	1	38	1	3.6
Total		3790		358.0

OIDA

Figure 6. While communication applications dominate laser diode revenues, by far the largest number of units are shipped for optical storage applications (CD, DVD etc).

The OIDA roadmap reveals potential bottlenecks. The major problems are in metropolitan area and access networks, routing and switching. WDM has made great strides in increasing network capacity, but a number of major components for this future network are missing, including optical cross-connects, optical switches, multiplexers, tunable lasers, amplifiers and low-cost receivers. Improvements in performance and reduction in costs are needed for these devices, and some of our projected benchmarks are shown in the OIDA roadmap shown in Figure 4. These bottlenecks all represent potentially large markets for optoelectronics manufacturers.

The Market

In 1999, the optoelectronic communication market was about $50 billion, up from $30 billion in 1997, an average growth rate of 29%. Sales of semiconductor optoelectronic components, which includes the product categories shown in Figure 5, totaled $9.6 billion in 1999. Laser diodes account for $3.7 billion of that market. Over 70% of laser diode revenues are directly tied to communications, as shown in Figure 6. While this makes communications a dominant force in terms of laser diode revenues, in terms of the number of devices sold, the story is quite different. Laser diode unit sales amounted to 358 million in 1999, of which only 2% were for communication, with the majority being used for optical disk applications. This situation arises because high-end communication lasers are priced around $1000, while low-end storage lasers cost as little as $1. The resulting average price of a semiconductor laser is around $9.

While 358 million units may sound impressive, it is insignificant as compared to the 50 billion LEDs produced annually. However, with an average cost much less than that of a laser diode (approximately $0.06 each), the total LED market is around $3.2 billion. As mentioned earlier, relentless decreases in cost are a characteristic of our industry. Bear in mind that the silicon IC industry generates impressive annual revenues of $150 billion by fabricating transistors that have a unit cost on the order of one-millionth of a cent.

Another way of looking at the economics of optoelectronics is in terms of “real estate”. The $3.7 billion in revenues generated by semiconductor laser sales can be produced using substrates areas measured in hundreds of square meters, while the $3.2 billion generated by the less expensive LEDs require in excess of 5,000 m^2 of substrate material. However, as shown in Figure 7, the silicon industry needs 40,000,000 m^2 of substrate to generate its $150 billion in revenues.

Optoelectronics are at the very beginning of a growth era. It is doubtful that compound semiconductors will ever catch up with silicon, but they will certainly come much closer than they are today. And the Internet will be the engine behind much of the growth.

Currently there are roughly 40 million people in the US having access to the Internet, but only 1.7 million of these users have broadband access. However, in the next 2 to $2^1/_2$ years, this figure will grow to 18 million, creating an enormous market for optoelectronics. In the near term, the demand for broadband access will increase the demand for optoelectronics in such devices as optical cross-connects, optical switches, optical add-drop multiplexers, tunable lasers, optical amplifiers and optical transceivers. And once broadband starts reaching customers, a trickle-down effect will be felt in other parts of the industry, placing tremendous demands on both storage and imaging.

Solid State Lighting

After the Internet, a next major driving force in optoelectronics will be solid state lighting, using LEDs. The OIDA foresees major activity in this area in the next ten to twenty years.

The annual worldwide lighting market is currently around $16 billion, and is driven by three dominant lighting sources: incandescent, halogen, and fluorescent. The efficacy of a lighting source is measured by the ratio of optical output power adjusted to the sensitivity of the human eye to electrical input power. It is expected that there will be little to no improvement in the efficacy of incandescent and halogen lights, although the more efficient fluorescent sources still have slight room from improvement. But with solid state LED-based lighting, we can easily anticipate a light source with an efficacy which is 2X better than

Comparison of Semiconductor Markets

Component	Revenue ($ B)	No. of chips per year	Semiconductor area (m^2)
Semiconductor Lasers	3.7	360 Million	100*
LEDs	3.2	50 Billion	5,000*
Silicon ICs	150	285 Billion	40,000,000

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Figure 7. A comparison of the substrate "real estate" required to generate the total market revenue of three different semiconductor markets. Clearly, the laser diodes generate far greater value per unit substrate area than LEDs or silicon ICs. [*Approximate area assuming 100% yield].

the best fluorescent sources, and 10X to 15X better than halogen or incandescent lights. Tremendous savings in energy costs will result - perhaps as much as 50% [see Figure 8]. As a result, it is possible that we would not have to build any new power plants in the next 30 years.

Further down the road, the OIDA sees the possibility of a fundamental paradigm shift, in that many new opportunities

Potential Impact of LED Lighting

Potential Savings in One Year		US	ROW	Global
Dollar Savings	$ Billions	35	75	110
Electricity Savings	TeraWatt Hours	350	750	1100
Avoidance of CO_2 Emissions	Tons (Millions)	95	210	310

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Figure 8. LED lighting could have a huge impact on the consumption of energy and on CO_2 emissions. The figures represent the potential savings in 2025, assuming that solid state lighting achieves a 50% market penetration.

unfold through the integration of optoelectronics with various other technologies such as electronics, optics and microelectromechanical systems (MEMS). It is quite conceivable that most of the devices that we produce in optoelectronics can be mounted on silicon. And that really is a paradigm shift in all the market segments, including even the simplest one, in lighting, opening the door to what might be called "smart lighting".

But while these tantalizing prospects are still somewhere in the future, the Internet is here with us today. Broadband access will grow explosively over the next five to ten years, and it will be the primary driving force for optoelectronics components.