Early Experiments on Optical Disc Storage

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Invited Paper

***Abstract*—Optical technology was early proposed to attain information density higher than 10 Gb/in^2 with fast data transfer for storage of video, audio, or computer data either using holography or bit-by-bit memory architectures. We present in the paper how the concepts and technological issues have progressed at THOMSON-CSF and in other laboratories for the demonstration of an optical pickup enabling the readout of a 30-min TV program recorded as microtips on a spinning disc. The main technical breakthroughs are presented until first commercial success was achieved with the compact optical audio disc (CD) and evolution toward the optical CD-ROM and the DVD. Future research directions for achieving extremely high capacity in a compact system are also discussed.**

***Index Terms*—Holographic storage, optical disc, optical storage, recording media.**

I. Introduction

The need for a tremendous increase in data storage capacity at an affordable cost, that was anticipated in the early 60th for the forthcoming decades stimulated a large variety of studies (magnetic recording, semiconductor memories, optical memories, ...). Even though high-resolution optical media were used to store images (microfilms, electron video recording EVR system, ...), no real simple way existed for retrieving a huge amount of optically stored informations. The triggering event was the early recognition after its recent invention that the use of laser light would permit to attain high data storage densities for realizing new memories whose high performances would bring the opportunity of large applications in the professional or consumer market.

The authors of this paper which have been involved at the early days of the researchs and developments of optical storage techniques at THOMSON-CSF give their personal account of the development of the optical disc. They want to show that most of the innovative concepts issued from a long period of research and development which are presented hereafter, became progressively the ground of the today high-tech optical storage disc.

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II. Basic Concepts: Bit by Bit and Holographic Storage

Due to its coherence property, a low-power He–Ne Laser could be focused on a photosensitive media on a diffraction limited spot size. In such conditions, the theoretical ultimate storage density which could be envisioned on a planar optical recording media was in the range of 10^8 bit$\cdot$cm^{-2} for a visible wavelength $\lambda = 0.6$ μm. Beside this, the early works on holography also proved the capability of diffraction-limited storage density with parallel write-in and readout of data patterns.

Starting from these preliminary research activities, the laboratory experiments in the late 1960s based on sequential bit-by-bit recording or holography, proved the potential capabilities of the optical technology to complement, or substitute to magnetic technology for mass data storage. It was shown at that time that optics could provide the opportunity of higher bit densities, fast access with nonmechanical contact to information carried on a homogeneous and cheap media [1]–[3]. Moreover, it was proposed that the memory planes could be easily copied either by a photographic contact or by direct embossing on a plastic layer when information is stored as a micro deformation of the surface memory substrate. This last feature could insure the replication and large diffusion of the storage media at very low cost for the consumer market.

Having very early identified those new properties offered by optics, we, at THOMSON-CSF/LCR, initiated research programs as early as 1967 to assess the capabilities of both optical storage techniques based on the use of coherent sources: holographic as well as bit-by-bit storage have been investigated [3]–[6], based on the use of bulky gas lasers and available storage media such as high-resolution silver halide photographic plates (with the possible use of bleaching techniques to increase efficiency of holographic recordings), photoresist layers deposited on glass substrate, and also exploratory materials such as photochromic, thermoplastic, magnetooptic layers [5]–[8]. Also, in order to attain much higher storage capacities, we already proposed to use very thick photosensitive storage media in order to exceed by two or three orders of magnitude, the limitations due to planar substrate [9]. This motivated research works at THOMSON-CSF/LCR on volume holographic recording in ferroelectric electrooptic crystals which moreover had the potential capability to record, to multiplex and erase the holographically stored digital or analog data [10], [11]. First, topical meeting on optical data storage was organized by the IEEE and the OSA in 1972 [12].

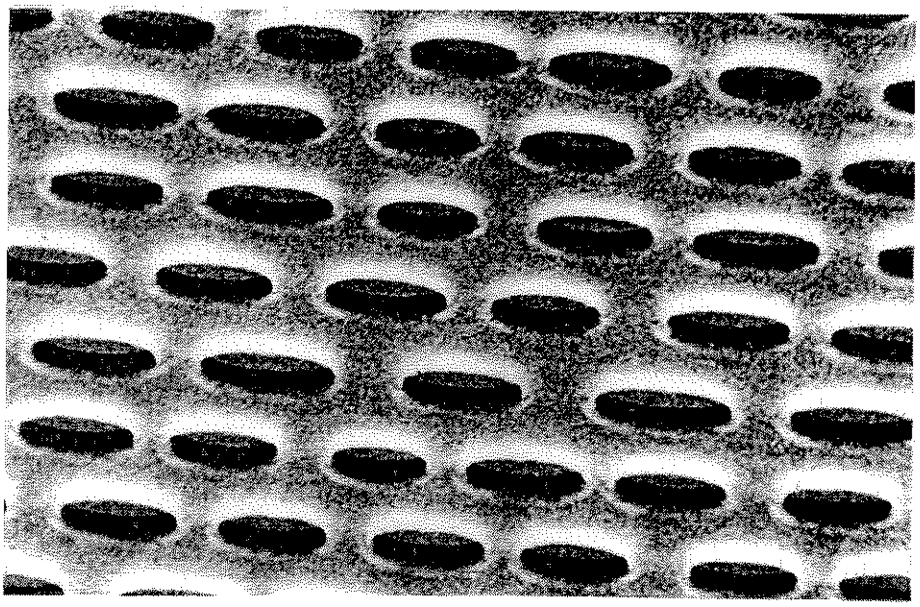

Fig. 1. Electron microscope view of the replicated embossed plastic optical videodisc realized in 1972: pits are 1 μm length–2 μm pitch.

III. From Early Work on Optical Videodisc to the DVD

For a few years, there was a quite large diversity on research activities and proposals for innovative storage systems, before it was realized, in 1970–1971, that the most realistic approach was to use a rotating disc as the storage medium. With the development of television, requiring new means to record and play video and audio signals, and with the early development of optical communications, significant needs would arise so as to provide customers with efficient and low cost techniques for the storage of TV images. This main idea was supported by simple arguments relevant to TV signal information content: one half-hour TV program could be stored on a 30-cm disc diameter, thus requiring a storage density of the order of 30 Mbit·cm^{-2}, that could be theoretically achieved with diffraction-limited optical storage [13]–[15]. Again, these objectives could be attained using either holography or bit-by-bit storage and we, as others, were engaged on both techniques. Having in mind the design of a consumer dedicated system, much concern of the possible drawback of dust and support imperfection (even with the use of error correcting codes), as well as rotation speed (one image per revolution), and precise tracking of the information during the readout of the data, led us to investigate holographic storage technique. Based on quasi-Fourier holography, this approach exhibited very interesting features: continuous diffraction of the whole image on a 2-D detector (cheap Vidicon tubes were available), immunity to dust or support imperfections, low rotation speed of the media, and invariance in translation of the restored analog images. Also, it was proposed to holographically record the analog video signal on a spinning disc. In that system readout of informations was made possible on a single detector. The operating principles were validated. Discs with several tracks of small holograms (of the order of one millimeter in diameter) were recorded on high-resolution photographic plates, processed and played. Replication process was also demonstrated. Input data were conventional movie films, and the recording process was done image by image.

While the expected advantages listed previously were noted in these experiments, we rapidly highlighted that several major problems arose due to the complex recording setup (color coding, sound tracks) and to coherent speckle noise which degraded the quality of reconstructed analog images (noise reducing techniques were experimented but were not totally satisfactory). At that time, RCA Laboratories was also working on an holographic technique [4], [5]—the first Selecta Vision process—using an embossed thermoplastic film as a media, however, making use of a much wider area for each image, thus reducing the noise problems but also decreasing the storage density (later, the name Selecta Vision was also used for the capacitive RCA videodisc). In a different nonholographic approach, Colombia Broadcast Society (CBS) was working on direct electron beam recording of micro images with optical readout.

The inherent limitations due to the holographic technique justified the fact that the research efforts were concentrated on the bit-by-bit recording approach, conducted simultaneously since the beginning. This is even today the only commercial optical memory product: the optical disc, now well known by the consumer as well as professional markets for audio, video, and computer storage. This orientation was also chosen by the major industrial laboratories who at that time were conducting research works on this subject (THOMSON, Philips, Zenith, MCA, RCA, Bell Labs ...). The general idea was to store a 30–40 min TV program (video signal and possibly several sound tracks) on a cheap disc support which could be replicated by an embossing process similar to the one used for producing audio records. The disc would then be read by focusing an

Fig. 2. View of the THOMSON-CSF flexible plastic videodisc. The disc is copied from a metallic master, disc diameter 30 cm, 30 minutes TV program.

He–Ne laser beam onto the surface of the disc spinning at 1500 revolutions per minute (1800 rpm for NTSC), and detecting an optical signal resulting from the diffraction of the light beam by embossed micropits. This leads to the restoration of the video signal and the display of a TV program [13]–[16].

The complete process started with the recording of a master disc: a photoresist layer deposited on a flat glass support was used as the photosensitive medium. It was written on a specific recording machine with a focused Argon ion laser beam modulated by an acoustooptic or electrooptic modulator [13], [15]. The blue laser beam was modulated according to the frequency-modulated video signal (luminance, chrominance, and sound) to be recorded. Due to the nonlinear response of the photoresist, this FM signal would, after the developing process of the layer, result in a succession of micropits, whose lengths and spacings vary in accordance with the video FM signal, with a constant width (0.8 μm or less), placed along a track whose pitch was 2 μm during the early experiments. Later on the spacing was reduced to increase the data storage capacity. Fig. 1 shows an electron microscope view of the micropits copied on the plastic disc. During the readout process, the disc (this master disc could be read directly in order to assess the quality of the recorded signal and to decide accordingly to proceed to the replication) would be illuminated by a focused low-power laser beam, so as to obtain a modulated signal allowing one to retrieve the FM signal. This modulated signal is generated by a diffraction process due to the interaction of the laser beam with the replicated micropits and detected by photocells. Modelization of the diffraction process was conducted so as to optimize the detected signal and the readout setup. It was theoretically demonstrated and experimentally verified that several parameters were important so as to optimize the readout process [13], [15]. Depending on the readout scheme, the optical depth of the pits (a fraction of a micrometer), the resulting signal and the duty factor of the pits could be optimized. If satisfactory, the disc was then fabricated by embossing a thermoplastic foil Fig. 1 or by injection molding of a plastic material. A metallic stamper usually made of nickel was manufactured by a galvanoplastic process in order to replicate precisely the micropit structure of the master disc. From the original master disc, several stampers could be fabricated, in order to then produce a large quantity of plastic discs.

Once the recording and replicating experiments were quite satisfactory, it was necessary to solve the complex technical problems for tracking and readout of the micropits. Of course, these difficulties were inherent to the bit-by-bit approach and were not encountered in the holographic approach. New ideas had to be proposed to allow simultaneously efficient tracking of the pits and appropriate readout of the video signal. Readout was imposing the use of a high numerical aperture objective, thus making tracking (vertical and radial) tedious due to the resulting small volume of the diffraction limited spot size! Typically it was required a vertical focus tracking precision $\Delta z \leq 2$ μm while for the radial it was $\Delta\rho \leq 0.3$ μm. This is why instead of having a high precision and rigid mechanical optical mounting, it was proposed to introduce a very flexible optical system in which the tracking and focusing functions would be controlled by judicious piezo or electromechanical servomechanisms driven by electronic feedback signals. The original approach proposed by THOMSON-CSF was to separate the vertical focusing and radial tracking problems. The choice of a thin flexible disc (Fig. 2) was imagined so as to permit the disc to be stabilized by aerodynamic forces by an appropriate design of

Fig. 3. Photograph of the early prototype of the THOMSON-CSF optical videodisc player.

the player [13]. TELEFUNKEN and DECCA in Germany had demonstrated a mechanical readout using this stabilization concept (Teldec system). It was shown at LCR that the surface of the disc, rotating above a specially design deck, could, within a gap, "fly" within the depth of focus of the objective, therefore allowing a good readout of the micropits. (In 1970, it was difficult to build a cheap electromechanical transducer to control the focusing.) Later, the introduction of cheap servo mechanisms for high precision optical focusing of the readout spot on the surface of the disc was one of the main breakthroughs that led to the development of the disc technology. The radial tracking was achieved by using an interesting property of the light pattern diffracted by the pits: this key feature anticipated and demonstrated in the laboratory relies on the fact that this pattern becomes asymmetrical (except for some "forbidden" optical depths of the pits) when the pits become off centered with respect to the readout beam. An error signal can then be obtained easily by detecting the diffracted light pattern with photocells, allowing the tracking to be obtained by moving either the readout lens, or a mirror. The combination of the aerodynamic stabilization plus radial servo, allowed THOMSON-CSF to demonstrate already in July 1972 the feasibility of the complete videodisc system design (Fig. 3). Several public presentations were subsequently performed [17], allowing for the exhibition of some very interesting features and advantages:

— freeze frame (one image per revolution);
— image-to-image periodic jump;
— slow-down, or speed-up, forward and reverse;
— disc with a low manufacturing cost (plastic, flexible and transparent, 6 mils thick, up to 12 in diameter).

Following those early days, several ideas were experimented in order to improve the reliability and the performances of the system:

- vertical tracking based on the use of error signal derived from an astigmatic sensor;
- protection against dust, scratches, fingerprints: it was demonstrated that, with the use of a sufficiently thick protective layer, on top of the recording, those spurious effects could be avoided, since all the defects were out of focus and could not spoil the readout signal (actually, the information was read through the disc, and the pits were protected by a thin layer of polymer);
- the possibility to superpose several discs, and to be able to retrieve the signal from each recording without being disturbed by the other recordings, by simply changing the focus of the readout objective; this feature allows higher storage capability and is now being used in some DVD arrangements;
- possibility to readout the discs either using the transmissive or the reflective way.

Several fields were envisioned for this new technology: consumer products, but also the professional market, education, library, etc.

Following this method of innovative applied research activities in the field for about ten years, most of the important technical issues were solved. It was shown that the optical pick-up and the 30-cm diameter disc were a realistic solution for TV program storage. The removable disc could be made inexpensively by replication for large diffusion, the nonmechanical contact with the optical head ensured extremely long lifetime. Several industrial companies such as RCA, JVC, Teldec, MCA, THOMSON, Zenith, and Philips, each one having his own proprietary designs, were convinced by the importance of the TV market and were ready to start system development. Some systems were proposed for the consumer market. However, at that time, in the early 1980s, there was also a rapid development of compact magnetic videotape recorders for consumer market applications by several companies such as RCA, Sony, JVC, Matsushita, and Philips. The magnetic videotape allowed the consumer either to record his own TV programs at home or to read prerecorded video cassettes with the same apparatus. Industrial companies were convinced that, at equivalent level of performances, in terms of program durations and image quality, magnetic heads and tape technologies were dealing with less technological risks and lower costs. Since these video products were a mature and existing magnetic technology, it prevented the TV optical disc from reaching the market at that time.

However, a second chance for success for the optical storage technology arose nearly at the same time due to the conjunction of two major events:

First, the introduction of the compact solid-state semiconductor lasers emitting in the near IR at wavelength range $\lambda = 0.8$–$0.9\ \mu m$, to replace the bulky He–Ne laser in the optical pick-up. This component was made reliablely and cheaper for telecommunication applications and its spatial and spectral properties were also the most convenient for the disc readout.

The semiconductor laser was close to the ideal coherent source and it helped a lot to miniaturize the optical head.

Second was the fact that the TV consumer market may not have been the best target and that the audio disc market could be addressed using this optical pick-up technology. Several industrial companies, including THOMSON, considered this opportunity. In fact, the move came from Philips and Sony, who contributed to promote the use of the concepts developed for video image storage and apply them for audio storage [18]. The storage density was much less than that required for the video image, and, consequently, it relaxed several constraints on the overall performances of mechanical components and on the frequency response of servo actuators. Due to the significant increase of sound quality, the laser audio disc is a now fully established and successful technology. After more than 15 years of active research and several technical doubts, the optical storage technology finally became a consumer product, and it represents today a huge multibillion dollar market. Starting from this success and taking into account the constant progress of the technology, further developments and new products were appearing in the 1990s: the optical CD-ROM and the digital versatile disc (DVD) which presently provide a storage capacity of 5 Gbytes per side.

IV. Future Trends

The field of research and development is again rapidly evolving, and many new concepts and technologies are being tested in the laboratories for increasing system performances. First, the capability of read–write of data using an erasable media based on magneto-optics (MO), or phase change physical mechanisms is now established. In particular, a new generation of MO disc systems has been developed in the late 1990s, where the areal storage density has been achieved around 5 Gb/in^2. The MO system also achieved high transfer rates of 40 Mb/s and overwrite cycles of more than 10^7. Second, the increase of the overall system storage capacity. To achieve this goal, optical discs consisting of two or four data layers of permanent or erasable media were proposed and validated in laboratory experiments. The choice of a shorter visible wavelength for the semiconductor laser is also an important issue. Red wavelengths of 650 nm are now the common standard and, for the near future, the gallium nitride blue lasers emitting at 410 nm or in the near UV are undoubtedly the best choices for the future generations of optical storage systems. Combining short wavelength, with a very high numerical aperture objective of the order of 0.8 and advanced concepts of optical super resolution experienced by several labs, the areal density of the MO disc would be expected in the range of 50–100 Gb/in^2 [19]. Using these principles together with advanced light sources, detectors and actuators would provide extremely compact and high-density MO systems in the near future.

There is now a large diversity of new basic concepts which are also under study in the labs: optical near-field optics promise capacities of 100 Gbytes but at the expense of an extremely short distance between optics and media; 3-D volumetric storage in bulky nonlinear materials with a threshold process at the location of focus demonstrated storage densities of more than 20 Gb/cm^3. Also, page-oriented volume holography is reconsidered again by several labs since it brings the opportunity of having both the storage capacity and multigigabit data transfer: some recent significant progress on the main components of the architecture and in particular the storage medium were achieved [20].

V. Conclusion

The need for storage is explosive and growing at an exponential rate. For such purposes, no doubt that the optical disc will play an important role in combination with other technologies. However, the key for future success is the availability of a storage medium having the required characteristics for read–write of data. This objective must contribute to stimulate basic material research activities, since it is now the most important point to consider for the design of extremely high-capacity optical storage systems enabling one to attain an equivalent density of 1 Tb/in^2 with a Gb/s data rate for the forthcoming decade.

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A Brief History of High-Power Semiconductor Lasers

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Invited Paper

Abstract—**The following is a historical perspective of the significant technological demonstrations that shaped the history of high power semiconductor lasers. This article is not meant to be a review article, as there are much better review articles and reviewers available, nor would the article try to cover all of the contributions to such a rich technology. Nonetheless, this article will, anecdotally, present a perspective on the technological advances that resulted in the enabling technology of high power semiconductor lasers for applications such as fiber optic communications, data storage, and material processing.**

Index Terms—**Optical communications, semiconductor lasers.**

I. Introduction

THE SEMICONDUCTOR laser, first discovered in 1962 [1]–[4], was thought to be a breakthrough invention that would revolutionize industry. As early as the late 1960s and early 1970s there were patents and articles proclaiming the utility of this technology for optical data storage and fiber optic and free space communications. However in its early form, the simple p-n homojunction device was a long way from realizing the dreams of these early inventors. To realize the capability of semiconductor lasers and specifically high-power semiconductor lasers a convergence of many technologies had to be realized. Advances in crystal growth technologies, the development of double heterostructure lasers and subsequently quantum well lasers, materials passivation technologies, heatsinking technologies, pseudomorphic materials; breakthroughs in device designs including single-mode lasers, laser arrays, distributed feedback lasers, and the simultaneous development of complementary technologies, the most significant of which is the rare earth doped fibers for fiber amplifiers and fiber lasers, all contributed to one of the most enabling technological industries today, that of high-power semiconductor lasers. In many ways semiconductor lasers are second only to the transistor and integrated circuit as to their impact on today's high-technology market place. The semiconductor laser is the conduit in which the internet became economically feasible and is the backbone of which the information age of tomorrow will depend. The following paragraphs will address specifically the technologies associated with the development of high-power semiconductor lasers from an historical and tutorial perspective.

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II. Materials Technologies

By the late 1970s, semiconductor lasers had advanced to where double-hetereostructure lasers had been developed resulting in reduced threshold continuous wave (CW) emission [5], [6]. In addition advances in laser design included the breakthrough realization of distributed feedback lasers. Liquid phase epitaxy (LPE) was used to fabricate these lasers [7]–[10], however, the performance was limited by the inability of LPE to grow uniform thin epitaxial layers and accurately tailored doping profiles. Nonuniform materials from LPE-grown wafers resulted in current crowding and optical self-focusing, thus limiting the aperture size of the laser to a few micrometers, and the thick active regions ($\sim$0.5 μm) were lossy limiting the efficiency of the laser. The consequence was a laser that could only operate reliably to a few milliwatts in output power and a manufacturing process that resulted in low yields.

The first key technology advancement necessary for the realization of high-power lasers was the development of two new growth technologies: metallorganic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE). These two key technological advancements, developed nearly simultaneously, created a tool that enabled the laser designer to control the crystal deposition to atomic layer accuracy which resulted in two benefits: uniform material deposition and ultimately quantum well active layers.

Uniform material deposition is critical to both laser performance and yields. The more uniform epitaxial layers enabled the development of large aperture laser structures, the first such device was the evanescently coupled laser array. Large aperture devices dramatically broke through the barriers of power output from a single laser. Output powers well in excess of several watts were demonstrated. Over the course of the next decade, higher and higher output powers will be developed where outputs exceeded 10 W CW from a 200-μm laser source [11]–[16].

The second effect of the conversion from LPE crystal growth technology to that of MBE and MOCVD was the ability to grow thin active layers on the order of 10 nm. LPE was typically limited to active layers on the order of 0.1–0.5 μm. Thin active layers were very difficult to grow by this technique. The consequence of a thick active layer laser structure was that there was a high overlap of the optical mode with the free carriers in the active layer. The propagation loss within the laser, being dominated by the free carrier absorption in the active layer, was therefore inherently high and consequently the threshold, efficiency of the laser, and the length of the laser cavity is limited. Fig. 1 depicts the impact of propagation loss on the efficiency of

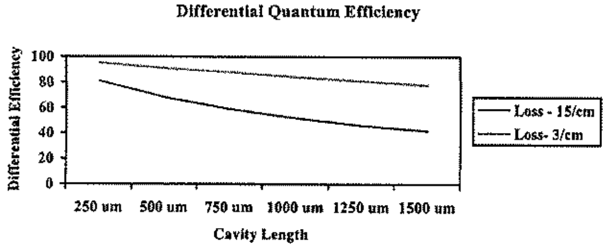

Fig. 1. Effect of distributed loss on a laser with reflectors of 4% and 100%, an internal conversion efficiency of 100%, and a distributed loss of 15 cm^{-1} (typical for thick active layer LPE materials) and 1.5 cm^{-1} (potential loss for quantum well lasers).

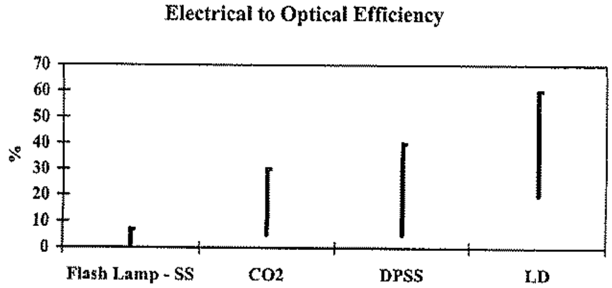

Fig. 2. Relative electrical to optical conversion efficiency.

a hypothetical laser with a device with 4% and 100% reflectors and an internal conversion efficiency of 100%.

The consequence of a high-propagation loss in the laser cavity not only impacted the laser efficiency, but it also impacted the ability to fabricate long cavity length lasers and therefore the thermal resistance of the laser. The thermal resistance of the laser is a critical design consideration for high-power lasers. The short cavity length of LPE grown lasers, typically less than 250 μm, increased the thermal resistance of the laser, limiting the ability to dissipate power and ultimately the output power of the laser.

The advent of MOCVD and MBE changed the way the research community could think about laser designs. The ability to control the crystal deposition on an atomic scale in a fashion that resulted in uniform epitaxial growth was the first major breakthrough for the development of high-power lasers. With this new tool the research community went to work and the first conceptual breakthrough was that of quantum well lasers. Quantum-well lasers, lasers with active layer thicknesses on the order of 10 nm, resulted in a number of advantages including a dramatic reduction in threshold current, a reduction in the free carrier loss, and a reduction in the temperature sensitivity of the threshold current. All of these effects increased the efficiency of the laser and the ability to make lasers with longer cavities and therefore lower thermal resistance. Furthermore, as the overlap of the optical mode with the active layer was much less, the power limitation caused by catastrophic optical damage of the laser was significantly improved. The net effect was the ability to demonstrate higher output power lasers.

A significant metric of semiconductor lasers as compared to other laser systems, and ultimately the determining factor in much of the performance of these lasers in ultrahigh-power applications such as welding, is the ability to demonstrate electrical to optical conversion efficiencies of greater than 60%. No other laser media can approach this type of efficiency (see Fig. 2) and therefore, in high-power applications where heat generation and removal are the limiting factors, semiconductor lasers have the distinct advantage.

III. Catastrophic Optical Damage (COD)

The next limitation to output power for semiconductor lasers after the initial advances in crystal growth technology was that of catastrophic optical damage (COD) to the end facet of the laser. COD is a result of surface recombination sites on the cleaved facet causing a depletion of charge at the crystal surface. The depleted bands absorb the laser emission that, when the absorption is sufficient, causes thermal run away effect, melting the end facet of the laser. COD is especially prevalent in Al containing materials and as a result greatly impacted the reliability of AlGaAs lasers, and therefore inhibited the introduction of high-power AlGaAs lasers into applications like communications and optical data storage.

Extensive research by several laboratories was performed on both materials technology and passivation techniques to eliminate COD. Several research organizations were able to come up with process technology necessary to eliminate COD, each organization having a different approach to the problem. Ultimately COD was eliminated as a reliability limitation for most laser diodes. It was these various techniques that enabled high-power lasers for both the communications market and the recordable optical data storage products. Furthermore, reduction in the impact of COD on reliability greatly improved the performance of high-power lasers for DPSS applications, enabling greater penetration of DPSS lasers into the material processing and thermal printing markets.

IV. Pseudomorphic Materials

The next major technology breakthrough for semiconductor lasers and specifically high-powered semiconductor lasers was the conceptual development and experimental realization of psuedomorphic materials [17]–[22], otherwise referred to as strained layer materials. Up to this time crystal growth was limited to the material systems that were lattice matched to a common substrate. In the mid-1980s, a series of conceptual developments occurred that resulted in the realization that a layer need not be lattice matched if its thickness was less than the critical thickness, at which point the material would no longer be single crystal. Layers that were on the order of 10 nm could be grown in the midst of a lattice match layer structure where the lattice mismatch could be significant. This concept lead quickly to the incorporation of In into AlGaAs quantum well material structures and was applied to all semiconductor laser material structures.

InGaAs active regions in AlGaAs layer structures resulted in several key benefits: higher gain from the materials, lower threshold current operation, higher efficiency, extension of the emission wavelength to longer wavelengths, and higher reliability. For AlGaAs lasers grown on GaAs substrates, emission wavelengths could then be extended from less than 780 nm to

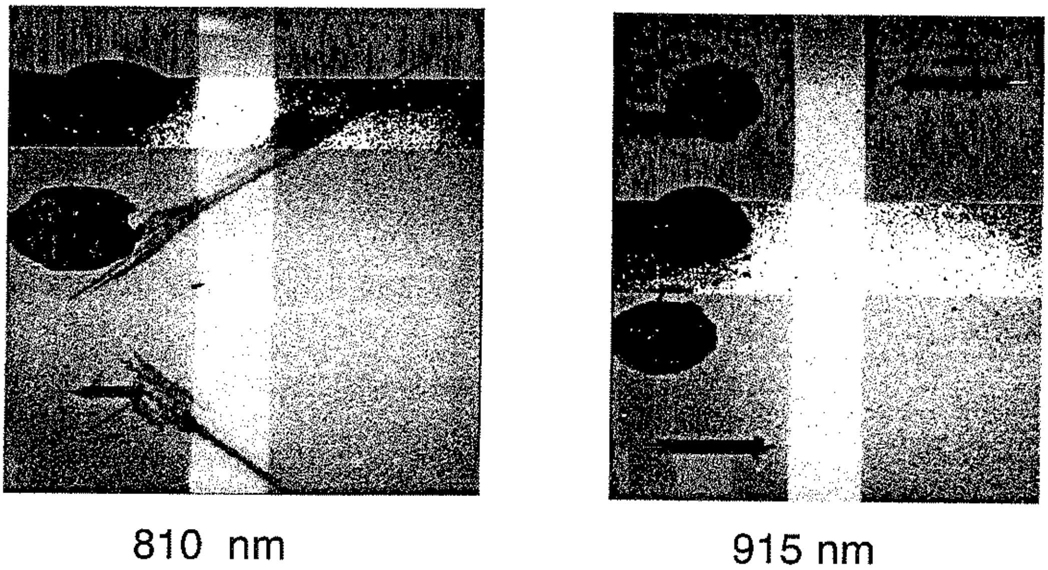

Fig. 3. Electroluminescent images of the surface of a broad-area laser operating at 810 and 915 nm. For this experiment defects were intentionally introduced in the chip and in the case of 810-nm lasers (no In) these defects are seen to propagate through the active region [22].

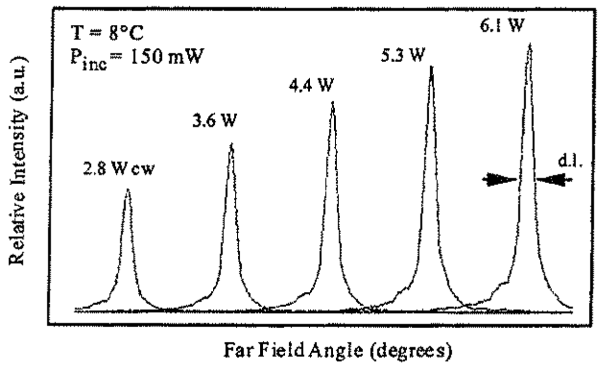

Fig. 4. Far field patterns from a BA amplifier for output powers from 2.8 to 61 W CW with an injected power of 180 mW.

longer than 1100 nm, easily reaching the emission wavelengths necessary for pumping of Er doped fiber amplifiers (discussed in more detail below). It was further shown that the incorporation of In in the active region of an AlGaAs laser inhibited the migration of defects in the material thus improving the reliability of the material. From these developments came high-power, highly reliable lasers operating at 980 nm and the first short wavelength laser that could meet the 20-year lifetime required for communication systems.

Pseudomorphic materials were critical to the development of another class of high-power lasers, that of AlGaInP lasers for the emission between 630 and 680 nm. AlGaInP lasers had been demonstrated for operation in the 680-nm region, however, these lasers when lattice matched resulted in high-threshold currents and limited their output power to a few milliwatts. With the introduction of pseudomorphic materials to the design of AlGaInP materials, the gain could be significantly increased resulting in lower threshold current densities. The result was the realization of high-power, high-efficiency lasers operating at 630 and 680 nm.

Pseudomorphic concepts have since been applied to most semiconductor material systems including GaInAsP–InP laser where efficiency, power, and polarization effects have been optimized, AlGaInN lasers for efficient operation in the 380 to 470 nm region and in AsSb-based materials for lasing properties in the mid-IR.

The above discussed material advances and the resultant laser design advances created the ground work for a number of critical applications that were enabled by high-power semiconductor lasers. As each relevant application is discussed, high power is qualified as a relative term to the state of the industry prior to these advances. As an example, high power in the realm of industrial lasers is measured in watts and kilowatts, while high power for optical data storage is discussed as the advances necessary to take the technology from the few milliwatts level to 30 mW and beyond. Often the impact of achieving high power directly correlates the overall reliability improvement of the laser.

V. Single-Mode Semiconductor Lasers

Advances in materials technology and process technology as discussed above have made dramatic advancements in the ability to efficiently generate power at high reliability and across extensive wavelength coverage in semiconductor lasers. There is an entirely different branch of semiconductor laser development associated with the generation of multiwatt output power in a single spatial mode. Standard techniques for generating single-mode waveguides have been demonstrated in high-power materials resulting in the demonstration of greater than 1 W of single-mode operation from a few micrometers aperture. The motivation to achieve output powers in excess of 1 W from a monolithic device was driven largely by the perceived need for transmitters for free-space communications and direct diode material processing applications.

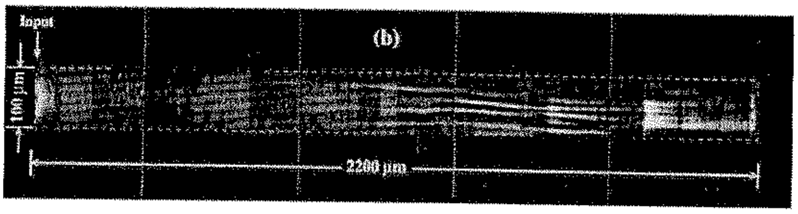

Fig. 5. Infrared image of the top of a broad-area gain region illustrating the effect of filamentation.

Semiconductor lasers, being highly nonlinear devices and having a large coupling between the gain of the laser and the index of refraction, made it difficult to fabricate a large aperture single-mode laser. Several conceptual techniques were pursued [23]–[38]: 1) coupled laser arrays through either evanescent or direct coupling of individual laser elements; 2) surface-emitting laser arrays where serial injection locking of multiple cavities were studied; 3) master oscillator power amplifier configurations on a monolithic chip; 4) externally injection locked lasers; 5) asymmetric gain profiles in large aperture lasers; 6) multimode large aperture devices with highly differentiated modal gain profiles; 7) external cavity lasers; and 8) unstable resonator lasers with large emitting apertures. Several general issues were barriers to a number of these potential solutions; first the output power needed to be efficiently coupled into a single emission radiation lobe, the radiation patter, or far field pattern, needed to remain stable over all power and temperature operating conditions, the discrimination between modes of operation had to be sufficient to insure single-mode operation as the gain uniformity and index uniformity changed during operation of the laser and the laser had to be able to be made reproducibly with high yield. All of these conditions became very problematic in a material system that was highly nonlinear and the index and gain were highly coupled. Finally and more importantly, the need for an application that is economically large enough that would justify the expense associated with the migration from a DPSS solution to a semiconductor manufacturing solution. To date some exceptional work by a variety of research organizations has resulted in the demonstration of single spatial mode laser at output powers in excess of 5-W CW.

In parallel with the development of monolithic single spatial mode lasers came the development of double-clad rare earth doped fiber. As discussed below, rare earth doped fiber originated around the need for optical amplification in the fiber where Er doped fiber amplifiers (EDFA) were developed. From the technology of Er fibers, which were originally developed for single-mode fibers requiring single-mode pump lasers, came the conceptual development of double-clad fibers. Double-clad fibers have a single-mode core surrounded by a second multimode optical cladding layer. In this configuration multimode light is injected into the outer cladding layer and the the light propagates over several tens of meters while it is absorbed by the rare earth dopant in the single-mode core of the fiber. This process has demonstrated to be a very efficient mechanism of conversion of the multimode radiation from the semiconductor laser to a single-mode output. While the Nd : YAG laser, discussed below, will result in optical to optical conversion efficiencies of 30%–50%, the double-clad fiber lasers could operate at optical to optical conversion efficiencies of 60%–80%. Although fiber lasers do not result in the broad wavelength coverage of semiconductor only solutions, fiber lasers have meet the power and scaling requirements of most potential multiwatt single-mode applications. Currently, fiber lasers are used in marking systems, thermal printing systems, and Raman amplifiers.

VI. Diode-Pumped Solid-State (DPSS) Lasers

The first use of MOCVD and MBE was in the fabrication of AlGaAs lasers operating between 780 and 860 nm. From this material system came the first application of high-power semiconductor lasers, that of pumping Nd : YAG lasers at wavelengths around 810 nm. The use of diode pumping of Nd : YAG lasers enabled a dramatic reduction in size and a significant increase in operating efficiency as compared to flash lamp pumped solid-state lasers. In later years as the semiconductor lasers became more reliable, so did the solid-state lasers. A steady progression in DPSS technology over the past 15 years has transformed the laser-based material processing industry to where DPSS lasers now compete with high-power CO_2 laser systems for cutting and welding applications, and a significant fraction of the market is the sale of DPSS lasers.

High-power semiconductor lasers used for pumping of Nd : YAG lasers were first commercially introduced in 1984 at output powers of 100 mW CW. Nd : YAG lasers have several distinctions compared to semiconductor lasers; first they have a long excited state lifetime and can therefore store energy and are applicable to Q-switched operation resulting in high-peak power applications, and second they have the ability to efficiently convert multimode light into single-mode light. The designers of DPSS lasers looked to use of high-power semiconductor lasers to replace that of flash lamp pumping for the advantages of greater efficiency and higher reliability. This gave great design flexibility to the DPSS laser designer in the choice of format for the high-power semiconductor laser. Quickly, the market moved to a design of a 1-cm-long monolithic semiconductor laser array that could be stacked to create a two-dimensional (2-D) emitting aperture, Fig. 5. The 1-D and 2-D arrays were used in either CW or what was noted as quasi-CW mode, where the quasi-CW operation was a series of long pulses used to match the upper state lifetime of the solid state laser, on the order of a few hundred microseconds to a few milliseconds. Today, monolithic laser arrays have been demonstrated at output powers approaching 200 W CW where reliable operation of 60 W is commercially available.

Emerging from the DPSS systems were first lasers operating in the few watts average power region. Applications for these lasers included marking on electronic packages, thermal or ablative printing on plates for offset printing applications, micro- welding for various applications in the hard disk and semiconductor industry, heat treatment of micromechanical components, and many others. A second class of applications arose from the ability to efficiently convert the output of the DPSS to green and UV for application to photosensitive materials.

The second class of products, which is just beginning today, are the applications that require high average power operation including cutting and welding applications where the average powers are in the range of 100–1000 W.

VII. Optical Data Storage

The second application that has been impacted by high-power semiconductor lasers has been optical data storage. Read-only applications within optical data storage have existed for a number of years at 830 and 780 nm. It has been the advances in high-power laser technology that hve pushed the reliable output powers to greater than 30 mW that has enabled the ability to write on optical discs. Initially, this was introduced to that market at 830 nm, followed closely behind by 780 nm and more recently 650–680-nm lasers, the movement to shorter wavelength for the benefits of higher storage densities. These devices are all single spatial mode operation.

Other applications that have benefited from higher power semiconductor lasers in the early years of their development include free-space/satellite communications, where extensive work and a number of demonstrations were successful at secure free-space optical links, direct diode material processing applications including heat treatment of metal surfaces, medical applications including photodynamic therapy, hair removal, and other therapeutic applications.

VIII. Telecommunications

In parallel with the development of high-power semiconductor lasers was the development of rare earth doped optical fiber. Rare earth doped fiber in conjunction with the advances in high-power lasers are, in this author's perspective, the true enabler to WDM communication systems. It was the ability to amplify light in fiber that eliminated the need for expensive regeneration every 100 km, thus enabling an economic solution for WDM fiber optic communication. The development of rare earth fiber has had two primary areas of impact: the first being Er: doped fiber for amplification at 1550 nm.

The first demonstration of Er doped fiber amplifiers (EDFA) was in conjunction with 1480-nm semiconductor lasers. The conversion efficiency of the 1480 pump lasers to 1550 amplification of the signal source is in the range of 70%. Rapidly, the communication system designs pushed for output powers from the amplifiers on the order of 20 mW (13 dBm), and for a variety of reasons due to multichannel inputs and multistage amplication, these amplifiers required pump powers of greater than 50 mW. As the channel count further increased over time the amplifier output power exceeded 23 dBm with some applications requiring greater than 30 dBm and therefore further driving the output power requirements from the emiconductor lasers. The research community implemented some of the technologies and designs discussed above, increasing the cavity length of the laser

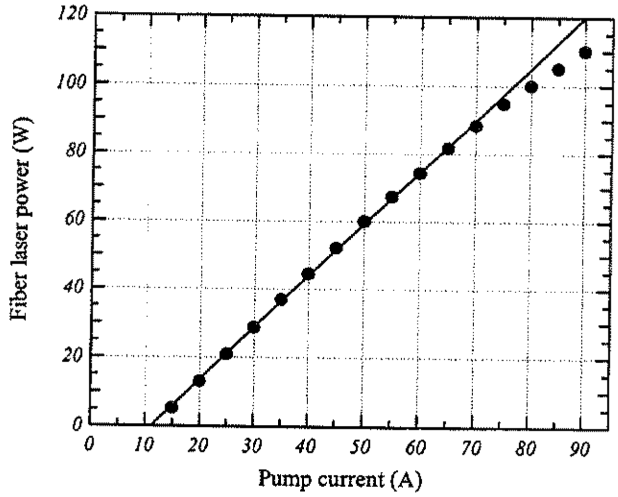

Fig. 6. Power output as a function of drive current for a diode-pumped fiber laser.

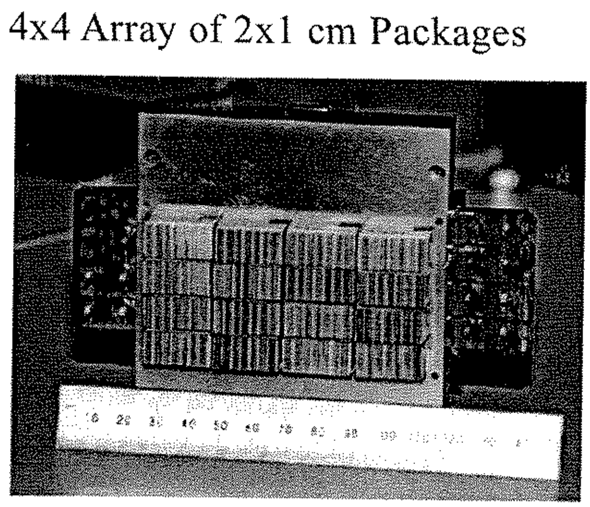

Fig. 7. Photograph of a 2-D array of laser diode bars; maximum output power of 2.56-kW average power.

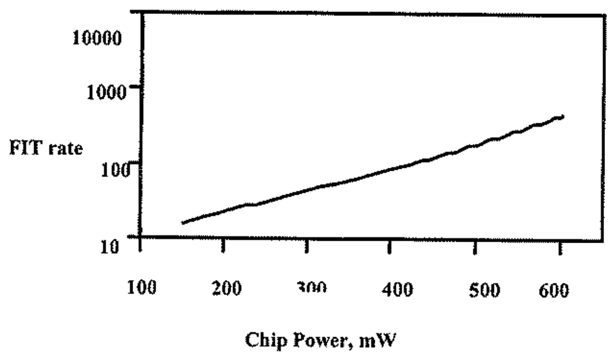

Fig. 8. FIT rate for 980-nm laser chips as a function of output power.

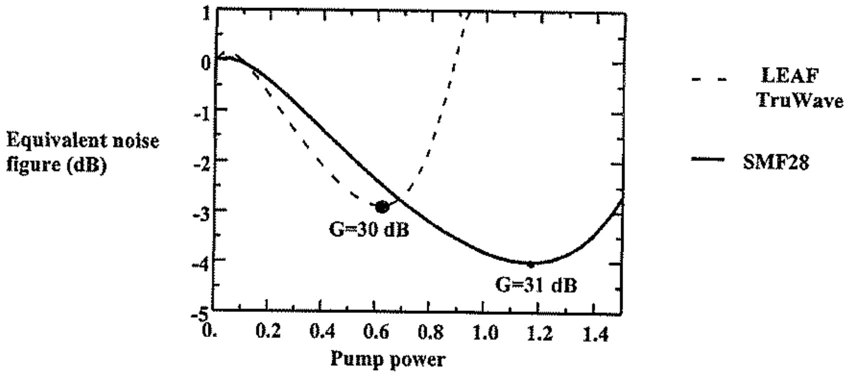

Fig. 9. Equivalent noise figure as a function of pump power for a Raman pump laser for both SMF28 and LEAF fiber.

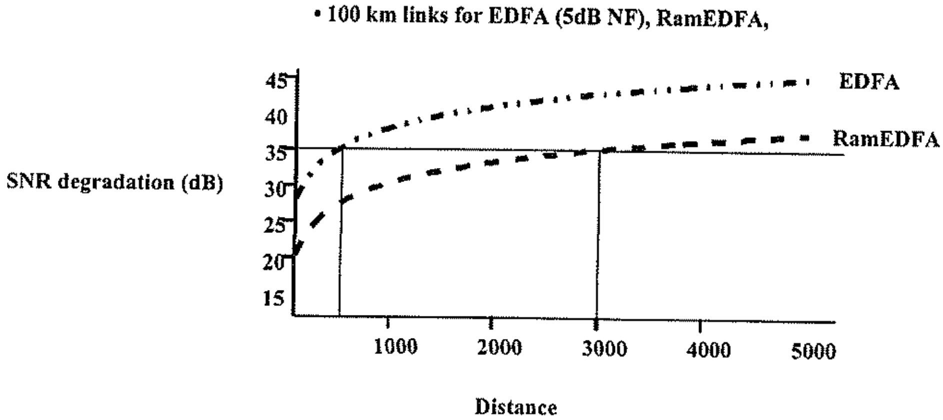

Fig. 10. Impact of Raman amplification on the SNR degradation in system performance. For a system designed for 35-dB degradation in SNR, the incorporation of Raman amplification in complement with EDFA (NF = 5 dB) extends the distance between repeaters from approximately 500 to 3000 km. For this example the amplifier spacing is 100 km.

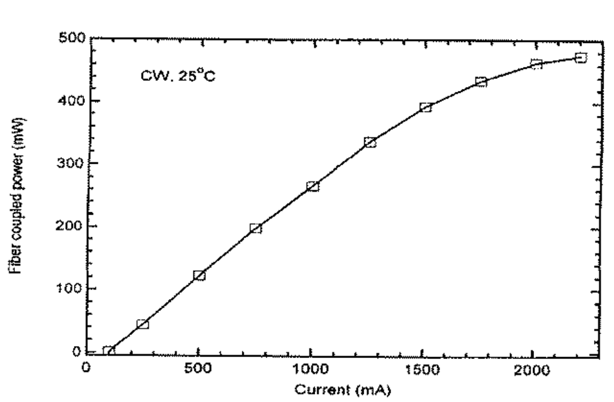

Fig. 11. Power output as a function of current for a fiber coupled 1455 nm laser [39].

to 1 mm and beyond in research devices to handle the thermal dissipation of the high-power lasers. The communication industry had significant data on the reliability of InP-based lasers in the form of DFB lasers, and InP lasers did not demonstrate COD, therefore the communications industry adopted 1480-nm lasers as the first high-power laser for communications. The first EDFA was deployed in an undersea communication link in the early 1990s.

The second absorption band of EDFAs was at 980 nm. The advantage of 980-nm pumping was that the noise figure was much lower than 1480-nm pumping. As the development of the EDFA was nearly simultaneous with the development of pseudomorphic materials and the processing developments that lead to the elimination of COD, the next high-power application to develop was that of 980-nm laser for EDFA pumps. There are several inherent tradeoffs between 980-nm lasers and 1480-nm lasers: 1) 980-nm pumping results in a lower noise figure from the amplifier than 1480-nm pumps; 2) the optical conversion of the pump laser to 1550-nm light is more efficient in 1480-nm lasers; 3) the drive current requirements are higher for 1480-nm lasers, an important parameter in the design of undersea equipment; and 4) the initial reliability of 1480-nm lasers was greater than that of 980-nm lasers. The result was that the communication industry wanted to use 980-nm lasers in the EDFA, however, the reliability of the 980-nm pump laser needed to be improved to the same level of performance as the 1480-nm laser. Over a number of evolutionary growth, processing, and packaging developments, several organizations were able to develop highly reliable 980-nm pump lasers that met both the terres-

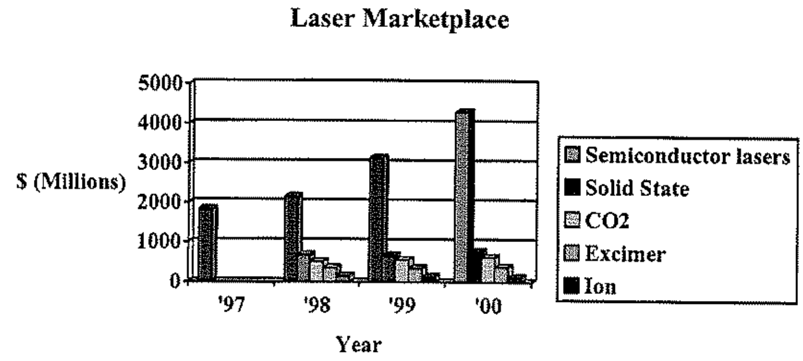

Fig. 12. Laser marketplace (Laser Focus World) [40].

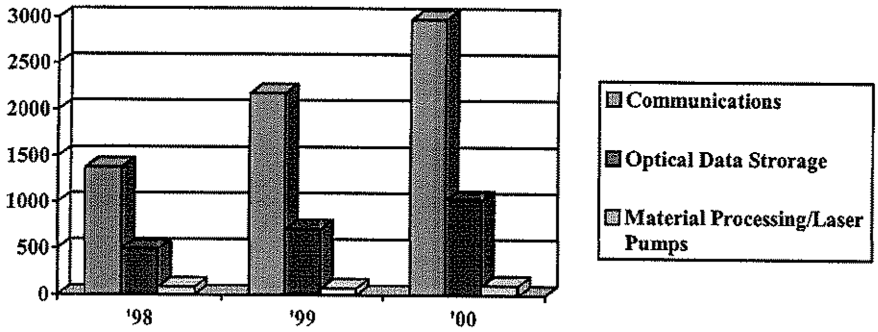

Fig. 13. Revenue by market sector for semiconductor lasers (Laser Focus World) [41].

trial and undersea reliability requirements. Today, high-power 980-nm lasers can be deployed with FIT rates less than 100 at powers of several hundred milliwatts.

The combination of Er fiber, and high-power 1480- and 980-nm lasers are the essential elements of the WDM long-haul communication systems. The 980-nm laser provides the noise performance, while the combination of 1480- and 980-nm for power generation enable the multichannel architectures of today. Without these technologies there would be no high data rate communication systems capable of handling the traffic needed for internet applications.

The next generation of amplification technology for communication networks is Raman amplification. Raman amplification transforms the network from amplification at discrete points to a network where the transmission fiber becomes part of the amplification network, resulting in a dramatically reduced noise figure of the amplifier, thus enabling ultralong haul transmission and 40-Gb/s transmission. Raman amplification grew out of two different high-power laser technologies. The first deployment of Raman amplification has come from the use of fiber laser-based pump sources. These amplifier pumps are currently being deployed in undersea festooning application and dry-side-based preamplifiers. As discussed above, the fiber laser configuration combines the technologies of high-power semiconductor lasers with that of double-clad fiber laser converting the multimode semiconductor light to single spatial mode output and subsequent Raman shifting to an output wavelength of 1455 nm at a power in excess of 1 W CW. These light sources were initially tools of the research community to investigate the properties of Raman amplification in fiber optic transmission. Optimum pump powers for fiber is dependent on the type of transmission fiber being used and the system implementation of the fiber and ranges between 500 mW and 1.5 W.

The alternative technology to fiber laser-based Raman amplification pumps is the use of direct high-power semiconductor lasers. For Raman amplification in the C and L transmission bands of the optical fiber, the semiconductor lasers need to operate in the 1450-nm range. To achieve the output power of 500 mW to 1 W, organizations are both polarization and wavelength multiplexing four–six pump lasers in to a single-fiber output. Raman amplification will require the output power of discrete 1455-nm pumps to approach 300 mW and beyond in order to optimize the performance and manufacturing cost.

Today, most next-generation long-haul transmission system designs will utilize Raman amplification. This technology is a breakthrough technology as it is the enabler for ultralong-haul transmission and high data rate (>40 Gb/s) transmission. Currently, the Raman amplification is designed to complement the EDFA.

IX. Conclusion

Over the past 20 years since the first work for high-power semiconductor lasers, the technology and market requirements have advanced dramatically. The market for semiconductor lasers has grown at staggering clips from 1980 to 2000 and is currently growing at greater than 40% per annum, the largest market being the communications market. The semiconductor laser is the largest market of all optical technologies (Figs. 12 and 13). High-power lasers as a segment of the overall market are growing even faster at a rate in excess of 90% per annum. For high-power lasers the growth and impact is substantial as high-power lasers enable dramatic cost reduction and performance enhancements in the communications systems. The trend is to shift value from the transmission products to the amplification products as a percentage of the overall systems cost. This trend represents the ability to replace the expensive repeaters with optical amplifiers.

High-power semiconductor lasers have become a pillar for a number of markets including fiber optic communications, materials processing/manufacturing technologies, printing, optical data storage, medical therapeutic and cosmetic applications, free-space communications, and many others. Research in this area has shifted from basic research to applications research as these markets have matured.

ACKNOWLEDGMENT

The advancements of high-power lasers is the culmination of thousands of research, development, manufacturing, and application engineers. To give adequate and definitive recognition across this industry would be a monumental task and was not the purpose for this paper. Nonetheless a number of key organizations have played a role in the development of the technology that has resulted in the above advancements, including (but not limited to): SDL, Spectra Physics, Coherent, Sony, Hitachi, Mitsubishi, IBM, Uniphase, Lasertron, Pirelli, U.S. Government, TRW, Hughes, Perkin Elmer, AT&T, Lucent, Nortel, Alcatel, Siemens, Philips, Polaroid, IPG, McDonnell Douglas, Sharp, Toshiba, NEC, NTT, EG&G, David Sarnoff Research Labs, Naval Research Labs, Philips Lab USAF, Rome Lab USAF, Cornell University, University of New Mexico, Caltech, Stanford, Oregon Graduate Research Center, and many others.

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