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A Report on Ten Key Technologies and Their Policy Implications

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LASERS

KEY TAKEAWAYS

- Laser technology has become essential for a wide range of applications, including communications, high-end chip production, defense, manufacturing, and medicine.
- Because advances in laser technology tend to occur in the context of specific applications, laser technology research and development is widely dispersed among different types of laboratories and facilities.
- Broad investment in next-generation lasers holds the potential to improve progress in nuclear fusion energy technology, weapons development, and quantum communication.

Overview

Improvements in laser technology since its invention in 1960 have allowed light to be manipulated and used in previously unimaginable ways. Lasers now underpin a huge range of scientific and industrial applications. Already, lasers with ever higher energy and power are being developed across a wider range of wavelengths and with pulse lengths that can illuminate many details of what is happening very rapidly at an atomic and molecular level.

A laser—an acronym derived from “light amplification by stimulated emission of radiation”—is a light source with three important characteristics. First, its light is monochromatic (i.e., single color), meaning the light is highly concentrated around a central wavelength, with very little emitted at other wavelengths. Monochromatic light enhances data transmissions by minimizing chromatic aberration, which occurs when a lens can’t focus different colors of light on a single point. Monochromatic lasers are also essential in scientific and medical applications that need specific wavelengths for controlled interactions with materials or tissues.

Second, a laser is directional, which means its energy can be concentrated into a small spot, significantly increasing intensity and making lasers useful for applications that require precision and high energy density, such as cutting, welding, and surgical procedures.

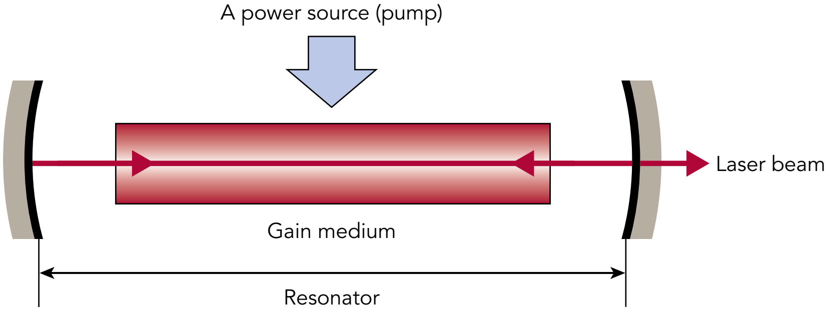
Third, laser light is coherent, which means that the light waves it uses are in phase with each other—that is, they repeatedly reach the same peak or trough at the same point in time and space. This property is important for holography, interferometry (the measurement of light sources), and optical sensing, where precise phase information is needed to create accurate and detailed images or measurements.

There are many ways to produce laser light. Lasers typically involve a power source (a pump), a gain medium (a material within which the energy supplied by the pump is turned into laser light), and a resonator that encloses the gain medium within which laser light is produced (see figure 4.1). Progress in laser technology depends on advancing one or more of these elements and is generally measured with respect to five technical characteristics (figures of merit) of the beam:

Peak power Generating the brightest possible laser pulses—which equates to the greatest possible power—for very short times. The 2018 Nobel Prize in Physics was awarded for the development of the chirped pulse amplification technique, a high-power, short-duration approach for producing laser pulses that significantly outperformed prior peak power achievements. Peak powers in state-of-the-art lasers can now reach levels that damage the laser itself. Because of this, to reach even higher power levels, scientists have used multiple beams from multiple lasers focused on a target. In 2024, one laser delivered a peak power of 10 petawatts (or 10^{16} watts) with a pulse time (duration) of 24 femtoseconds (a femtosecond is 10^{-15} seconds).[1] (For comparison, total global electrical generation capacity today is about 9 terawatts, or about 1/1,000th of the peak power of a 10-petawatt laser.)

Energy Delivering as much energy as possible in a beam. A high-energy laser beam generally delivers its energy on timescales of a few nanoseconds, or around a million times longer than the lasers

FIGURE 4.1 Typical components of a laser



discussed above. The highest energy lasers today are found at the National Ignition Facility of the Lawrence Livermore National Laboratory (LLNL). These deliver beam energies as high as 2.2 megajoules and have been used to drive controlled nuclear fusion reactions at the lab that produced a net energy gain.[2]

Average power Reliably delivering high power and energy at elevated repetition rates. Many laser applications need pulses whose quality is consistent and that are delivered frequently and reliably. An important technical challenge is managing heat buildup in the resonator, which can limit the number of pulses a laser can produce over a given time. Today, high-average-power lasers—ones rated in excess of 300 kilowatts—use active liquid or gas cooling in what is called a distributed gain laser architecture.[3] Some efforts to manage possible laser damage involve development of improved material production techniques that can, for instance, reduce erosion of the coating in lasers' optical systems. Other solutions involve the use of lasers based on gaseous media, which are inherently less prone to damage.

Pulse length Generating shorter laser pulses. Over the course of lasers' development, squeezing energy into ever shorter pulse lengths has been the primary way of generating beams with higher power. In addition, short pulse lengths can be used like a strobe light to observe rapid motion. For example, the generation of attosecond pulses (10^{-18} seconds) was recognized with the Nobel Prize in Physics in 2023.[4] These pulses are shorter than the timescale of electronic motion within atoms, enabling atomic processes to be observed with the electrons effectively frozen in place.

Wavelength Delivering laser-like pulses at more frequencies. Historically, the term *laser* is generally used to refer to devices operated near to optical wavelengths, distinguishing them from the microwave "masers" that preceded them. Today, however, pulses of radiation with the same properties that make lasers so useful can be generated and used across a far wider range of the electromagnetic spectrum. Being able to use a wider range of wavelengths enables the investigation and manipulation of matter under a wider variety of conditions.

The engineering characteristics of lasers are also an important aspect of how fast the technology advances. For example, different configurations of power sources, resonators, and gain mediums can result in lasers of different sizes, weight, reliability, cost, and other key features. Moreover, some applications require mechanisms that can steer beams in particular directions. Addressing these and other engineering issues helps take lasers from labs to the commercial world, where many non-research applications make important use of them.

For example, researchers have miniaturized a titanium-sapphire laser by polishing and etching a bulk titanium-sapphire crystal to a nanoscale-thick layer on a silicon dioxide support.[5] They then patterned a circular waveguide into the titanium-sapphire layer. The intensity of the generated light is increased over the length of the waveguide. The miniaturized laser is several orders of magnitude smaller and significantly less expensive than existing titanium-sapphire lasers, which are currently the best ones for a variety of applications including quantum optics, spectroscopy, and biomedical research.

Key Developments

The basic operating principles and physics of lasers are generally well understood. What stands out in reviewing key developments in laser technology is the wide variety of applications to which the technology is relevant. Below is a list of some examples of important applications.

Medicine

Lasers in medicine have historically been used to ablate, cut out, or vaporize tissue or to clot bodily fluids.[6] For example, a robot-guided laser has been used to perform bone surgery.[7] Traditional tools like saws, drills, and burs can cause mechanical and thermal damage to bone and tissue and are also limited to simple cuts. In contrast, lasers offer more precise, cleaner cuts with less damage to surrounding tissue, and they can handle complex trajectories, especially when guided by a computer-controlled robot arm for fully automated surgery. This technology not only enhances accuracy but also reduces recovery time for patients.

A well-known example is laser eye surgery, where ultrashort laser pulses are used to remove small amounts of corneal tissue with great precision, thus reshaping the cornea to improve how light is focused onto the retina (see figure 4.2). Interestingly, this technique, popularly known as LASIK, was inspired by a laser eye injury in a research lab.[8]

Lasers can also be used to destroy subsurface tumors with minimal thermal damage to surrounding healthy tissue. Researchers have demonstrated the use of a focused laser beam from an ultrashort-pulse diode laser source.[9] The beam is intense enough to destroy a tumor but focused enough and short enough that it causes only minimal damage to the surrounding tissue.

FIGURE 4.2 Laser eye surgery uses laser pulses to remove corneal tissue

Source: Shutterstock / Terelyuk

Lasers may come to play an important role in certain cancer treatments. Specifically, some recent cancer research has discovered that charged particle beams delivered at extremely high dose rates to cancerous tissue may have unique benefits. A very high dose of proton beam radiation delivered to a cancerous tumor over a very short time will kill it while significantly reducing collateral damage to surrounding tissue compared to current approaches. The production of such proton beams was driven by a laser whose operating characteristics could be very tightly controlled, leading to a beam precisely tailored for the tumor in question.[10]

Military Applications

Lasers as weapons could serve a variety of ground-based missions,[11] including attacking satellites and providing short-range air defense to counter drones, rockets, artillery, and mortar rounds. In these roles, lasers have several advantages over conventional munitions—in particular, lower cost per shot and potentially more rounds in their magazines (assuming their power supplies are not exhausted). But they have certain disadvantages as well—most importantly, rain, fog, and some other atmospheric conditions potentially limit their range and beam quality.

Because a laser beam traveling through the atmosphere loses energy as the range to the target increases, laser weapons need high-power beams to damage distant targets. These two conflicting requirements can be resolved with a laser that delivers a beam with a very long pulse length. This means the beam must dwell on its target for the entire duration of the pulse—and if the target moves during that time, the weapon must have a pointing mechanism that keeps the beam on target for a few seconds. Another way to resolve these requirements is to select a wavelength for laser operation that is not strongly absorbed by the atmosphere. But since some degree of absorption will occur in any event, the tension between these requirements can only be reduced and not eliminated.

In general, laser weapons require a laser to supply the necessary beam, a power supply (typically an electrical battery source or chemicals that are mixed to produce energy), and a way of tracking a target and directing the beam to remain trained on it while it is in motion so enough energy can be delivered to destroy or disable the target. (When the mission is to disable things like sensors that a target may be carrying, such as cameras on a reconnaissance satellite, the power required is much lower than if the target's entire physical structure must be destroyed.)

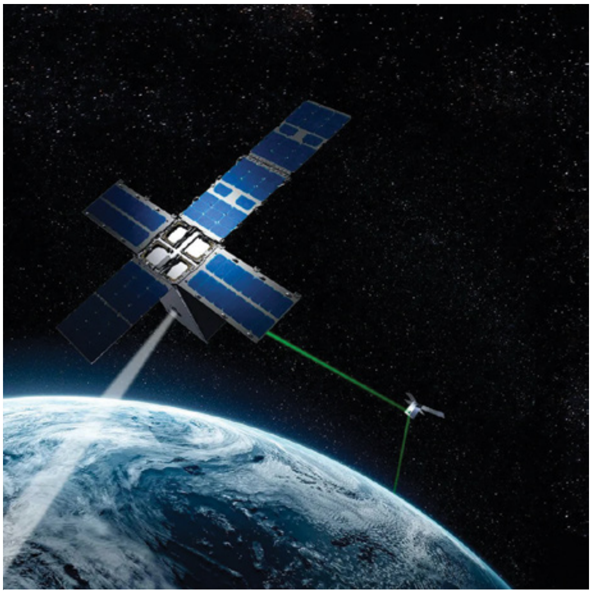
Progress in laser weapons involves making them smaller and lighter, more rugged for an operational military environment, more powerful, and more efficient in their conversion of energy in the magazine to shots fired. Auxiliary technologies such as those for beam tracking and target sensing must also work in concert with the lasers themselves.

Communications

Lasers play a key role in communications by transmitting data through fiber-optic cables, which make up the bulk of the infrastructure behind the internet. As demand for information transfer grows, approaches that raise data transfer rates are increasingly important. Recent results have shown that data can be sent through fiber-optic cables using much shorter laser pulses without a loss of transfer fidelity, potentially lowering power requirements significantly.[12]

Lasers can transmit data over long ranges and are even being used to enable satellites in orbit to communicate with one another.[13] Compared to traditional radio transmission systems, laser communications allow for data-transfer rates that are 10 to 100 times faster than radio. They are also more secure than radio systems because they have directed narrower beam widths that make them harder to intercept. Laser communications systems are also more energy efficient, and the hardware required is smaller and lighter. The primary technical challenge they face is the issue of beam alignment: Because the beams need to be very narrow, aligning the sending laser and the laser receiver properly is hard if they are far apart.

FIGURE 4.3 Lasers are well suited for space-to-space communications



Source: General Atomics Electromagnetic Systems

Lasers are well suited for space-to-space communications, where there is very little to interfere with the beam (see figure 4.3). Starlink—the space-based internet service provider wholly owned and operated by SpaceX—uses laser communications to transfer data at high speeds directly between satellites in low Earth orbit (LEO) without going through ground stations.[14] In December 2023, NASA successfully demonstrated its first two-way laser communication link between the International Space Station in LEO and a geostationary satellite.[15] Efforts are also underway to adapt laser communications for ground/air/sea-to-space applications, which will mean overcoming challenges posed by atmospheric interference with data-carrying laser beams.

Additive Manufacturing

Lasers are useful for additive manufacturing (also known as 3-D printing), enabling precise and efficient creation of complex structures through various techniques. For example, in stereolithography an ultraviolet laser is used to cure a photosensitive resin layer by layer. The laser selectively turns on and off, curing the layer with the appropriate structure. The next layer is treated similarly until the artifact is fully formed. Another method, selective laser sintering, uses a laser to harden (sinter) a layer of powder, such as nylon or metal. These laser-based techniques can be adapted for various materials, making them suitable for rapid prototyping and other manufacturing applications.

Particle Traps / Quantum Computing

Lasers can be used to create the coldest temperatures achieved on Earth—significantly colder than the void of interstellar space. The record low temperature is around a few millionths of a degree kelvin from absolute zero (about minus 273 degrees Celsius) for small material samples, with parallel work focusing on cooling larger samples, such as the mirrors at the Laser Interferometer Gravitational-Wave Observatory, in order to reduce thermal noise in the system that interferes with the detection of gravitational waves from space.

Laser-cooled atoms demonstrate measurable quantum behavior and hence are one of the approaches being pursued to work with quantum bits, or qubits, in labs.[16] (Qubits are the building blocks for quantum computers, which are discussed in chapter 8 on semiconductors.) By focusing laser beams into a very small space, scientists can trap atoms and other particles and manipulate them into quantum states to produce qubits using yet more lasers.

Orbital Debris Removal

Chapter 9 on space describes the Kessler syndrome, a scenario in which the density of objects both large and small in LEO becomes so high that collisions between some of them create a cascade of debris, potentially rendering space activities and satellite operations in certain orbital ranges difficult or impossible for many future generations. Technologies for debris removal may become important in the future, and lasers could be used for this purpose.

Specifically, NASA is supporting a project to research a network of lasers mounted on space platforms.[17] These lasers are supposed to deflect debris of various sizes through ablation, which involves an intense laser pulse vaporizing surface material on an object. The material is ejected away from it, altering the object's momentum. If the impulse of that ejection is properly oriented, the object's speed can be reduced, and eventually it will deorbit and burn up in the atmosphere on reentry.

Imaging

At short wavelengths, pulses from an X-ray free-electron laser (XFEL) can penetrate through materials to image structures and measure a material's physical properties. The current Linac Coherent Light Source (LCLS)-II High-Energy upgrade to the XFEL at the SLAC National Accelerator Laboratory will push the maximum energy that it can reach even higher, allowing heavier and denser materials to be probed.[18]

XFELs are particularly useful for imaging where the shorter wavelengths of X-rays allow better spatial resolution compared to visible light—an example is the coherent X-ray imaging end station of SLAC's LCLS.[19] In addition, XFELs can emit very short pulses, which helps them excel at tracking changes over very short time periods. Previous results have allowed new proteins to be imaged and have enabled researchers to observe phase transitions of quantum materials in real time[20] or observe materials under extreme conditions of pressure, such as those in the center of the sun. The approach has also shown how biomolecules move in real time, and an extended research effort has followed the complex series of reactions that occur throughout the process of photosynthesis, with implications for future photovoltaic cells and other devices that seek to harness solar power.[21]

Materials Processing

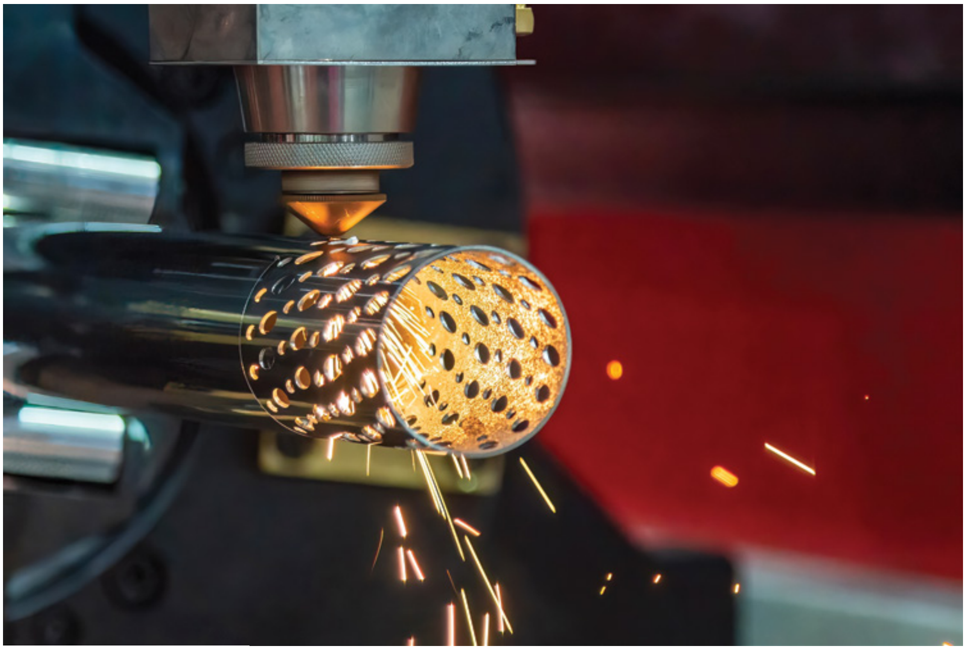
Lasers are now used for a wide range of applications in materials processing, including laser cutting of precise shapes (see figure 4.4), laser drilling of micron-scale holes, and laser peening—deliberately deforming surfaces—to add stress to materials. Ultrashort pulse lasers enable material to be ablated precisely with minimal damage to surrounding areas—a process useful both in manufacturing and in surgery. This process, sometimes called cold ablation, works by vaporizing material faster than heat can spread through it. However, to prevent overheating, each spot must be processed slowly, which limits overall throughput. To address this challenge, a beam from a powerful laser is split into smaller beams, which can work on multiple areas simultaneously.[22]

The limited collateral damage it causes means laser processing can be used even on biological samples. The benefits of short pulses also extend to surgery, as described above, and to dentistry, where the wavelength can be chosen to reduce the risk of damaging soft tissue. Both approaches are now being combined with robotics to automate treatments.[23]

Chip Fabrication

For a long time, the mass production of chips with structures smaller than 100 nanometers relied on the availability of high-average-power lasers that can produce light for lithography purposes, which involves transferring circuit patterns onto silicon wafers. In recent years, new processes have pushed average power requirements even higher, reflected in both peak power and the rate at which laser pulses can be generated. These new processes entail evaporating tin droplets with lasers to generate a plasma, which is then stimulated to produce extreme ultraviolet (EUV) light to project a mask that carries circuit

FIGURE 4.4 A laser is used to cut precise shapes in a metal form



Source: Shutterstock / Pixel B

patterns onto wafers. Since the process is not very efficient—a few hundred kilowatts to operate the laser generates only a few hundred watts of EUV light—power demands for state-of-the-art foundries have already grown dramatically and keep rising.

Producing structures smaller than 2 nanometers on very high-end chips relies completely on this technology. These chips are critical for applications that require high processing power, extremely energy-efficient operation, and miniaturization—requirements that characterize many systems of economic and national security importance. Although the capability originated from laser research programs in the United States, the chips are now being produced by a number of companies around the world, many of which are outside the United States.

Nuclear Fusion

Fusion occurs when two light atomic nuclei (usually deuterium and tritium, both isotopes of hydrogen) collide to form a heavier nucleus, releasing a large amount of energy in doing so. As an energy source, fusion energy is still in the research and development stage, as described in chapter 10 on sustainable energy technologies.

Today, the central issue in research on fusion for producing energy is the confinement problem—how to confine the fuel for long enough to ensure "ignition" of the fusion reaction. One approach to solving this problem is magnetic confinement fusion, which uses powerful magnets to contain and control a superheated plasma of deuterium and tritium. A second is inertial confinement fusion, which calls for rapidly compressing a deuterium-tritium fuel pellet using lasers to ignite the fusion reaction.

For inertial fusion energy to become commercially viable, high-energy, high-repetition-rate laser beams are needed to drive the samples to the extreme states required. The necessary lasers must deliver high energy beams at the relevant wavelength without the risk of damaging their components and with a much higher energy efficiency than is possible with current facilities.

In conjunction with operating the world's most powerful XFEL, SLAC is developing a major laser facility that will house a petawatt peak power laser and increase the beam energy of another of its lasers to hundreds of joules.[24] An important feature of this facility will be its ability to achieve highly symmetrical compressions of fusion targets, which will enable much more accurate measurements of implosion phenomena, both spatially and temporally, and support more precise modeling techniques.

Over the Horizon

Impact of Laser Technologies

As described earlier in this chapter, lasers are critical components across a wide range of applications, including communications, high-end chip production, defense, manufacturing, and medicine. This range is so broad that lasers could fairly be regarded as an enabling technology—that is, a technology whose existence and characteristics enable applications that would not otherwise be feasible or affordable.

Improving key laser figures of merit—peak power, energy, average power, pulse length, and wavelength—is a primary focus of extensive laser research. A recent Basic Research Needs report from the US Department of Energy's Office of Science emphasized that progress in all these areas is crucial for future scientific advances and new applications.[25] The report highlighted that progress requires novel approaches and techniques. It also noted the importance of additional engineering advances that address the limitations of current inefficient laser architectures and easily damaged optical components, calling for advancements in laser architectures, gain mediums, components, and control techniques.

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Challenges of Innovation and Implementation

For lasers, the challenges of innovation and implementation are addressed in a highly distributed fashion—that is, across a multitude of laboratories and facilities. The reason is that progress in laser technology seems to be highly dependent on the specific application that requires a laser. An improvement in laser technology useful for application A may not be particularly useful for application B. For example, improvements in the average power of lasers used at the National Ignition Facility at LLNL will be of little value to lasers used in space-to-space communications. However, developments in beam pointing and alignment technology in a laser communications context may be helpful for laser weapons development, as some of the same problems arise with both the latter and the former.

Policy, Legal, and Regulatory Issues

Given that lasers are an enabling technology for many applications, public policy issues tend not to arise for lasers per se. Rather, they arise in the sectoral, societal, or policy context of a particular application. These issues could include the following:

Technological maturity Is laser technology at a state of maturity to support a given application? What are the alternatives to using lasers for that application? Is the growth path for a particular laser technology expansive and promising, or does it appear that it has plateaued?

Cost-effectiveness Are lasers really the best way to support a given application? Given total life-cycle costs, are there more cost-effective ways of performing the same missions?

Adequacy of the industrial base To what extent is the present industrial base capable of producing laser systems and components in necessary quantities? What resources are needed, if any, to develop its capacity for procuring a given laser-based system?

Dual-use considerations As laser technology advances, what are the implications, if any, for controlling dual-use laser technologies that have both military and civilian applications?

Environmental and safety concerns What, if any, are the environmental and safety concerns raised by the deployment of a given laser-based system? How should such concerns be addressed?

For illustrative purposes, consider how some of these questions might play out in two specific contexts.

Lasers as a defense against ballistic missiles The problem of using lasers for intercepting ballistic missiles is primarily characterized by the distance at which such intercepts must occur. Today, short-range rocket intercepts appear to be possible,[26] but longer-range intercepts are not, at least not with ground-based systems for most feasible laser technologies. Against short-range rockets, lasers have an economic advantage over missile interceptors, costing only a few dollars per laser shot as opposed to tens or hundreds of thousands of dollars per missile interceptor. Some technology usable for laser weapons has important civilian use—one example is deformable mirrors that can be used to enhance the quality of laser beams propagating through the atmosphere. When chemical lasers were contemplated for military use, environmental considerations were one negative aspect, as the lasers' exhaust was toxic.

Lasers for surgery Key concerns here include safety and cost-effectiveness. Safety guidelines for healthcare are constantly being updated and refined. For instance, in 2022 the American National Standards Institute released a new standard for the safe use of lasers that includes an updated section on maximum permissible medical-related exposures in terms of illuminance, or the amount of light allowed to fall on a given surface area.[27] In terms of cost, while some lasers for highly specific applications can be very expensive, others that can be used for multiple applications are much cheaper. For example, some excimer lasers, which emit short pulses of high-energy light and are used for medical procedures, such as LASIK and treating eczema, as well as in manufacturing, are available for under $100,000.

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