History and Developments of Semiconductor Lasers

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Abstract: A brief history of the creation of semiconductor lasers is presented. Basic attention is given to injection lasers including homo- and heterojunction laser diodes, quantum-well heterostructures, quantum cascade systems, *etc*. General steps in the development of the semiconductor lasers and inventions in the injection lasers are described. Theory modeling the spectral and output characteristics of the laser semiconductor sources is discussed. Set of applied semiconductor materials for laser technology and techniques and number of corresponding lasing wavelengths are listed. In addition, principal fields of application of semiconductor lasers and as well as growing total volume in the laser market are involved. Modern trends in semiconductor quantum electronics are also grounded.

The year 2010 marks the 50th anniversary of the creation of the world's first laser – a quantum generator of coherent optical radiation that employs stimulated (induced) radiation of atoms and resonant feedback (cavity). This event triggered rapid development of quantum electronics in the optical range. Undoubtedly, the early studies in microwave quantum electronics set the stage for extending the principles of quantum electronics to the optical range, *i. e.*, for going over from the maser to the laser [1, 2].

In 1964, Townes, Basov and Prokhorov are awarded the Nobel Prize in physics for their “fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser-principle”.

This applies first of all to three key components of the quantum generators: the matter gain medium with the energy level structure in which radiation can be generated in the desired frequency range, methods for achieving population inversion, and the electrodynamic system where radiation interacts with the gain medium. The 50th anniversary of the laser has stimulated greater interest in the system where radiation interacts with the gain medium.

Since 1939, V.A. Fabrikant in his Doctor of Science (Habilitation) Thesis points out that population inversion should lead to light wave amplification and suggests the use of second-kind collisions to achieve such an inversion. Conditions for observing “negative absorption” in gas discharge are analyzed in 1940 [3].

In May 16, 1960, Theodore H. Maiman, a physicist at Hughes Research Laboratories in Malibu, Calif., constructs the first laser using a cylinder of synthetic ruby measuring 1 cm in diameter and 2 cm long, with the ends silver-coated to make them reflective and able to serve as a Fabry–Perot resonator. Maiman uses photographic flashlamps as the laser’s pump source.

To obtain negative temperatures (the phenomenon of stimulated emission) [4] it is proposed to use the impurity ionization mechanism that operates in a semiconductor specimen at a low temperature when an electric field pulse is applied [JETP **37**, 587 (1959)].

If a *p*–*n* junction in a semiconductor is biased in the forward direction, then there will be a decrease in the potential barrier due to space charge in the *p*–*n* junction, and the concentration of minority carriers near the junction will increase. A negative temperature [5] can arise in a junction only when the quasi-Fermi levels corresponding to the non-equilibrium concentrations of electrons and holes satisfy the relation $\mu_e+\mu_p > \Delta$, where μ_e and μ_p are the quasi-Fermi levels for electrons and holes, and Δ is the width of the forbidden band [JETP **40**, 1879 (1961)]. See also: [Bernard M.G.A. and Durraffourg G. Phys. stat. sol. **1**, 699 (1961)], [Adirovch E.I. and Kuznetchova E.M. Solid State Phys. **3**, 3339 (1961)].

Mention that the first indication of the stimulated emission in the GaAs *p*–*n* junction has been discovered earlier at the Ioffe Physico-Technical Institute (Fiztekh) [Nasledov Д.N. *et al*. Solid State Phys **4**, 1062 (1962)].

In 1962, Robert N. Hall invented the semiconductor injection laser [6], a device now used in all compact disk players and laser printers, and most optical fiber communications systems [Hall R.N. *et al*. Phys. Rev. Lett. **9**, 366 (1962)].

Robert Hall and his group at General Electric (Schenectady, NY) published the first report of laser action in a semiconductor (GaAs) in September 1962, and groups at IBM (Yorktown Heights, NY) [Nathan M.I. *et al*. Appl. Phys. Lett. **1**, 62 (1962)] and the Massachusetts Institute of Technology (Cambridge, MA) [Quist T.M. *et al*. Appl. Phys. Lett. **1**, 91 (1962)], reported success within weeks of his results [7, 8]. Soon after, researchers reported lasing in a variety of materials, all with wavelengths in the near-IR.

In the USSR the first results [9] have been obtained in January 1963 by the team from Lebedev Physics Institute (PhIAN), Moscow [Bagaev V.S. *et al*. Dokl. **150**, 275 (1963)]. Visible coherent light emission was obtained from GaAsP [10] by Holonyak N. and Bevacqua S.F. [Appl. Phys. Lett. **1**, 82 (1962)].

The first experimental results on stimulated emission at electron beam pumping from a CdS crystal have been given in 1964 [11]. An irradiation of a CdS single crystal, mounted on a cold finger in a liquid-helium cryostat, by a 200-keV electron beam led to intense green emission from the crystal at a wavelength of 4966 Å. The experiments performed showed that semiconductor lasers could be pumped by a fast electron beam.

The results of the preliminary studies of the induced radiation and lasing of a GaAs semiconductor crystal pumped by a Q-switched ruby laser are reported in 1965 [12]. An exposure of the GaAs sample to an unfocused ruby laser pulse with an energy of about 0.1 J (power 2 MW) yielded a rather narrow recombination luminescence line in the spectral range from 8340 to 8400 Å. An increase in the pump pulse energy to 0.15 J led to a sharp narrowing of the lasing line at the wavelength $\lambda = 8365$ Å.

In 1963, the team of Rudolf Kazarinov and Zhores Alferov of Ioffe Institute in Leningrad, USSR, and Herbert Kroemer of the University of California, Santa Barbara, independently propose ideas to build semiconductor lasers from heterostructure devices. The work leads to Alferov and Kroemer winning the 2000 Nobel Prize in physics.

In 1970, researchers at the Ioffe Institute in Leningrad, USSR, made the first double-heterostructure laser [13] and achieved CW operation at room temperature [Alferov Zh.I. *et al*. Semicond. **4**, 1826 (1970)]. Their success was followed almost immediately by a nearly identical but independently conceived design [14] from Bell Labs (Murray Hill, NJ) [Hayashi I. *et al*. Appl. Phys. Lett. **17**, 109 (1970)]. The double heterostructure became the basic framework for all future development.

In 1966, Charles K. Kao, working at Standard Telecommunication Laboratories in Harlow, UK, makes a discovery that leads to a breakthrough in fiber optics. He calculates how to transmit light over long distances via optical glass fibers, deciding that, with a fiber of purest glass, it would be possible to transmit light signals over a distance of 100 km. Kao receives a 2009 Nobel Prize in physics for his work.

1972: Charles H. Henry invents the quantum-well laser, which requires much less current to reach lasing threshold than conventional diode lasers and which is exceedingly more efficient. Holonyak at the University of Illinois at Urbana-Champaign first demonstrate the quantum-well laser, published in 1978. But practical interest to lasers of such type appeared from 1982, when technology became more precise.

1994: The first semiconductor laser that can simultaneously emit light at multiple widely separated wavelengths – the quantum cascade (QC) laser – is invented at Bell Labs by the team of Federico Capasso. The laser is unique in that its entire structure is manufactured a layer of atoms at a time by the crystal growth technique called molecular-beam epitaxy. Simply changing the thickness of the semiconductor layers can change the laser's wavelength. With its room-temperature operation and power and tuning ranges, the QC laser is ideal for remote sensing of gases in the atmosphere.

1995: Shuji Nakamura (now at the University of California, Santa Barbara) announces the development of a gallium-nitride (GaN) laser that emits bright blue-violet light in pulsed operation.

History of semiconductor lasers

1. Idea of semiconductor lasers (electrical field): *Basov, Vul, Popov* (1958).
2. **Idea of junction lasers (injection, *p–n* junction)**: *Basov, Krokhin, Popov* (1961).
3. First observation of the gain (GaAs): Fiztekh, Leningrad (1961).
4. **Development of injection lasers (GaAs)**: USA (*Hall*, September, 1962), USSR (January, 1963).
5. Pumping by electron beam (CdS): PhIAN, Moscow (1964).
6. Optical pumping (GaAs): PhIAN (1965).
7. Injection under electric field: USA (1965).
8. **Heterojunction lasers (GaAs–AlGaAs)**: *Alferov* (1968).
9. **Using of quaternary compounds (GaInAsP)**: GIRETMET, PhIAN (1971).
10. Streamer discharge laser (CdS): *Nicoll*, USA (1973).
11. **Lasers with distributed feedback (DFB) and Bragg reflectors (DBR)**: Fiztekh (1974).
12. **Quantum-well laser (QW)**: *Holonyak*, USA (1978).
13. **Lasers with vertical-cavity surface-emitting structures (VCSEL)**: *Iga*, Japan (1979).
14. Lasers (masers) in crossed **E**×**H** fields (*p*-Ge): *Vorob'ev*, USSR (1982).
15. Lasers with *n–i–p–i* structure (GaAs): FRG (1985).
16. **Quantum-wire lasers**: USA, Japan (1989).
17. Asymmetric multiple-quantum-well heterostructure (AMQWH) lasers: *Shimizu*, Japan (1989).
18. II–VI compound quantum-well heterostructure lasers (ZnSe): *Haase*, USA (1991).
19. **Quantum-dot lasers**: Japan, USA, Germany, Fiztekh (1994).
20. **Quantum cascade lasers** (QC, unipolar): *Capasso*, USA (1994).
21. **GaN-based heterostructure lasers (blu)**: *Nakamura*, Japan (1995).
22. Organic semiconductor lasers (tetracene): *Batlogg*, USA (2000).
23. Terrahertz radiation emitting laser diodes: Russia, USA, Italy, UK, Switzerland (2002).

Main applications

1. **Optical storage** (above 1.6 B$)
2. **Telecommunications** (1.2 B$)
3. **Solid-state laser pumping** (0.2 B$)
4. Medical therapeutics
5. Image recording
6. Barcode scanning
7. Inspection, measurement & control
8. Materials processing
9. Entertainment
10. Sensing
11. Basic research

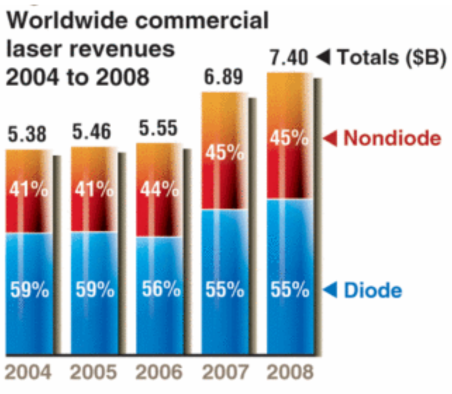


Fig. 1. Worldwide commercial laser revenues (2004–2008).

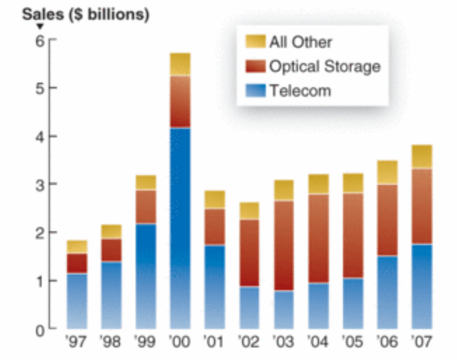


Fig. 2. Worldwide diode-laser market (1997–2007).

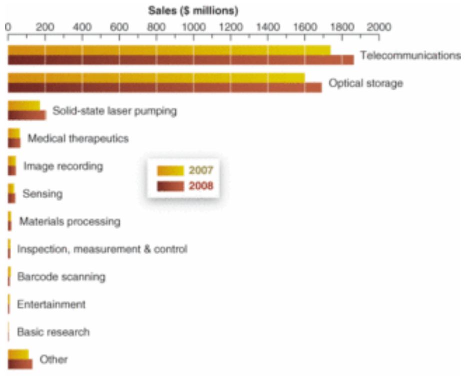


Fig. 3. Worldwide diode-laser sales by application (2007, 2008).

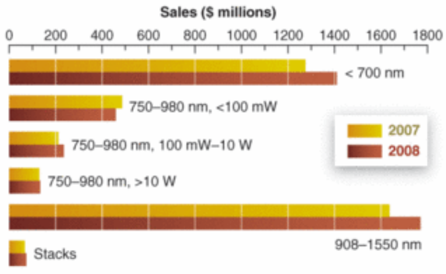
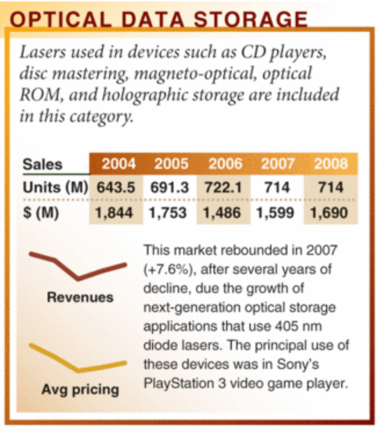


Fig. 4. Worldwide diode-laser sales by types (2007, 2008).



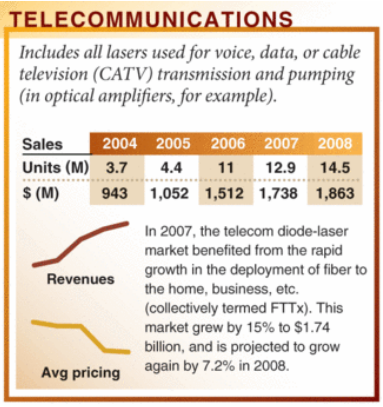
OPTICAL DATA STORAGE

Lasers used in devices such as CD players, disc mastering, magneto-optical, optical ROM, and holographic storage are included in this category.

Sales	2004	2005	2006	2007	2008
Units (M)	643.5	691.3	722.1	714	714
$ (M)	1,844	1,753	1,486	1,599	1,690

This market rebounded in 2007 (+7.6%), after several years of decline, due the growth of next-generation optical storage applications that use 405 nm diode lasers. The principal use of these devices was in Sony's PlayStation 3 video game player.

Fig. 5. Optical data storage application.



TELECOMMUNICATIONS

Includes all lasers used for voice, data, or cable television (CATV) transmission and pumping (in optical amplifiers, for example).

Sales	2004	2005	2006	2007	2008
Units (M)	3.7	4.4	11	12.9	14.5
$ (M)	943	1,052	1,512	1,738	1,863

In 2007, the telecom diode-laser market benefited from the rapid growth in the deployment of fiber to the home, business, etc. (collectively termed FTTx). This market grew by 15% to $1.74 billion, and is projected to grow again by 7.2% in 2008.

Fig. 6. Telecommunication network and system applications.

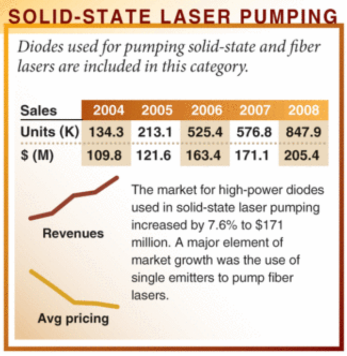
Bolstered by gains in all market segments and strong contributions from newer applications like flexible time-triggered (FTT) communication and next-generation DVDs, diode-laser market growth remained consistent with its history, gaining 10% in 2007 [15]. According to analysts from Strategies Unlimited of Mountain View, CA, the global market for lasers is expected to grow about 11% in 2010 bringing total revenues to $5.91 billion for the year, including approximately the level of 55% for diode-laser market (Figs. 1–6).

Many of the advances in laser technology over the past two decades have been enabled through the use of diode lasers as pump light sources. However, just as with other laser types, the diode laser itself started out as a low-power lab novelty with limited reliability. But the need for compact, long-lived sources in data storage and telecommunications drove these devices to higher output powers, narrow linewidths and increased reliability.

Producing even higher power diode lasers and arrays with increased brightness remained a challenge (Fig. 7). The principal problems were heat load management and facet failure, since a large amount of optical power is channeled through a facet measuring, at most, tens of microns. In addition, many applications needed a system design that could withstand repeated on/off cycling.

The laser industry met this need by incremental improvements in power, lifetime and brightness. Key technical innovations were the introduction of aluminum-free active region devices to address facet lifetime and indium soldering to address the mounting/cooling interface issues. Market success followed suit, with applications such as optically pumping solid-state lasers in tasks such as chemistry, holography, materials science, biology and industrial micromachining, and materials processing using the direct diode output in tasks such as welding, cladding and hardening. Today, few would argue with the fact that laser diodes (individually or aggregated) are the single most important technology in the laser industry.

Multiwatt, CW, visible technology was revolutionized by the introduction of diode-pumped solid-state (DPSS) lasers. Unlike ion lasers, these DPSS lasers could emit only one wavelength, 1064 nm, which was then intracavity doubled to produce 532 nm. But this single-wavelength functionality was considered a small price to pay for the massive gain in efficiency, longer lifetime, lower cost of ownership, a ten times reduction in size and the fact that these lasers could be factory-sealed with no subsequent use tweaking required. Needless to say, applications for these solid-state lasers expanded overnight. And existing scientific applications, such as pumping for both CW Ti: sapphire and ultrafast laser systems, switched from ion to DPSS. Other important uses for these lasers included forensics, inspection and holography.


SOLID-STATE LASER PUMPING

Diodes used for pumping solid-state and fiber lasers are included in this category.

Sales	2004	2005	2006	2007	2008
Units (K)	134.3	213.1	525.4	576.8	847.9
$ (M)	109.8	121.6	163.4	171.1	205.4

The market for high-power diodes used in solid-state laser pumping increased by 7.6% to $171 million. A major element of market growth was the use of single emitters to pump fiber lasers.

Fig. 7. Application in solid-state laser pumping.

Despite the advantages of DPSS, commercial and scientific applications continued to demand even lower cost of ownership and greater flexibility and reliability, but without any sacrifice in output characteristics. A third generation of visible lasers based on optically pumped semiconductor laser (OPSL) technology arose to meet this need. Here a laser diode pumps a semiconductor chip rather than a doped crystal. This eliminates the thermal lensing issues that plagued DPSS lasers. OPSL also enabled automated "pick and place" manufacturing methods and economies of scale. And today this technology can be tailored to output specific wavelengths over a near-IR range that, when intracavity doubled, provides a selection of visible wavelengths.

The result is that OPSL technology exceeds the best of ion and DPSS characteristics: It is wavelength-flexible and power-scalable, yet inherently compact and efficient. As a result, we are now at a point where laser output can be defined by the application, rather than vice versa. So while these lasers are available at legacy wavelengths, such as 488 and 514 nm, they are also offered at completely new wavelengths to optimize targeted applications. A standout example is the 577-nm yellow laser that is matched to oxyhemoglobin absorption. This wavelength provides superior results in the photocoagulation used to treat wet-form macular degeneration. This has also turned out to be a useful and popular wavelength for use in laser light shows.

Most recently, multiwatt OPSLs in the red have become available. These wavelengths were developed to provide brighter images and a wider color gamut in entertainment applications as well as to support faster DNA sequencers, which now use a combination of 488-, 532- and 639-nm laser wavelengths.

The 50th anniversary of the laser has stimulated greater interest in the history of quantum electronics in the world. Special project of journals Quantum Electronics and Proceedings of Prokhorov General Physics Institute RAS presents early Soviet pioneering works that had a significant impact on laser science and quantum electronics (Fig. 8). This collection of early Soviet papers would be helpful for both Russian- and English-speaking readers, especially for the latter since several papers have never been published in English.

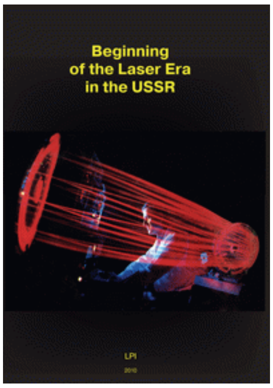


Fig. 8. A cover title of the special book that presents early Soviet pioneering works on lasers.

[1] M. Rose. A history of the laser: A trip through the light fantastic. *Photonics Spectra* **44** (5), 58 (2010).

[2] L. Savage. On the shoulders of giants. *Photonics Spectra* **44** (5), 70 (2010).

[3] V.A. Fabrikant. *Proc. All-Union Electrotech. Inst.* Iss. 41, 236R (1940).

[4] N.G. Basov, B.M. Vul, Yu.M. Popov. *Sov. Phys.-JETP* **10**, 416 (1960).

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[6] R.N. Hall *et al*. *Phys. Rev. Lett*. **9**, 366 (1962).

[7] M.I. Nathan *et al*. *Appl. Phys. Lett*. **1**, 62 (1962).

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[11] N.G. Basov, O.V. Bogdankevich, A.G. Devyatkov. *Sov. Phys.-Dokl.* **9**, 288 (1964).

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[13] Zh.I. Alferov *et al*. *Semicond*. **4**, 1826 (1970).

[14] I. Hayashi *et al*. *Appl. Phys. Lett*. **17**, 109 (1970).

[15] R.V. Stelle. Laser marketplace 2008: Diode lasers track long-term trend. *Laser Focus World* **44** (2), 59 (2008).