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TECHNOLOGY FOCUS

MAY 2010

LASER ANNIVERSARY

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MILESTONES

Nature Milestones: Photons

Nature Milestones: Photons is a collaboration from *Nature Materials*, *Nature Physics* and *Nature Photonics*, and marks the occasion of the 50th anniversary of the first realisation of the laser on 16 May 1960. The field of light has always captivated scientists, and in particular during the last century our fundamental understanding of photons has opened new avenues of enquiry.

The *Nature Milestones: Photons* supplement contains a series of short articles, called Milestones, presenting key developments in the field, written by editors from Nature Publishing Group. In addition to the Milestone articles, the supplement includes a Timeline — a chronology of the earliest papers connected with each Milestone — and a reprinted Collection of relevant articles and selected reviews from *Nature* and *Nature Physics*. The Milestones web site also includes an extensive Library of related material from across the Nature Publishing Group.

For more information please visit: www.nature.com/milestones/photons

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HRL

COVER IMAGE

Ted maiman at Hughes Research Laboratories surrounded by the parts of the first laser — a flashlamp-pumped ruby design.

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50th anniversary

Many of us take the invention of the laser for granted. It is a technology that we have grown up with, and has always been a part of our everyday lives. It is not until you speak to people such as Charles Townes (see page 294), or read the first description of the laser by Theodore Maiman (see page 281), that you realize how amazing the breakthrough of the laser was.

It all began in Bell Labs over 50 years ago, when Charles Townes was thinking about ways of creating a new optical source to help him perform spectroscopy. The consequent development of the laser changed science forever, and its various forms continue to have considerable impact in many areas of science, technology and industry. For example, semiconductor lasers have revolutionized telecommunications (see page 287); Nd:YAG lasers have changed the way we perform materials processing (see page 285); excimer lasers drive the semiconductor industry (see page 286); Ti:Sapphire lasers enable ultrafast studies of matter (see page 289); fibre lasers are changing the face of manufacturing (see page 290); and quantum cascade lasers are turning out to be a valuable source of mid-infrared and terahertz radiation (see page 291).

We hope that this special issue of *Technology Focus*, which celebrates the 50th anniversary of the report of Maiman's ruby laser in May 1960, will give an overview of how various laser technologies have evolved over the years, and provide an insight into their origins. Those reading this issue in its new interactive electronic form will have the added bonus of additional video content, featuring interviews with both Townes and Maiman (courtesy of the Optical Society of America and LaserFest). Here's to fifty more years of exciting laser developments.

CONTENTS

Laser celebrations

SEE THE VIDEO

A major celebration of the 50th anniversary of the laser is planned for 16 May — the date of the first demonstration of lasing by Theodore Maiman at the Hughes Research Laboratories. A special afternoon symposium, part of the year-long anniversary programme called LaserFest, will take place at the Conference on Lasers and Electro-Optics/ Quantum Electronics and Laser Science Conference (CLEO/QELS) in San Jose, USA, and will involve talks from many of the original pioneers as well as several Nobel Prize winners.

The symposium entitled 'Retrospectives on the invention of the laser' will take place from 3 pm to 6 pm at the San Jose McEnery Convention Center. It will feature contributions from Zhores Alfernov (Ioffe Physico Technical Institute), Nico Bloembergen (University of Arizona), Jeff Hecht (freelance writer), Ali Javan (MIT), Kathleen Maiman, Kumar Patel (University of California at Los Angeles), Tony Siegman (Stanford University), Peter Sorokin (IBM), Charles Townes (University of California at Berkeley) and Orazio Svelto (Politecnico di Milano).

"To mark the anniversary date of this historic occasion, 16 May, we've gathered laser pioneers, historians and others to talk about their experiences and contributions to one of the greatest inventions of the twentieth century," explained the organizers of the CLEO conference.

LaserFest was set up by the American Physical Society (APS), the Optical Society of America (OSA), SPIE and the IEEE Photonics Society, with the aim of emphasizing the laser's impact throughout history and highlighting its potential for the future.

BAER

Tom Baer says the aim of Laserfest is not just to honour pioneers of laser science but also to inspire students and young scientists to study photonics.

Thomas Baer, from Stanford Photonics Research Center and a member of LaserFest's technical advisory committee, told *Technology Focus*, "LaserFest has several aims. We want to honour the original innovators of the laser; educate the general population about the important role lasers are playing in our everyday lives; inspire students and young scientists into the dynamic field of photonics; and promote investment in basic research."

This is being achieved through laser-oriented seminars and conferences across the globe, as well as by outreach programmes such as 'LaserFest on the Road', in which experienced outreach teams from universities and science museums conduct laser-based demonstrations in the community. LaserFest even has its very own superhero, Spectra. "LaserFest Physics Quest is an educational activity for middle-school students to solve a mystery involving a famous physicist," explains Baer. "Experiments involving lasers and light provide clues to the mystery. The quest features superhero Spectra and her epic battle with the evil Miss Alignment. Spectra also will be making appearances throughout LaserFest as a symbol of laser power."

LaserFest has had considerable involvement from the founders' student chapters. For example, 'Hit the Target', a laser kit learning activity, has been distributed to OSA/SPIE student chapters for educational demonstrations to middle-school students, and a Laser Graffiti video competition has been organised in which student chapters are creating educational videos about the science and technology of lasers. These are to be posted on YouTube and entered into a competition, with awards given at CLEO/QELS.

Events are scheduled throughout the year, but for the OSA specifically, the closing event will be at its annual meeting, Frontiers in Optics, 24–28 October, in Rochester, New York. "There we will recognize all of the organizations participating in LaserFest from countries around the world," says Baer. "Among other events, we are planning a special programme for our student chapter leaders in which they will meet with many of the original laser pioneers to discuss the historic developments that occurred 50 years ago."

For more information about LaserFest and its planned activities throughout 2010, please visit www.laserfest.org.

European group develops long-wavelength VCSELs

A pan-European research project has developed long-wavelength vertical-cavity surface-emitting lasers (VCSELs) for next-generation high-speed communications systems. Called MOSEL, the three-year project was led by CEA-Leti (France) and included three academic partners, DTU Fotonik of Denmark, EPFL of Switzerland and KTH of Sweden, and two industrial partners, Alight Technologies of Denmark and BeamExpress of Switzerland.

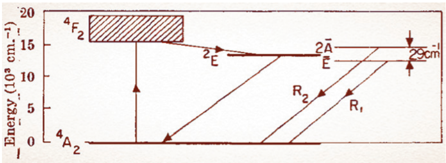
The researchers demonstrated error-free 10 Gbit s^{-1} operation up to 100 °C, concurrently with record performance: single-mode (>30 dB side mode suppression ratio) power of >1 mW up to 100 °C (>2 mW at room temperature) and 10 Gbit s^{-1} modulation and transmission over 10 km of single-mode fibre with a bit error rate of $<10^{-11}$ up to 100 °C with <1 dB power penalty.

Each of the partners played specific roles in the development of the technology. For example, EPFL and BeamExpress worked closely together to improve the performance of VCSELs in the 1,310 nm waveband and to reach the commercialization stage based on their proprietary InP–GaAs wafer-fusion technology. The devices are fabricated using 2-inch wafer technology, and incorporate patterned tunnel junctions and other intra-cavity structuring elements for efficient carrier and photon confinement.

KTH has used a novel regrowth technology with mode-selective elements for high-power single-mode emission; Alight has refined its photonic crystal structuring of its long-wavelength GaInNAs/GaAs VCSELs; CEA-Leti has developed new VCSEL designs using a recently suggested high-reflectivity-mirror concept based on subwavelength grating mirrors; and DTU Fotonik has carried out extensive numerical investigation of VCSELs with nano- and microstructures.

The 'laser'

Nature **187,** 493–494 (1960)



The paper that described the first ever laser was incredibly short, considering the impact it would have on the world. In around 240 words and without using the word 'laser', Theodor Maiman's paper, entitled 'Stimulated Optical Radiation in Ruby', summarized what was to be one of the most important scientific breakthroughs of the twentieth century.

Maiman, a researcher at the Hughes Research Laboratories in Malibu, California, USA, described how he used a fluorescent solid and an optical pumping technique to obtain stimulated optical emission at a wavelength of 6,943 Å. The active material was a piece of ruby 1 cm long and coated on two parallel faces with silver. When the active material was irradiated with energy at a wavelength of around 5,500 Å, the chromium ions in the ruby were excited to a higher state, following which they slowly decayed by spontaneously emitting a sharp doublet, the components of which were 6,943 Å and 6,929 Å, at a temperature of 300 K. Under very intense excitation, the population of this metastable state became greater than that of the ground state. This is the condition for population inversion and hence for amplification by stimulated emission.

At the end of his short paper Maiman stated: "I expect, in principle, a considerably greater (~10^5) reduction in linewidth when mode-selection techniques are used," but did not explain the motivation behind his work or mention any potential future applications.

The gas laser

Phys. Rev. Lett. **6,** 106–110 (1961)

Less than a year after Maiman's paper, researchers at Bell Labs in New Jersey, USA, described the first gas laser. Again, the term 'laser' was not used. Instead, their paper was entitled 'Population Inversion and Continuous Optical Maser Oscillation in a Gas Discharge Containing a He–Ne Mixture'.

Ali Javan and his colleagues described the successful operation of a continuous-wave maser at five different near-infrared wavelengths. The maser oscillation takes place in a narrow beam with a diameter of 0.45 inches. The power of the strongest beam was 15 mW, at a wavelength of 11,530 Å.

This work was so new that the equipment required to confirm it had not yet been developed. Thus, to verify their experimental results, Javan and his colleagues devised several electronic detection schemes. One of these responded only over a small period of the lasing time and was therefore synchronized with the radiofrequency pulsed discharge. The researchers admitted that "in addition to the extreme difficulties encountered in the interpretation of the results, the gain measurement alone was not sufficient to shed light into the nature of the physical processes involved in the discharge." Furthermore, they were not able to measure the linewidth using standard optical techniques as it was many orders of magnitude narrower than the resolution of the best spectrometers or interferometers available at the time. Instead, they analysed the Fourier spectrum of the maser output, which was observed through a photomultiplier tube.

The semiconductor laser

Proc. IEEE **51,** 1782–1783 (1963)

By 1963, researchers all over the world were working on different types of lasers, with the word 'laser' now being commonplace. Herbert Kroemer from the Central Research Lab of Varian Associates in the USA was the first to describe a class of lasers that he called heterojunction injection lasers. He proposed that laser action should be achievable in many of the indirect-gap semiconductors, and also improved in the direct-gap ones, if they were supplied with a pair of heterojunction injectors. He explained that these should consist of heavily doped semiconductor layers with a higher energy gap than the radiating semiconductor, and ideally should be of opposite polarity. Kroemer and his colleagues investigated most of the possible combinations available at the time (containing Ge, Si, III–V and II–VI compounds), and claimed to find at least 27 pairs with lattice misfits below 10^{-2}. Kroemer stated that "besides Ge–GaAs, the most interesting combination appears to be GaP–AlP, which might provide an indirect-gap visible laser."

The fibre laser

Electron. Lett. **22,** 159–160 (1986)

In 1986, David Payne and colleagues from Southampton University in the UK developed the first single-mode continuous-wave erbium-doped fibre laser operating at room temperature and the all-important telecommunications wavelength of 1.55 μm. They believed that their laser would find immediate applications in tunable backscatter and chromatic dispersion measurements of optical fibre, with important long-term roles as sources and amplifiers for telecommunications. The laser was tunable over 25 nm and produced powers in excess of 2 W in a *Q*-switched mode.

Previous work involved doping the fibre laser with Nd^{3+}, but this new work used Er^{3+}. The researchers claimed that their results were particularly important as the laser operated in continuous-wave mode, despite erbium being a three-level laser system and thus normally operating in pulsed mode.

The quantum cascade laser

Science **264,** 553–556 (1994)

Just when the laser community thought that no more fundamentally new designs of laser could be invented, a team from Bell Labs described the first quantum cascade laser. Jerome Faist and his colleagues explained that quantum cascade lasers are fundamentally different from diode lasers. The wavelength, which is entirely determined by quantum confinement, can be tailored from the mid-infrared to submillimetre wavelengths in the same heterostructure material. Quantum cascade lasers can also be made using relatively wide bandgap materials without having to rely on temperature-sensitive and difficult-to-process small bandgap semiconductors. The idea of the quantum cascade laser was first proposed by researchers in the early 1970s, but until the work of Faist and his colleagues, no-one had managed to successfully realize one. The group's laser operated at 4.2 μm with peak powers in excess of 8 mW in pulsed mode.

The blue laser diode

Jpn J. Appl. Phys. **35,** 74–76 (1996)

In 1996, Shuji Nakamura, then at Nichia Chemical Industries in Japan, reported the first electrically pumped blue InGaN semiconductor laser diode. His multi-quantum-well laser diodes were fabricated from III–V nitride materials and grown by metalorganic chemical vapour deposition on sapphire substrates. Optically pumped stimulated emission from GaN had been observed more than 20 years beforehand, but stimulated emission by current injection had yet to be demonstrated and so was an important breakthrough. The diodes produced 215 mW of power at a forward current of 2.3 A. A sharp peak in light output at 417 nm was demonstrated, with a full-width at half-maximum of 1.6 nm under pulsed current injection at room temperature. Although other researchers at the time had produced lasers from II–VI materials such as ZnSe, Nakamura believed that his III–V system had significant potential because of its longer lifetime.

Making history

The initial concept of the laser was pioneered at Bell Labs, as were many other technologies that are fundamental to the photonics industry. **Nadya Anscombe** finds out how the company has changed in recent years and what technologies are being researched at Bell Labs today.

Things have changed a lot at Bell Labs since its employees came up with the principle of the laser more than 50 years ago. Set up originally to develop telephone exchange systems, Bell Labs became renowned for its ground-breaking research and for producing Nobel Prize winners. Indeed, just a few months ago, half of the 2009 Nobel Prize for Physics was awarded to former Bell Labs researchers Willard Boyle and George Smith for their invention of the charge-coupled device, bringing the total number of Bell Labs' Nobel Prizes for Physics to an impressive seven.

Since 1925, Bell Labs has generated more than 33,000 patents and has had a pivotal role in either inventing or perfecting key communications technologies such as transistors, digital networking and signals processing, lasers and fibre-optic communications systems, communications satellites, cellular telephony, the electronic switching of calls, touch-tone dialling and modems.

Despite its many great successes in photonics (see Table 1), Bell Labs has had several low points in recent years, including the scientific scandal in 2002 when Jan Hendrik Schön — one of its researchers at the time — was investigated for falsifying data in a score of high-profile scientific papers on organic optoelectronics (among other topics), and was subsequently fired. Bell Labs has also come under criticism from scientists for scaling back on its research activities into fundamental physics, but the reality is that times have changed and Bell Labs has adapted. Now part of the telecommunications giant Alcatel-Lucent, Bell Labs has responded to the same industry forces that its parent company has, and thus moved into new areas of more applied research.

Andy Chraplyvy, optical network research vice president, points out that these new areas of research are still highly valuable. "Our research is still 'fundamental' in the sense that we are inventing techniques never before used," he told *Technology Focus*. "We cannot re-invent the laser, but we are doing basic research into the fundamentals of optical communication. This may not be the kind of basic physics research that Bell Labs has carried out in the past, but it is basic engineering research and it is research that has a very high value."

BELL LABS

Bell Labs pioneered many of the important techniques and technologies that have allowed high-capacity optical communications, including research on the semiconductor laser, dense wavelength-division multiplexing and the Raman amplifier.

> "Our research is still 'fundamental' in the sense that we are inventing techniques never before used"
> Andy Chraplyvy

He cites Bell Labs' work on the Shannon limit as an example. In 1948, Bell Labs researcher Claude Shannon published a theory on the maximum amount of error-free information that can be sent down a linear information channel. His mathematical models told engineers how much information could theoretically be transmitted over communication channels, and he outlined the mathematical principles of coding and error correction that make high-speed transmission possible today. In reality, signals transmitted over optical fibres are subject to the effects of 'nonlinear propagation', which is caused by the interaction between the light signals and the glass medium through which they are travelling. "For many years no-one was able to solve the nonlinear Shannon problem, which describes the limits of optical fibre communication," says Chraplyvy. "But an interdisciplinary group of researchers at Bell Labs has recently published calculations that show we are a lot closer to the fundamental limits than we first thought." The implications of these results are tremendous because they suggest that bandwidth capacities are approaching the Shannon limit much more rapidly than anticipated, and that the availability of almost 'limitless' optical bandwidth cannot be taken for granted. As a result, research projects have been earnestly undertaken to focus on finding radically new and innovative ways of providing more bandwidth capacity across the fundamental layers of data networks.

In addition to photonics, Bell Labs researchers also work in areas as diverse as wireless networks, mathematics, 3D displays and immersive communication, and computer and software sciences. For example, in wireless network technology, Bell Labs pioneered the multiple-input multiple-output technique, which reduces interference in wireless networks and increases efficiency. This technique has been widely adopted by network operators around the world and has become an indispensable method for boosting the performance of a diverse range of networks such as WiFi, indoor networks, and now 'long-term evolution', the next generation of wireless network technology.

Bell Labs has also increasingly focused its research efforts on technology that will benefit the environment. Recent research conducted by Bell Labs concludes that today's telecommunications networks could be far more energy-efficient than they are currently. This conclusion led Bell Labs to create Green Touch, a global industry-wide initiative whose ambitious long-term goal is to achieve a 1,000-fold reduction in the energy consumption of communications networks. The initiative aims to achieve this by creating a new, radically different communications network that is optimized for energy efficiency. Achieving this goal involves developing the required technologies — the basic network, electronics, transport media and semiconductors — within the next five years.

Bell Labs' researchers are no strangers to doing things for the first time or breaking records. Even today, they continue to break records in optical communication, with one of the most recent being the transmission of 1.2 Tbit s^{-1} of data over 7,200 km of fibre using a single laser transmitter. Through clever multiplexing and modulation techniques such as coherent optical orthogonal frequency-division multiplexing, polarization-division multiplexing (PDM) and quadrature phase shift keying (QPSK), the team transmitted data down 72 separate 100-km ultralarge-area fibres to create this 1.2 Tb s^{-1} superchannel. "The team was surprised when it worked over such long distances," explains Chraplyvy. "This represents a record spectral-efficiency–distance product of 27,000 km bit s^{-1} Hz^{-1} for terabit per second per channel transmission, which exceeds the previous record by over ten times to achieve terabit capacities."

At around the same time, a different group of researchers at Bell Labs reported another record — the achievement of a 112 Pbit km s^{-1} capacity–distance product. This was achieved using 155 channels with 100 Gbit s^{-1} PDM–QPSK modulation over 7,200 km of pure silica-core fibre, exploiting hybrid Raman/erbium-doped-fibre amplification and digital coherent detection.

"We don't break records just for the sake of it," says Chraplyvy. "The global demand for capacity is continuously growing and research needs to keep up with this demand. For example, 100 Gbit s^{-1} systems will be commercially available this year and we are already looking at developing technology for 400 Gbit s^{-1} or even 1 Tbit s^{-1} systems to stay ahead of the game."

Chraplyvy has been at Bell Labs for more than 30 years and, together with this colleague Rob Tkach, recently won the Marconi Prize for innovations in high-speed broadband optical communications networks. "The capacity of single-mode optical fibre has grown by a factor of one million in the last 30 years," says Chraplyvy. "That didn't happen by chance. We are continuously pushing the boundaries of what is possible, and the unique working environment at Bell Labs helps us do this."

For example, while developing the idea of orthogonal frequency-division multiplexing, the researchers did not know if it would work. It was considered a high-risk project but they were encouraged to continue investigating. The gamble paid off, and it was this type of technology that enabled them to achieve their record-breaking capacities. "We are actively encouraged to go and 'poke around in the woods'," says Chraplyvy. "This policy of encouraging researchers to take on high-risk projects is important, and is how it has always been here at Bell Labs. Without this freedom we are not going to find solutions to the problems of the world." ❒

Nadya Anscombe is a freelance science and technology journalist based in the United Kingdom.

Table 1 | Some of the major milestones and optical innovations from Bell Labs.

Year	Achievement
1927	First long-distance television transmission
1947	The transistor
1948	Claude Shannon quantifies 'information' and gives engineers a mathematical theory for calculating the maximum information that any communications system can carry
1954	The solar-cell battery
1956	First trans-Atlantic telephone cable is put into service, handling up to 36 simultaneous calls
1958	Concept of the laser is first described
1962	Bell Labs builds and successfully launches Telstar I, the first orbiting communications satellite
1964	The CO_2 laser
1969	The charge-coupled device
1980	Digital signals processing chip
1983	First high-capacity long-haul lightwave transmission system between New York City and Washington DC
1984	First gigabit per second transmission using optical communications technology
1994	The quantum cascade laser
1995	First commercial dense wavelength-division multiplexing system
1996	Terabit per second transmission through optical fibres
1999	The Raman amplifier, a device that boosts the signal in an optical fibre by transferring energy from a powerful pump beam to a weaker signal beam
1999	First bi-directional laser, which emits light at two very different wavelengths depending on the direction of electrical current flowing through it
2002	Broad spectrum laser, the world's first semiconductor laser that emits light continuously and reliably over a broad spectrum of infrared wavelengths
2003	Bell Labs earns its 30,000th patent since 1925: a method to solve VoIP congestion by creating virtual trunk groups over which information can flow between senders and receivers without interruption
2003	A team led by scientists from Bell Labs builds a new semiconductor laser based on a photonic crystal
2006	The first optical transport of electronically multiplexed 107 Gbit s^{-1} data
2009	Bell Labs sets 112 Pbit km s^{-1} optical transmission speed record using 155 lasers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THE ND:YAG LASER

From a rod to a disk

Paul Seiler, Klaus Wallmeroth and Kurt Mann

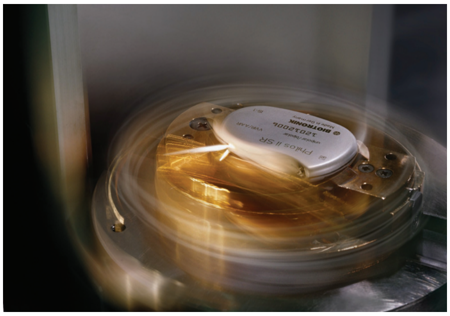
The Nd:YAG was one of the first ever industrial lasers, and even today it still has many advantages over other laser technologies. Competition from newer laser technologies, however, has made its evolution critical to its survival.

The year 1964 is recorded as being the birth of the Nd:YAG laser. Made from an yttrium aluminium garnet (YAG) crystal doped with neodymium, Nd:YAG has optical and mechanical properties similar to ruby, which was used in the first demonstration of lasing in 1960. However, Nd:YAG has a much lower excitation threshold than ruby and can therefore be operated at room temperature in continuous-wave (CW) mode. This represented a huge breakthrough in the development of laser technology. The optical resonator and pump arrangement (including the lamp, reflector and electrical supply) were well known from earlier ruby laser technology, and this allowed the ruby rod to be simply replaced by the Nd:YAG rod.

Today, YAG lasers — doped not only with neodymium but also with other rare earth elements — are used as tools in materials processing, ranging from precision engineering at the microscale to the welding of ship panels. But these lasers are not just significant for materials processing, even though this is their primary focus; they are also used in the medical industry, in measurement technology and in the military.

There are three properties that make this type of laser particularly useful: the high amplification of laser light; the option to store energy in the active medium; and the wavelength of operation (1,064 nm).

Single-rod YAG lasers allow pulses of several kilowatts in power and durations of several milliseconds to be produced. Although the first lasers had average outputs of less than 10 W, the high level of amplification offered by YAG made it possible to produce small spot-welds. Today, pulsed lasers for spot welding have average outputs of 20–500 W for a multitude of applications. Another interesting feature of early pulsed lasers was the introduction of *Q*-switching — a shuttering scheme for the creation of large laser pulses — for distance measurements in the military. *Q*-switching is able to provide pulses with powers in the megawatt range (with corresponding nanosecond pulse durations), and was later used to write information on metal/plastic media. More recently, ultrashort-pulse YAG lasers in the picosecond range have been introduced for applications involving high-precision processing.



TRUMPF

With its ability to weld and cut many different materials, the Nd:YAG laser has become the workhorse of many industries.

Advantageously, the use of fibre-optic guiding made it possible to separate the laser from the processing location. This means that one laser can be used in multiple locations, either simultaneously, by splitting the laser into multiple fibres, or by time-sharing, with the help of an optical switch. Connecting the laser to a robotic head via the fibre optics enables 3D processing, with the laser moving around the object.

The kilowatt CW YAG laser was adopted for use in large-scale industrial applications in the early 1990s, but this would not have been possible without the flexibility of fibre-optic delivery. Today, these lamp-pumped multi-kilowatt lasers are still running very successfully in the automotive industry. Nevertheless, new solid-state laser concepts based on diode pumping — the fibre laser and the disk laser — have been developed since the mid-1990s, and are now proving highly successful.

A fibre laser generates a diffraction-limited beam by using doped monomode silica glass fibres as its laser active material. These fibres have a core diameter of 10–20 µm, and are doped with rare earth elements such as ytterbium or erbium. High-power output is realized through a combination of oscillators and amplifiers, and through the parallel coupling (fibre bundling) of those arrangements.

In contrast, the active medium of a disk laser is a YAG crystal disk that is 0.1 mm thick and around 15 mm in diameter. Because the disk is very thin it can be cooled efficiently, and is therefore able to deliver excellent beam quality. Ytterbium is used as the doping element because it can be strongly concentrated without causing quenching, which negatively affects the amplification and occurs for doping elements such as neodymium. Today, disk lasers with 4 kW of power from each disk are commercially available. The output power of disk lasers can be increased by putting additional disks into the resonator, and this does not change the beam quality of the system.

Although flashlamp-pumped pulsed Nd:YAG lasers are still widely used for precise spot- and seam-welding, diode-pumped fibre lasers are now entering this domain. For CW applications, diode-pumped fibre and disk lasers have completely exceeded the capabilities of flashlamp-pumped rod lasers, and their performance is improving all the time. Most applications today need a laser power of less than 10 kW, but these new laser designs are ready for applications that require power levels of up to 100 kW. For these high outputs, however, the optical components for beam transmission and focusing will need to be improved, and this will happen over time. Fibre and disk lasers have recently been finding important applications in the domain of CO_2 laser cutting.

In the next few years, the diode laser will probably oust the fibre and disk laser as the most popular CW laser, at least at output ranges of up to several kilowatts. Investment costs and energy consumption will be the deciding factors here. However, if a high beam quality and laser power is required, fibre and disk lasers will remain the tools of choice. ❒

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THE EXCIMER LASER

Precision engineering

Ralph Delmdahl

The excimer laser is synonymous with precision. Today it is enabling the production of integrated circuits and next-generation displays, as well as new breakthroughs in eye surgery.

The UV excimer laser is one of the most precise industrial processing tools on the market and has many applications, of which eye surgery and semiconductor lithography are perhaps the best known. The great precision of excimer lasers results from the fact that the resolution achievable in laser materials processing is inversely related to the laser wavelength — the shorter the emission, the greater the achievable resolution. A UV excimer laser therefore offers considerable advantages over visible or infrared lasers for many applications.

Excimer lasers take their name from the term 'excited dimer' and are gas lasers that are electrically pumped using a high-voltage discharge. The gases commonly consist of an inert gas such as argon, krypton or xenon, and a reactive gas such as fluorine or chlorine. When electrically excited, the gas mixture temporarily forms excited states that emit UV light. The first laboratory demonstration of an excimer laser took place in 1970 at the Lebedev Physical Institute in Moscow. This laser was based on a xenon dimer and operated at a wavelength of 172 nm.

Today, most industrial excimer lasers operate at wavelengths of 193 nm (ArF), 248 nm (KrF) and 308 nm (XeCl), corresponding to photon energies of 6.4 eV, 5.0 eV and 4.0 eV, respectively. Depending on their wavelength of operation and substrate material, state-of-the-art excimer laser micromachining systems are capable of achieving lateral machining resolutions down to 1 μm, with vertical machining resolutions as small as 10 nm per laser pulse.

The first industrial excimer lasers in the early 1980s had organic polymer-based laser chambers, which fundamentally limited both the operational lifetime of the active gas and the chamber itself, owing to outgassing effects and material aging. The early 1990s saw the transition to metal/ceramic chambers entirely composed of special alloys and corrosion-resistant high-density ceramics. This major technological breakthrough immediately boosted gas lifetimes and increased chamber lifetimes by an order of magnitude.

The mid-1990s saw the duty cycles and pulse frequencies of excimer lasers increase, after which the operational lifetime of the thyratron switch — used to trigger high-voltage discharges in the laser gas — became the bottleneck for industrial use. The introduction of low-voltage semiconductor switching technology, combined with magnetic isolators and pulse transformers to achieve the required discharge voltages, eliminated the need for thyratron switches by the end of the 1990s. The replacement of the thyratron switch by its maintenance-free solid-state-based counterpart laid the foundation for the successful use of excimer lasers on the industrial production floor. In addition, the development of bandwidth-narrowing techniques that reduced excimer laser bandwidths from around 500 pm to less than a thousandth of this value enabled excimer lasers to be used in photolithography.

COHERENT

Excimer lasers are used in low-temperature poly-silicon annealing to transform thin layers of amorphous silicon into poly-crystalline silicon with largely enhanced electron mobility.

Today, the two most prominent applications of excimer lasers are in semiconductor chip manufacturing and refractive eye surgery. Both of these rely on the deep-UV emission wavelength of 193 nm, with semiconductor chip manufacturing capitalizing on the optical resolution of excimer lasers, and refractive eye surgery on its ability to ablate the cornea. For example, high repetition rate line-narrowed excimer laser models with 10 mJ per pulse, pulse frequencies of up to 6 kHz and narrowed bandwidths of 0.35 pm are used in advanced photolithography to produce computer chips with feature sizes of 45 nm.

Another major industrial growth market for excimer lasers is low-temperature polysilicon annealing. Here, the 308 nm wavelength transforms 50-nm-thin layers of amorphous silicon into high-quality polycrystalline silicon with greatly enhanced electron mobility, for use in flat-panel displays for mobile phones and flat-screen televisions.

In the low-temperature annealing of polysilicon, excimer lasers with UV output energies of over 1 J per pulse and output powers of 600 W are used to manufacture liquid-crystal and organic LED backplanes at a rate of 100 $cm^2 s^{-1}$.

The excimer laser is also used in the precision machining of medical devices made from polymers, glass or ceramics, and has a key role in the production of high-brightness LEDs, where its 193 nm and 248 nm wavelengths are crucial for the uniform lift-off of the GaN die from the sapphire substrate.

Ongoing miniaturization in microelectronics and the trend towards thin-film technologies demands increasing lateral resolution and selective machining. Functional structures and active layers are often only tens of nanometres thick and have to be annealed, patterned and removed in a selective manner without damaging underlying layers or substrates. Because excimer lasers provide the shortest wavelength of all laser technologies, they will continue to have a crucial role in many industries over the next decade.

In years to come we will see high-power applications of excimer lasers, with output energies reaching 2 J and output power levels of 1,000 W and above. ❐

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THE SEMICONDUCTOR LASER

Enabling optical communication

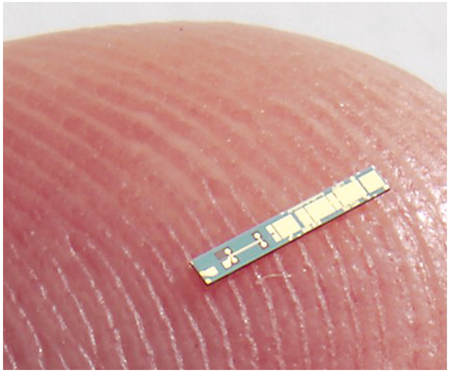
Ed Murphy

The semiconductor laser has revolutionized the way the world communicates, and it is continuously evolving with our ever-increasing demand for higher bandwidths.

At the birth of the laser in 1960, the primary modes of communication in the most technologically advanced nations were wired phone lines for voice communication, and broadcast transmission for television. Today, high-definition television, video-on-demand, broadband internet and mobile phones are available all around the globe. This exponential rise in cost-effective information transmission would not have been possible without the introduction of optical transmission systems, which in turn are enabled by semiconductor lasers. A hundred million new semiconductor lasers are deployed in communications systems every year, generating several billion dollars of annual revenue at the component level.

The first semiconductor laser was demonstrated in 1962, but it was not until the mid-1970s that the device design and materials science were advanced enough to allow for reliable room-temperature operation. These first lasers were made of gallium aluminium arsenide (GaAlAs) and operated at a wavelength of 0.8 μm. In 1976, the first optical transmission system was put into service, operating over 11 km of fibre at 45 Mbit s^{-1}. In the late 1970s, indium gallium arsenide phosphide (InGaAsP) lasers operating at longer wavelengths were demonstrated, enabling systems to transmit data at higher speeds and over longer distances. By the mid-1980s, transmission distances had increased to hundreds of kilometres and bit rates to 500 Mbit s^{-1}. Today, single fibres carrying signals at hundreds of different wavelengths can transmit terabits of information per second over transcontinental and transoceanic distances.

Semiconductor lasers have many intrinsic properties that make them ideal for fibre-optic transmission. These include high power outputs, small spot sizes and inherent coherence. Furthermore, it is possible to fabricate semiconductor materials that lase at wavelengths corresponding to the low loss and low dispersion regions of optical fibres. Semiconductor lasers for optical communications are formed on either InP (1.3 μm and 1.55 μm wavelengths) or GaAs (0.8 μm and 0.98 μm wavelengths) wafers.



State-of-the-art indium phosphide laser chip. This combined laser and Mach–Zehnder interferometer monolithically integrates tunable laser chip technology with a 10 Gbit s^{-1} modulator.

Devices can be designed with well-controlled and narrow lasing linewidths, thus minimizing the effect of fibre dispersion and allowing multiple (~100) wavelengths to be carried in the same fibre without interference between the channels. Furthermore, they can be modulated at high rates. Today, signals are transmitted at data rates of up to 100 Gbit s^{-1}, which is equivalent to more than a million voice calls or thousands of video channels.

The development of efficient optical amplifiers in the 1990s was another major milestone for semiconductor laser technology. Such amplifiers compensate for the scattering loss experienced by optical fibres, and hence enable even longer transmission distances. Semiconductor lasers have a vital role in optical amplifiers because they act as a convenient pump providing optical power to the gain medium. In 1996, optical amplifiers with semiconductor pump lasers enabled the deployment of 5 Gbit s^{-1} transoceanic systems spanning more than 6,000 km without the need for any optical-to-electronic conversion.

There are two basic semiconductor laser configurations: edge emitters and vertical-cavity surface-emitting lasers (VCSELs). For edge emitters, epitaxial layers of various compositions of InGaAsP or GaAlAs are grown to form light-emitting p–n junctions. Photolithography and etching are used to form the laser waveguide, and emission is parallel to the plane of the wafer surface. The typical chip length of such devices is 500 μm to 2 mm, and the typical output spot size is of the order of 1 μm.

There are several types of edge emitters in common use today. Fabry–Pérot lasers, in which the end facets of the chip form the laser cavity, are used in short reach, low speed applications. Fabry–Pérot structures are also used for amplifier pump lasers. Distributed feedback lasers rely on a grating that is etched into the crystal surface along the length of the waveguide. This structure results in a narrower spectral line width, which is required for long-reach applications. Electro-absorption-modulated lasers monolithically integrate a modulator structure in series with a distributed feedback laser to separate the lasing and modulation functions, and thus enable even longer reach applications. In more advanced structures, current-tunable Bragg reflectors are integrated in series with a gain region, resulting in a laser that can be tuned over a broad range of wavelengths.

In contrast, VCSELs are designed for emission perpendicular to the surface of the wafer. These devices are cheaper to produce than edge emitters and are used as single devices or monolithic arrays in short-reach, cost-sensitive applications.

The next generation of optical transmission systems require higher speeds, lower production costs, lower power dissipation and smaller form factors, and semiconductor lasers are evolving to meet these needs. Semiconductor lasers have so far been the principal enablers of optical transmission systems, and they will continue to be a core technology as new and more capable systems are deployed. ❒

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THE TI:SAPPHIRE LASER

The flexible research tool

Julien Klein and James D. Kafka

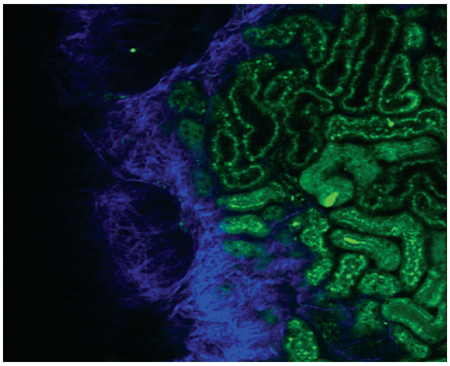
When the Ti:Sapphire laser was first invented, it took the research community by storm. Today, it has an important role in imaging, spectroscopy and many other applications.

Ti:Sapphire (Ti:Sa) was initially proposed and demonstrated as a near-infrared gain medium in 1982, and was commercialized by Spectra-Physics in 1988 with the launch of a continuous-wave laser. This was followed in 1990 by a picosecond mode-locked oscillator, and in 1991 with a femtosecond version. Soon after this, the whole ultrafast research community, which until then had been using visible-wavelength dye lasers for the generation of ultrafast tunable pulses, adopted Ti:Sa technology in a matter of months — an instant shift rarely seen in research.

Table-top commercial amplified systems followed during the mid-1990s, leveraging chirped pulse amplification techniques. In 1996, the introduction of the first high-power diode-pumped solid-state 532 nm laser significantly reduced the complexity of pumping ultrafast Ti:Sa lasers (which until then had relied on argon-ion gas laser technology), and drastically reduced the amplitude noise — important for femtosecond spectroscopy experiments.

Another milestone in the development of Ti:Sa technology was the stabilization of the carrier–envelope phase of ultrafast pulses, paving the way for the generation of attosecond (10^{-18} s) pulses in the X-ray spectrum using high-harmonic generation. Attosecond laser sources are now poised to become the next tool for probing dynamic chemical processes with unprecedented time resolution. An octave-spanning carrier–envelope phase-stabilized ultrafast oscillator can also be used as a frequency comb. Frequency combs are accurate 'optical clocks' that can be used to measure optical frequencies with extraordinary precision, a technique for which Theodore W. Hänsch and John L. Hall received the Nobel Prize for Physics in 2005. Furthermore, the Ti:Sa crystal has been at the heart of numerous large amplifier systems that deliver terawatt and petawatt peak powers.

Ti:Sa technology offers unique benefits and a tremendous flexibility in performance over competing gain media. No other material can offer: 1) spectral outputs that range from ultra-narrow single frequencies to wide bandwidths spanning several hundred nanometres, providing ultrafast pulses as short as a few oscillations of the electric field; 2) repetition rates that range from maximum-energy single shots to multi-gigahertz quasi-continuous-wave output; 3) a tunability of 400 nm; and 4) average powers of many watts.



CLAUDIO VINEGONI, HARVARD

Image of a mouse kidney, using second-harmonic generation imaging for collagen (blue) and multiphoton microscopy imaging for protein (green).

As the technology has matured over the past two decades, a complete set of accessories has been developed to support and complement Ti:Sa lasers. Optical parametric oscillators and amplifiers can extend wavelength tunability to the deep-ultraviolet (<200 nm) and mid-infrared regions (>20 μm).

Ti:Sa lasers and amplifiers have enabled countless applications for fundamental research in physics, biology and chemistry. Femtosecond chemistry, the science that studies chemical reactions on ultrafast timescales, was developed mostly using Ti:Sa lasers. This research earned Ahmed H. Zewail the Nobel Prize for Chemistry in 1999. Recently, the sophistication of coherent control has grown significantly, and devices to control the spectral phase and amplitude of ultrafast pulses have now been developed. Other applications include nonlinear physics, terahertz generation, micromachining that requires the cutting, drilling and scribing to be free of undesirable thermal effects, and multiphoton microscopy.

Multiphoton microscopy takes full advantage of the high power, short pulsewidth and wide wavelength tunability of Ti:Sa lasers to enable high-contrast and high-resolution *in vivo* imaging of living deep tissues. This technique is based on the two-photon absorption of dyes and the extended tunability of Ti:Sa lasers, thus allowing the use of various dyes with distinct absorption spectra and chemical properties. Multiphoton absorption is highly dependent on the laser peak power, and hence on the pulse duration. By focusing an ultrafast pulse train to a tight focal spot, one can selectively generate two-photon absorption in a small sample volume, greatly enhancing the spatial resolution of the image in all three dimensions while also reducing the background signal from the out-of-focus regions of the sample.

Although Ti:Sa technology is now fairly mature, it is interesting to note that Ti:Sa oscillators are still limited principally by the green pump source. Other ultrafast lasers such as chromium-doped colquiriites (for example, Cr:LiSAF) are more suitable for direct diode pumping than Ti:Sa, but have not been commercially successful due to their lower average powers and reduced tunability. Fibre lasers have recently attracted much attention for their average power scalability and turn-key operation, but are much less tunable than Ti:Sa and do not produce very short pulse durations. Looking to the future, for ultrafast applications such as micromachining and terahertz generation, in which neither tunability nor the shortest pulses are required, fibre lasers will have an important role. However, for research and spectroscopy in which flexibility in wavelength, pulse duration and power are essential, the Ti:Sa laser will continue to be the source of choice for a significant period of time. ❐

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THE FIBRE LASER

Delivering power

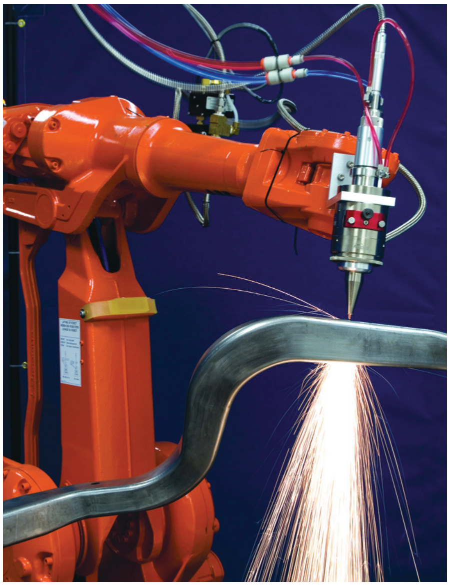
Bill Shiner

With its high wall-plug efficiency and record-breaking power output, the fibre laser has made the use of lasers in manufacturing more acceptable and cost-effective.

Fibre lasers have developed rapidly over the past several years. Single-mode lasers with powers of around 10 W were first introduced in 1996, and today multimode fibre lasers with powers that exceed 50 kW are available. Owing to significant improvements in performance since their introduction, fibre lasers are now an accepted laser technology in materials processing applications and are rapidly expanding the roles they have. The majority of fibre lasers are ytterbium-doped lasers operating at wavelengths of ~1 μm, serving as replacements for or alternatives to both YAG-crystal and CO_2-gas lasers.

Like conventional solid-state lasers based on doped laser crystals, fibre lasers rely on glass doped with a rare earth element (ytterbium or erbium being the most common) as a gain medium. The key difference is that the geometry of the gain medium is now a thin length of fibre rather than a small rod. This brings many benefits in terms of deployment and convenience of operation, as well as for thermal management and power scaling. Fibre lasers are optically pumped, usually by high-power semiconductor laser diodes.

The technology behind fibre lasers has made their use in manufacturing more acceptable and cost-effective than previous laser technologies, and their high wall-plug efficiencies (around 30%) greatly reduce the electrical operating costs associated with an industrial laser. Fibre lasers are also maintenance-free. This allows the technology to compete, on a cost-of-manufacturing basis, with many of the more conventional materials processing technologies. Fibre lasers are also extremely rugged and compact, allowing their deployment in mobile and outdoor applications for which lasers could never have previously been considered. Fibre lasers are also now available at very high power levels, with systems offering output powers up to 50 kW and thus greatly expanding the applications of the technology. The excellent beam quality of fibre lasers has expanded the use of long-focal-length lenses that are required for many remote welding applications; for example, fibre lasers can produce a 500 μm focused spot at a distance of 4 m. These long focal lengths are required for high-speed welding applications that use robots or high-speed scanning systems.



IPG

The fibre laser has become a valuable materials processing tool, with output powers reaching 10 kW for single-mode devices and 50 kW for multimode devices.

In 2009, industry saw the increased acceptance of fibre lasers, particularly in the number of sales to companies that manufacture standard two- and three-axis sheet-metal cutting machines. This achievement, in a market previously totally dominated by the CO_2 laser, marks the beginning of a shift that is accelerating towards the mass-adoption of fibre lasers. The advantages are clear: fibre lasers can cut thin materials faster than, and with a quality equal to or superior than, CO_2 lasers. Furthermore, the fibre-based method of delivery eliminates costly beam paths and alignment requirements, and produces the same spot size over the entire cutting envelope.

The fibre laser has also made significant progress in the extremely competitive automotive market, where it is exploited for single-use welding and cutting applications. These applications include the cutting of hydro-formed rails and high-strength body sheet metal, as well as the welding of tailored blanks and seat structures, many of which are manufactured from high-strength steel. The acceptance of fibre lasers has been aided by the ease at which they can be integrated into robots, and the elimination of expensive helium cover gas for welding. High-power fibre lasers with outputs of 10–20 kW have been deployed for deep-penetration welding in the nuclear, railroad, shipbuilding and land-based turbine industries. Many of these applications previously required an electron-beam welding machine operating in vacuum, but instead can now weld in air using an ultrahigh-power fibre laser. Another growth industry for fibre lasers is the welding of the new battery designs for the electric car industry. This application includes both the hermetic sealing and welding of the copper contacts that combine individual cells. Low-power fibre lasers in the range of 5 W to 1 kW — both pulsed and continuous wave — have gained significant market share over previous technologies in the computer, solar, medical device and marking industries, with more than 6,000 units being shipped worldwide every year.

Two recent products introduced to the market are a 10 kW single-mode fibre laser and pulsed and continuous-wave green (532 nm) fibre lasers. Such fibre lasers are continuing to increase their double-digit market share in the materials processing sector, with laser output powers now available from 5 W to 50 kW. These lasers also are being used for many other applications such disarming land mines at great distances, shooting down airborne devices, light detection and ranging mapping applications, optical pumping, skin wrinkle reduction and surgical applications. In the future, the brightness and compactness of fibre lasers will continue to improve, opening up many new applications and, most importantly, reducing the cost of ownership. ❐

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THE QUANTUM CASCADE LASER

Ready for take-off

Antoine Müller and Jérôme Faist

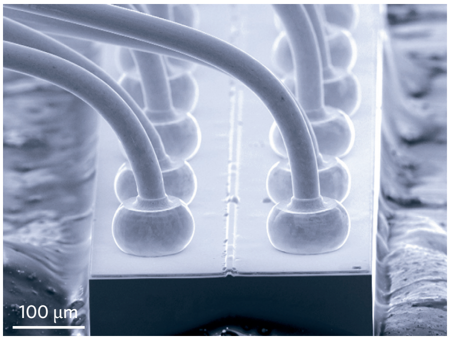
Since their invention, quantum cascade lasers have made considerable progress in terms of their wavelength range and efficiency. Today, they have important applications in environmental science, process control and medical diagnostics.

The first demonstration of the quantum cascade laser (QCL) in 1994 came somewhat as a surprise. A semiconductor laser based on inter-subband transitions (energy levels within a single band) had been proposed by Kazarinov and Suris as early as 1972. However, it was widely believed that the extremely short upper-state lifetime of electrons in quantum wells, although not suppressing laser operation completely, would impede the realization of a QCL laser with a performance suitable for practical applications.

Luckily, this turned out not to be the case, and the inter-subband transition approach of operation was shown to have some very attractive features. First, the wavelength could be adjusted over a very wide range from the mid- to far-infrared at the design stage by simply scaling the quantum well thicknesses. Second, the transitions could be cascaded over a large number of well periods in such a way that a single electron passing through the structure can emit a large number of photons in the process (10–100, in practice). In addition, growth and processing technologies already developed for telecommunications lasers were capable of fabricating this new device.

In any kind of laser, the threshold for lasing occurs when the gain balances the optical losses. The very short upper-state lifetime (subpicosecond) in the first QCLs meant that the gain would be very limited. However, this drawback was offset to a large extent by low waveguide losses and a low sensitivity of the gain to temperature. As a result, two key milestones demonstrating the potential of QCLs for applications were achieved a few years after its first operation. In 1997, pulsed single-frequency operation at room temperature was achieved, and in 2002 continuous-wave operation was demonstrated.

Since then, considerable progress has been made. Today, QCLs have been fabricated to operate over a very wide wavelength range of 2.9–250 µm, spanning the mid-infrared and terahertz regions. Furthermore, these devices operate at room temperature throughout a large portion of this frequency range. Devices operating in continuous-wave mode with 3 W of optical power and wall-plug efficiencies above 10% have been achieved, thanks to the low waveguide losses. Owing to the low temperature-sensitivity of the gain coefficient, single-mode devices operating in continuous-wave mode at temperatures of up to 150 °C have also been realized. Unlike conventional semiconductor lasers based on inter-band transitions, active regions operating at different wavelengths can be combined in a single waveguide, enabling the creation of QCLs with very broadband operation. Recently, a room-temperature device with a tuning of over 435 cm^{-1} was achieved, which corresponds to a bandwidth of 40% of the centre frequency. A number of companies are now selling devices with performances approaching these results.



ALPES LASERS

Scanning electron micrograph of a high-power QCL soldered on its submount. The waveguide ridge is visible between the rows of bonding wires, which bring current to the device.

As for applications, a large number of molecules have their fundamental vibrational mode in the mid-infrared region. This makes optical sensing and spectroscopy with QCLs a very powerful technique that combines both selectivity and absolute sensitivity. In contrast with other sensing techniques based on reactive membranes or surfaces, optical sensing is relatively immune to problems arising from chemical cross-talk or poisoning. Because QCLs are the first semiconductor laser sources to operate over the whole mid-infrared range at room temperature, they have enabled the development of sensing techniques that were previously limited by a lack of convenient optical sources. Applications of these optical sensing techniques are in areas such as environmental monitoring, process and combustion control, oil and gas industries, and medical diagnostics. As an example, a QCL-based spectrometer is due to be launched into space in the next few years to probe the isotopic content of the atmosphere on Mars.

Back on Earth, QCL-based spectrometers are also being used to provide continuous sampling of the C^{12}/C^{13} and O^{16}/O^{18} isotope ratios in the atmosphere. These instruments surpass mass-spectrometer-based instruments in terms of performance, and help to trace the sources and sinks of atmospheric CO_2. Monitoring the exhaust gases of ships is an example of how combustion diagnostics is now being implemented.

In addition, QCL-based sensors promise to bring about a shift in the way sensing is performed, as they allow a simple change in optical source to address a different chemical compound.

Quantum cascade lasers are used in many other application areas, and the spread of the technology will be further increased by future advances in performance, such as ultralow dissipation to allow long-life battery-operated systems; increased wavelength ranges and broadly tunable devices; and terahertz operation with thermoelectric coolers. Increasing production volumes will also reduce the price of the technology, making it highly competitive with existing techniques. ❒

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THE FUTURE OF PRIVACY
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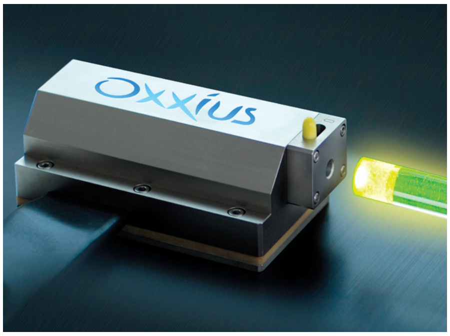
Yellow source aids fluorescence studies



OXXIUS

French company Oxxius has released the SLIM-550 — a diode-pumped solid-state laser that emits up to 200 mW of yellow light at 550 nm. The company claims that the laser's monolithic resonator guarantees outstanding performance, with optical noise of <0.2%, pointing stability of <5 microrad and power consumption as low as 10 W. These features make the SLIM-550 ideal for fluorescence applications, and in particular enable very efficient light collection from the fluorophore phycoerythrin without unwanted excitation of allophycocyanin. It also allows optimal excitation of fluorescent proteins such as DsRed and dTomato.

www.oxxius.com

Combiner enables power scaling

Australian firm AOFR, a supplier of fused fibre-couplers and a subsidiary of Aegis Lightwave, has released a laser combiner with a high-power handling capability yet small form-factor. The 5 mm × 5 mm × 50 mm product combines the output from up to seven pump lasers, each up to 25 W in power. It is available for use at the popular wavelengths of 1,064, 1,550 and 2,050 nm. AOFR says that the combiner is a key building block for constructing kilowatt-class fibre lasers, which are now replacing gas and solid-state lasers in materials processing applications. "We bring to the industrial laser market our decades of experience in telecommunications, where we have a proven track record for high-quality and high-reliability products and where we have shown the ability to scale manufacturing to high volumes," commented David Moser, product lifecycle manager at AOFR. "Working with a reliable laser-combiner supplier will be a key factor in enabling fibre-laser vendors to meet the rapid growth in demand while continuing to achieve record levels of output power."

www.aofr.com

Kaai reports direct green diode

US firm Kaai claims to have fabricated green laser diodes that operate at 523 nm, filling the gap between blue- and red-emitting devices. The lasers are based on InGaN semiconductor technology and are fabricated on innovative non-polar and semi-polar GaN substrates. Direct diode green lasers offer dramatic improvements in size, weight and cost over conventional green sources based on frequency-doubled solid-state lasers. Once commercially available they will enable a variety of new applications in consumer projection displays, defence equipment and illuminators, biomedical instrumentation and therapeutics, and industrial imaging applications. Kaai was founded in 2008 by the world-renowned semiconductor laser pioneers Shuji Nakamura, Steven Denbaars and James Speck of the University of California at Santa Barbara in the USA.

www.kaai.com

RGB laser light source is energy efficient

Sony has developed a red–green–blue (RGB) laser light source module for use in large-screen digital projectors. The module uses semiconductor diodes for the red and blue lasers, and a compact, high-power solid-state green laser based on second-harmonic generation wavelength conversion. The three lasers generate output powers of 10 W for red, 6 W for green, and 5 W for blue, resulting in a total power output of 21 W. Energy conversion ratios for the lasers range from 15% to 22% (18% on average), representing extremely high efficiencies for visible-wavelength lasers. The module can be used as the light source for a range of projectors, from 1,000-lumen home theatre projectors to 10,000-lumen large-screen projectors, and even digital cinema projectors. This is due to the scalability of the module design, which outputs collimated light beams for each of the three colours, enabling multiple modules to be stacked.

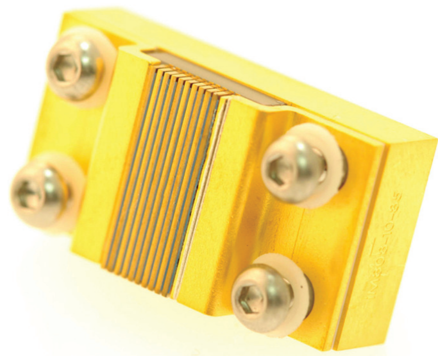
www.sony.com

Argon-ion alternative now ready for orders

Orders are now being taken for the Axiom laser developed by Solus Technologies, a Glasgow-based manufacturer of semiconductor disk lasers. The Axiom laser emits up to 0.5 W of continuous-wave power at 514 nm, allowing it to replace bulky and expensive argon-ion lasers for some applications. According to its UK distributor Elliot Scientific, the Axiom combines excellent beam quality with high power and a narrow linewidth to suit a broad range of laboratory and industrial applications, including metrology and biophotonics. Furthermore, the laser's operational wavelength can be specified anywhere in the 500–599 nm range with an accuracy of 1 nm. Axiom comes complete with a simple graphical user interface as well as integrated control and monitoring systems, making it a convenient and compact source of visible light.

www.elliotscientific.com

Laser stack offers high optical power density



INTENSE

Intense, a developer of semiconductor lasers in Glasgow, UK, has added the 600 W Mini stack to its Hermes family of high-power quasi-continuous-wave stacked arrays. The 600 W Mini stack is an ultra-compact 600 W quasi-continuous-wave stack with an emission area of less than 3 mm × 3 mm and an optical power density in the range of 7.6 kW cm^{-2}. The device is built for standard wavelengths of 808 and 940 nm, but custom wavelengths, including multicolour options, are available on request.

The company claims that the 600 W Mini stack offers an optical power density that is 50% higher than some 2 kW stacks that use standard bar technology. The standard 600 W Mini stack is suitable for operating conditions of around 60 °C, but high-temperature versions covering 70–130 °C are available. Power levels and emission areas can also be custom-designed to meet the specific needs of OEM customers.

The 600 W Mini stack and all Hermes bars and stacked arrays use Intense's patented quantum well intermixing technology. This increases the brightness and reliability of the lasers while dramatically reducing instances of catastrophic optical damage.

www.intenseco.com

Exciting times

SEE THE VIDEO

Nadya Anscombe talks to Charles Townes, Nobel Prize winner and inventor of the maser, the forerunner to the laser, to find out how the invention of the laser came about and how he struggled to convince people of its importance.

How did the invention of the maser, and then the laser, come about?
I was working at Bell Labs doing spectroscopy with microwaves and wanted to reach shorter wavelengths and higher frequencies. I didn't know how to do it and consulted a lot of people, but no-one knew the answer. I was even appointed chair of a national committee to try and get to shorter wavelengths. After several years we came to the conclusion that we could not do it, and organized what was to be the last meeting to plan our final report. I woke up early in the morning worrying about it. It was a sunny morning and breakfast wasn't ready yet, so I went for a walk and sat on a park bench to contemplate the problem. That was the first time I thought that perhaps atoms or molecules could be used to amplify radiation by exciting them to upper energy states. I was really excited, but I wasn't entirely sure it would work. I didn't even mention it in our last committee meeting because I realized it was a strange idea. When I started trying it, few people thought it would work, and I was even asked by one professor to stop my research. But I continued because I truly believed it would work — and it did. That is when the competition started and other researchers began to show interest. I wanted to know if my maser could go to optical wavelengths and so I consulted my brother-in-law, Arthur Schawlow, who was also working at Bell Labs at the time. When we realized it might be possible, we published a theoretical paper and applied for a patent for what we then called an optical maser. We had a difficult job convincing the patent attorneys at Bell Labs that it was worthwhile applying for a patent. Their attitude was: 'Great idea, but what use is it? Light has never been used for communication.' The first working laser was built in 1960 by Theodore 'Ted' Maiman at the Hughes Research Laboratory using a ruby rod. Getting enough excitation energy into the system was the main challenge. It was Maiman who came up with the idea of using a high-energy flash of light for excitation, and it worked first time. Early lasers included ruby systems, which used a piece of ruby of around half an inch in size, semiconducting systems of a similar size, and gas discharge tubes. These were very exciting times.

TOWNES

"We had a difficult job convincing the patent attorneys at Bell Labs that it was worthwhile applying for a patent. Their attitude was: 'Great idea, but what use is it?'"

Did you realize what impact your invention would have?
My aim was to develop a scientific instrument that I could use in my research, and I was very excited about the fact that we had managed to do it. I did realize that the laser had wider applications such as communications and cutting and welding, but I never envisaged the breadth of applications for which it is used today. The fact that so many Nobel Prize winners use the laser in their work is a measure of the impact the invention had on society, and I am still amazed at the exciting fields in which it is used. For example, I never envisaged the many medical applications a laser could be used for, including eye surgery, minimally invasive surgery and medical imaging. I am also interested to hear about the really big lasers, such as the one at the National Ignition Facility, and when researchers extend the boundaries of the laser, for example going down to wavelengths near the X-ray region of the spectrum. The laser today is so much more than just a scientific instrument.

What are the most important technology milestones over the past 50 years of laser development?
The use of lasers in communications has had a huge impact on society. The speeds and bandwidths available to us are incredible. The amount of power the laser can now produce is also amazing. Focused laser beams provide the greatest concentration of power humans can produce, and this can be used for applications such as fusion and nuclear energy. Furthermore, the lasers ability to perform precise measurements has changed the way we see the world. Measurements of distance, position or frequency can be made very precisely. This accuracy is allowing new kinds of experiments to be made, including measurements of the distance to the Moon, and of the distortion of space by gravity.

Does your current work involve lasers?
Yes it does. My current research at the University of California in Berkeley is in the field of astrophysics — the laser is a very important tool in this field. The laser has been used for astronomy in many ways, such as for improving the imaging of telescopes, and in my case, for performing interferometry on stars. The laser's narrow bandwidth means that I can avoid the gas around a star and measure the size of the star itself, rather than the size of the gas cloud that surrounds it. Ironically, when we invented masers and lasers, we were inventing something that had already existed in space for many years; masers and lasers can be found around stars, but we just didn't look! I still very much enjoy my work, and I am still having fun. Science is fun. But I suppose I must stop soon. I am, after all, turning 95 this year.

INTERVIEW BY NADYA ANSCOMBE

Nadya Anscombe is a freelance science and technology journalist based in the United Kingdom.

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Theodore Maiman discussing the first laser

Video of an interview with Theodore Maiman discussing his first ruby laser and its constituent parts. Courtesy of the Optical Society of America and Laserfest.

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Sound bite from Charles Townes

A few words from Charles Townes at the University of California, Berkeley about the importance and joy of conducting scientific research. Townes received the Nobel Prize for Physics in 1964 for his contributions to the invention of the maser and the laser. Courtesy of the Optical Society of America and Laserfest.

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Nobel Prize winner and inventor of the maser, the forerunner to the laser.
Video courtesy of the Optical Society of America.

Theodore Maiman – 50th anniversary of the laser

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Interview with Theodore Maiman discussing his invention of the laser and describing the components used. For more information about Laserfest and its planned activities throughout 2010 please visit **www.laserfest.org**

Video courtesy of Laserfest.