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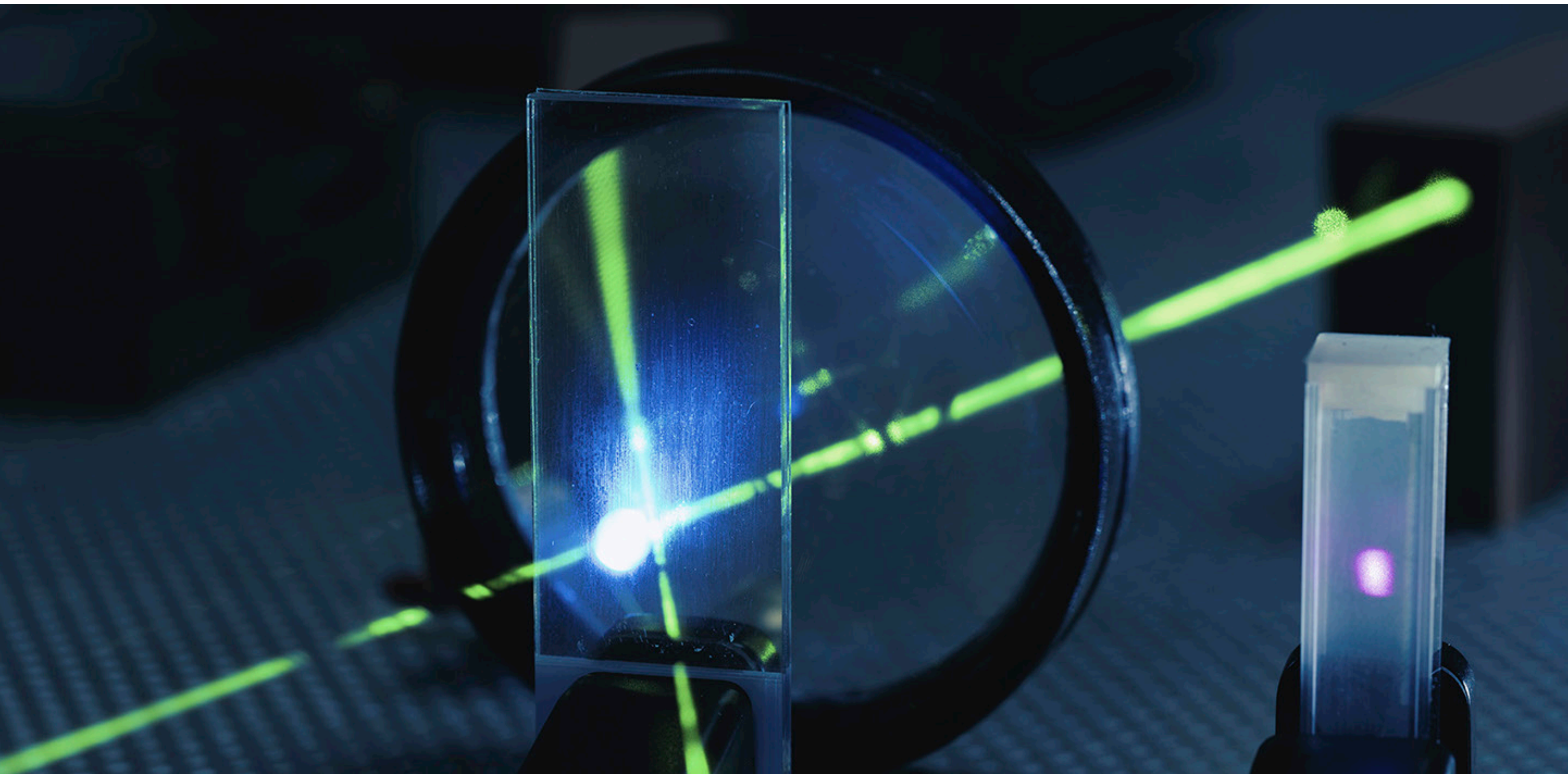
Advanced Electronics Practice

The next wave of innovation in photonics

More end products are integrating lasers with sensors and optics, opening new opportunities for photonics manufacturers.

This article is a collaborative effort by Gaurav Batra, Ryan Fletcher, Kairat Kasymaliev, Abhijit Mahindroo, and Nick Santhanam, representing views from McKinsey's Advanced Electronics Practice.



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Einstein laid the foundations for laser technology in his groundbreaking article "The quantum theory of radiation," published in 1917. After years of development, the first widely commercialized lasers hit the market in the 1960s, when they were used for applications ranging from science to surgery. Since those early days, the unique ability of lasers to create a narrow, focused beam of light has enabled many other use cases, including barcode scanning, DNA sequencing, and semiconductor-chip manufacturing. In one of the most novel applications, the NASA rover *Curiosity* used laser-enabled equipment to blast rocks on Mars, allowing scientists to analyze chemicals in the resulting vapors.

Although the laser market has steadily increased since the 1970s, innovation and revenue growth have slowed over the past decade. Many low-cost companies have entered the market as the core technology matured. That put pressure on the average sales price for lasers used in high-volume end products, including those related to telecom transmission, marking and engraving, and biosensing. But the sector may now be on the cusp of a new age of innovation in which lasers are increasingly combined with optics and sensors to enable even more sophisticated applications. These integrated devices, many of which are still in development in a number of industries, could not only put the laser market back on a high-growth trajectory but also become the main source of value.

To help photonics-industry stakeholders evaluate the opportunities ahead, we assessed recent developments across laser end markets. We then explored the optics and sensor sectors in detail, focusing on the unique capabilities that such technologies can provide when combined with lasers. Industry stakeholders—including owners, operators, and board members—have recognized these advantages and are quickly moving to broaden the technological capabilities of their companies through mergers, acquisitions, and strategic partnerships. Investors too are taking heed.

An evolving and exciting market

Although laser technology has continuously matured since its inception, two eras of innovation stand out. Through the 1970s and 1980s, researchers made important discoveries in core laser physics that advanced the technology, although many applications were limited to scientific, laboratory, and R&D settings. And over the most recent three decades, laser devices truly moved from the lab to the commercial sphere as they were refined to improve performance, robustness, and reliability. Many new laser applications, such as surgery, lithography, and welding, emerged at this time, enabling breakthroughs in industries ranging from healthcare to electronics to industrial manufacturing. These innovations helped the laser-device market achieve a value of $17 billion by 2020.

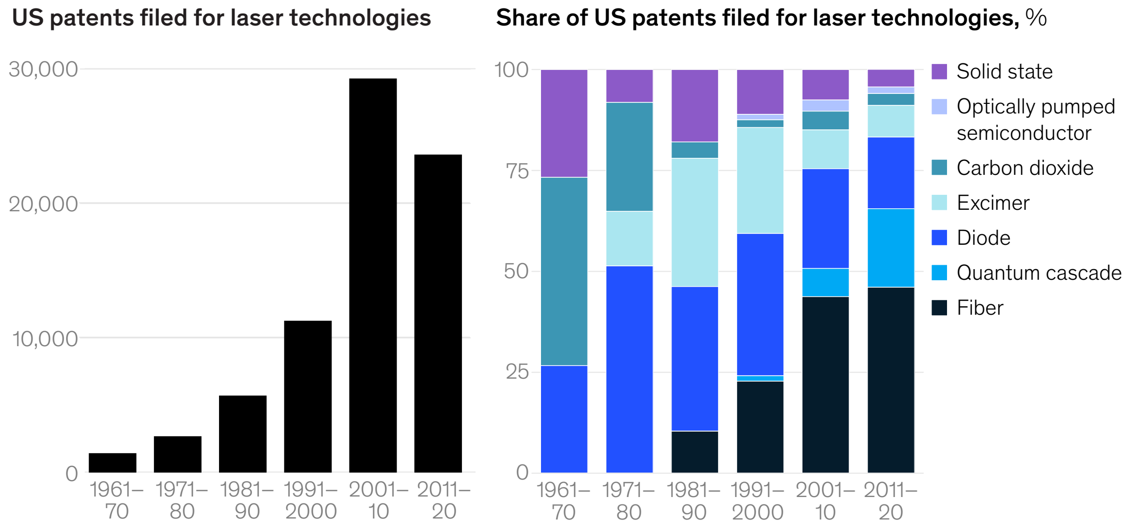
Despite the industry's technological advances and strong revenues, some recent indicators raise concerns. Take the pace of innovation as measured by the number of patents registered. From 2001 through 2010, researchers filed more than 29,000 US applications for laser-related patents—up more than twofold from the previous decade (Exhibit 1). For the years from 2011 through 2020, however, only about 24,000 applications were filed. This drop was an aberration in an industry where patent filings have traditionally doubled each decade.

In tandem with the fall in the number of patent applications, the focus of technology is shifting for some of the most important laser technologies—fiber, diode, solid state, carbon dioxide (CO_2), excimer, and quantum cascade. (These categories are briefly described in the sidebar "An overview of laser technology.")

Fiber, the largest laser category, now accounts for more than 45 percent of all patents filed. Fiber has gained share, in part, because it can focus the beam size down to the micro level and generates more power in a smaller package than CO_2 does. It thus provides optimal speed and precision for cutting metal and welding, among other applications. Fiber has also enabled new medical applications, especially for dermatology procedures.

Exhibit 1

The number of new patents is dropping, and the focus of technology continues to shift.



Source: US patent-registration data

Although quantum-cascade lasers have encountered significant development challenges over the past 20 years, their efficiency and wavelength range have opened up new opportunities in medical diagnostics, optical communications, and industrial-process monitoring. Recently, this category has grown more rapidly than fiber. It accounted for 19 percent of patents over the past decade, up from 7 percent from 2001 to 2010.

Overall, the number of laser patent applications is declining because these devices tend to have staying power once they gain a foothold within an industry. Innovative laser technologies traditionally require decades of R&D and hundreds of millions in funding before they are market ready, so companies are not likely to search for alternatives once they find a workable solution for an application. That in turn means that the category share for all core laser technologies is not expected to shift substantially over the next few years (Exhibit 2). Diode, fiber, solid-state, and CO_2 technologies, which now account for 90 percent of laser revenues, will continue to dominate the market. Fiber technology is projected to see the most growth, primarily because of its simple design and cost advantage over other laser types.

As in the past, most industries will rely on more than one type of laser, since their applications have diverse needs. For example, industrial companies may use fiber lasers to cut metal but rely on CO_2 lasers for plastics, glass, and wood, given different emission wavelengths and performance requirements by material type.

An overview of laser technology

Lasers can use solids, liquids, or gases as a gain medium (a source of optical amplification) to create the desired beam of coherent light. Such beams are composed of photons—particles representing the smallest discrete amount, or quantum, of electromagnetic radiation—that have the same frequency and waveform. This uniformity prevents the beam from spreading and diffusing. Gas lasers use CO_2 or other gases as their gain medium and typically provide more uniform emission, with less loss, than solid-state or liquid lasers do.

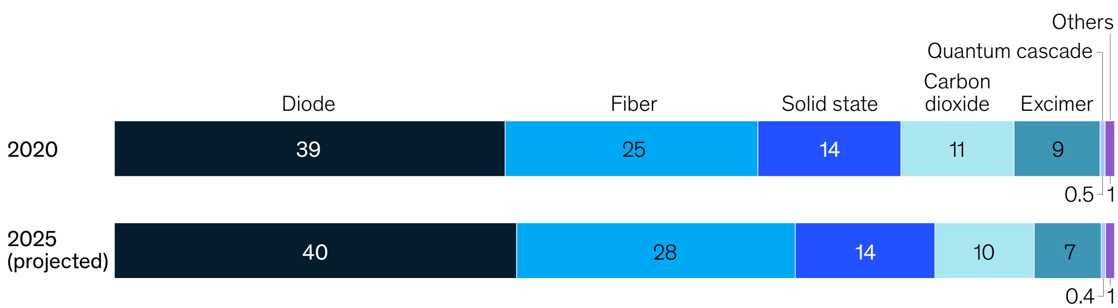
Examples of laser categories include the following:

- Quantum-cascade lasers emit light in the mid- to far-infrared portion of the electromagnetic spectrum. Often used in military-sensing applications, they have promise for optical communications, medical diagnostics, and industrial-process control. Their high cost is still prohibitive in many cases, however.
- Excimer lasers emit very concentrated light in the ultraviolet region of the spectrum. They are far costlier than fiber but can produce high power at lower wavelengths.
- CO_2 lasers, the highest-power continuous-wave gas lasers now available, are still some of the most widely used devices. They can be less expensive than other types of lasers, but maintenance costs outweigh this advantage in high-use applications, such as materials processing.
- As their name suggests, solid-state lasers use a solid gain medium. They have recently been losing market share to fiber and diode lasers because they are often less robust and efficient, as well as more costly to maintain.
- Fiber lasers rely on optical fibers doped with rare-earth elements, such as erbium, neodymium, or ytterbium. Their use has grown steadily because of their simple, robust design and cost advantages versus other categories.
- Diode lasers generate radiation through semiconductors composed of alloys of aluminum or gallium rather than silicon. They are seeing steady growth as their power levels increase and range of wavelengths expands. Their cost is also falling.

Exhibit 2

The use of core technologies is expected to remain relatively stable through 2025.

Laser devices' share of revenue by technology, $ billion[1]



[1]Complete laser device, including emitter, primary optics, power supply, basic driving electronics, and thermal management (if required).
Source: McKinsey analysis

Even with the number of patent applications down, the laser-device market should experience relatively strong 10 percent growth through 2025, reaching a value of about $28 billion (Exhibit 3). The aerospace-and-defense sector is well positioned to achieve the highest growth per year (24 percent), given increased use of high-performance, high-cost lasers for sensing, tracking, and countermeasures. A few applications, such as data storage and printing, are likely to decline as next-generation technologies shift away from laser.

The industries seeing the strongest growth increasingly depend on applications that combine lasers with advances in other technologies:

— optics, including a range of active and passive materials that can direct, filter, or change certain portions of light

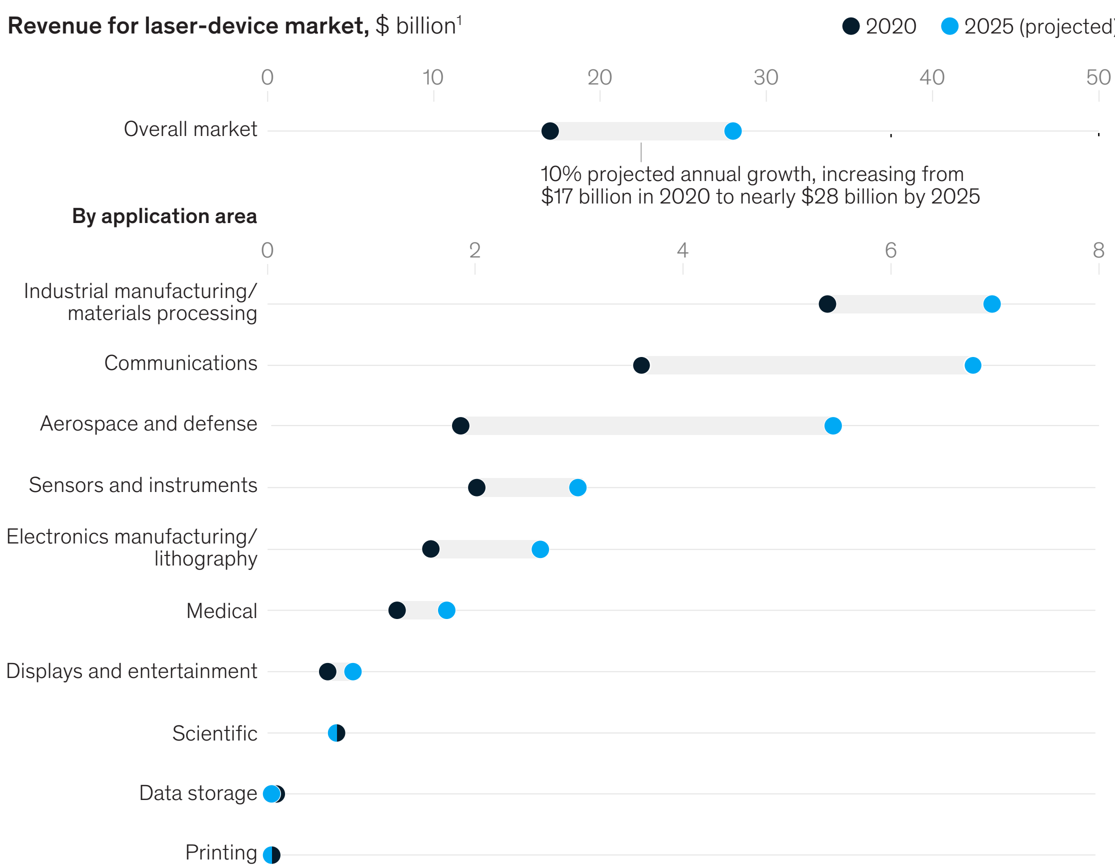
— photonic sensors (which detect precise emissions of light or energy within the photonic spectrum), including some UV and IR wavelengths, which are processed into information about the environment or application in which the sensor operates

Carefully coordinating optic, laser, and sensor technologies—particularly for power, wavelength, and optical design—is critical for their success.

In addition to expanding the number of potential applications, optics and sensors can also take laser performance to a new level. For example, integrated devices are already critical to optical-coherence tomography, a noninvasive procedure for taking 2-D and 3-D images of retinal tissue. To determine the full potential of integrated laser-based systems, we first examined the precision optics and photonic-

Exhibit 3

The laser-device market is expected to grow by 10 percent annually through 2025.



[1]Complete laser device, including emitter, primary optics, power supply, basic driving electronics, and thermal management (if required).
Source: McKinsey analysis

sensor sectors, looking at core technologies, recent growth, and go-forward adoptions. We found that both markets are now thriving and that the uptick in integrated laser devices could increase their value even further.

The optics market

With an overall value of $33 billion, the optics market includes components that can enhance the precision and performance of laser-based systems, such as:

— filters, usually consisting of coated glass or plastic, that selectively transmit specific wavelengths of light while blocking or reflecting others

— lenses, classified by the type and degree of their curvature, that focus or disperse light

— mirrors that selectively reflect light, typically to steer or fold beams

— beamsplitters, which separate light (typically by wavelength or direction), and are often used in devices that include both lasers and sensors

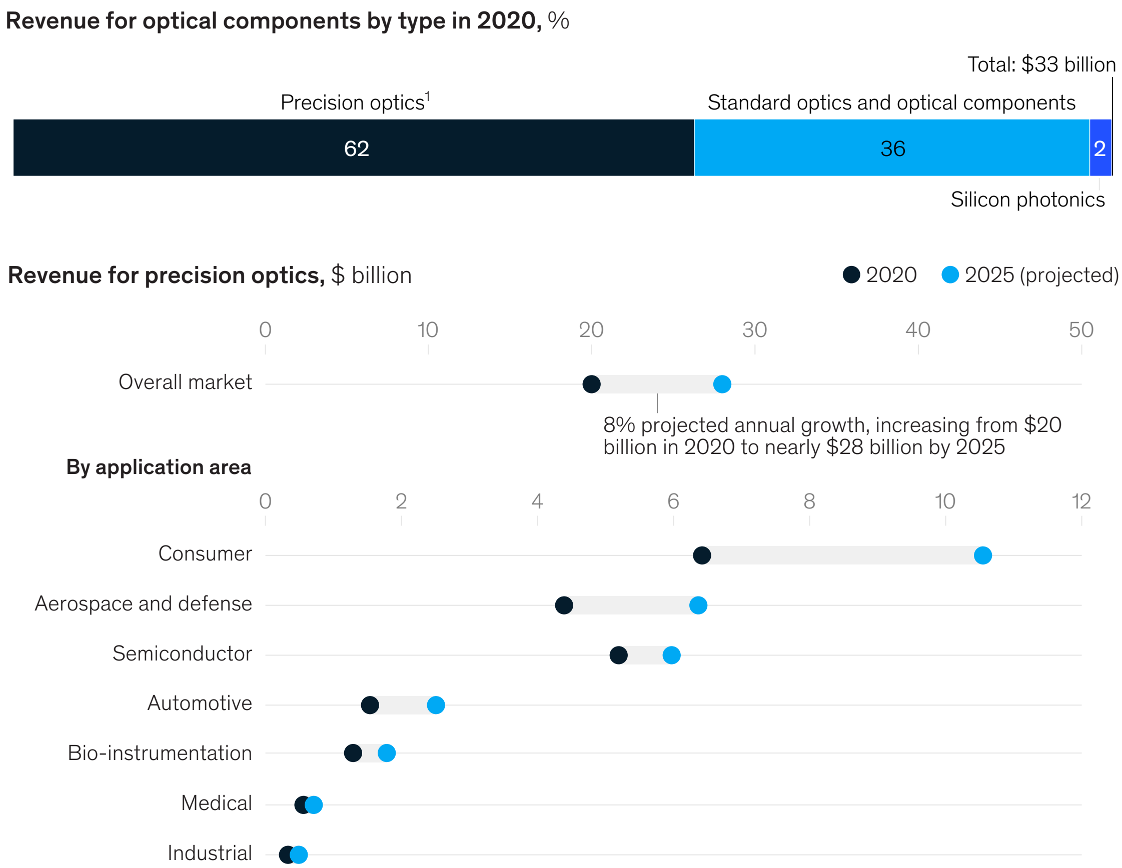
— prisms, typically machined from glass, that disperse light into its components by wavelength

— adaptive optics, which typically integrates multiple optical components and adjusts their properties through mechanical or electrical articulation and control

Precision optics, valued at $20 billion, represents about two-thirds of the value of the total optical-components market, and strong growth of 8 percent is expected through 2025 (Exhibit 4). Consumer

Exhibit 4

Most segments of precision optics are growing significantly.



[1]Precision optics is defined by tighter manufacturing tolerances (eg, thickness, diameter, centering, curvature, surface, and coating uniformity) 2–10x higher than those of standard optics, at a minimum.
Source: McKinsey analysis

applications, such as biosensing, security, and portable device LiDAR, are likely to drive most of the demand. The automotive, semiconductor, and space sectors will also account for a large proportion of precision-optics revenues.

To understand the increasing impact of precision optics on the performance of laser-based devices, consider flow cytometry. In this process, a laser is projected through a biological sample to evaluate the physical and chemical characteristics of individual cells or particles, including those in blood. Flow-cytometry systems use bandpass and dichroic filters to restrict the wavelengths of light that pass to detectors, allowing scientists to identify specific cells or particles within each sample (Exhibit 5).

In recent years, researchers have improved flow-cytometry filters to increase their accuracy and precision and to make it possible to identify multiple components within a single sample simultaneously. These upgrades have pushed the limits of design and manufacturing. The importance of leading-edge bandpass and dichroic filters is reflected in the fact that they can represent, on average, 10 to 20 percent of overall flow-cytometer system costs.

Other innovators have enhanced flow cytometry by replacing traditional optics, including mirrors and filters, with a dispersive optic spectrometer. In addition to improving the accuracy of these devices, such innovations have significantly accelerated the throughput of samples.

Exhibit 5

The performance of flow cytometers relies on the precision and consistency of optical filters.

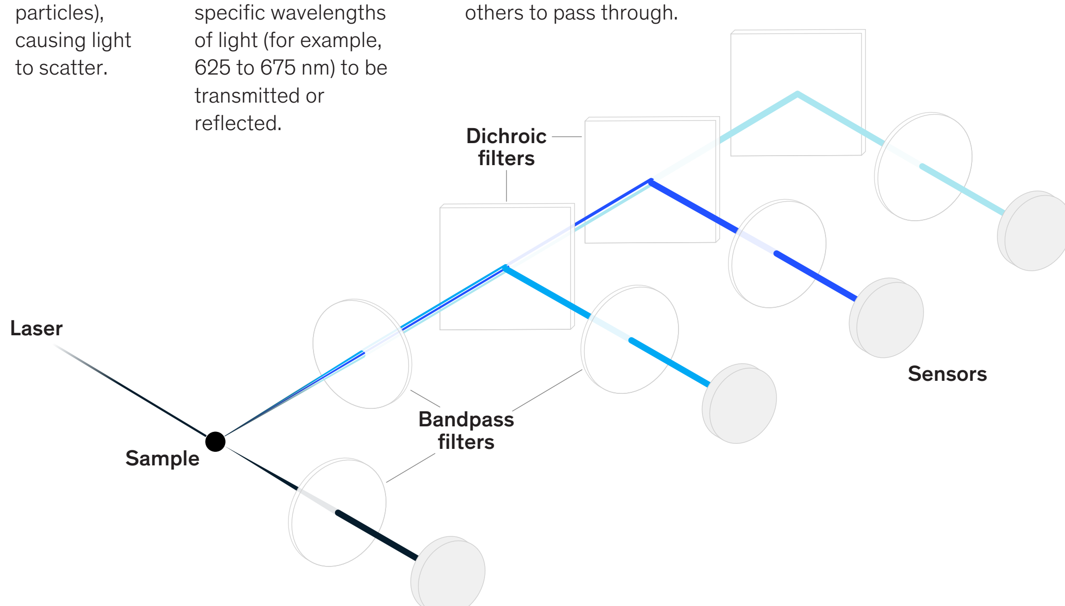
How filters are used in a flow cytometer to determine the characteristics of a cell or particle[1]

1. A laser is directed at a sample (a collection of cells or particles), causing light to scatter.

2. The scattered light passes through optical filters, typically bandpass and dichroic. These cause only specific wavelengths of light (for example, 625 to 675 nm) to be transmitted or reflected.

3. Dichroic filters are arranged at an angle to reflect specific wavelengths toward a sensor while allowing others to pass through.

4. The filtered light is received by sensors, each of which detects the presence or absence of different parameters, corresponding to specific wavelengths of light, within the sample.

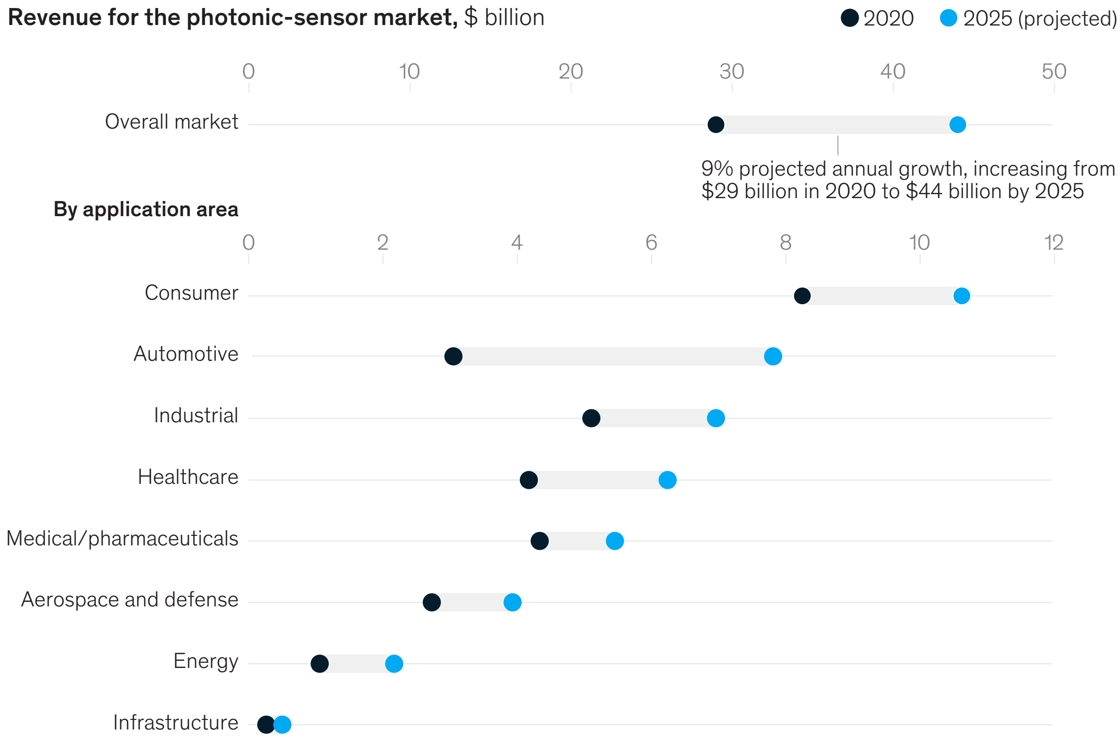


[1]Specific requirements vary depending on the parameters of a given detection system.
Source: Discussions with experts; McKinsey analysis

Exhibit 6

Photonic sensors are expected to experience 9 percent annual growth through 2025.

Revenue for the photonic-sensor market, $ billion



Source: McKinsey analysis

The sensor market

Photonic sensors represent a $29 billion market—about 16 percent of the broader $180 billion sensor market. This segment is projected to see strong growth of 9 percent annually through 2025, reaching $44 billion in revenues that year (Exhibit 6). A few application areas stand out:

— In automotive, demand is expected to grow by 21 percent a year because advanced driver-assistance and autonomous-driving systems require sensors with high precision and resolution.

— Within infrastructure, sensor demand will rise by an estimated 14 percent as innovators develop more integrated laser devices to measure the physical characteristics of buildings, including strain and vibrations.

— The energy sector could grow by 15 percent a year as fiber-optic sensor technology is incorporated into monitoring and measurement applications, some of which can help reduce waste and pollution.

— Annual growth is expected to reach 8 percent for aerospace and defense as automated applications, the expanded use of aerial LiDAR, and new remote-sensing tools drive demand.

Photonic-sensor technologies include silicon photodiodes, which are broadly used in applications where a large quantity of detectors are required. For instance, silicon photomultipliers are employed in LiDAR (which uses light in the form of pulsed lasers to measure distance) and time-of-flight use cases (which involve determining distance or depth between the source and another object).

As OEMs increasingly turn to photonics systems to address customer needs, the lines between component suppliers, subsystem providers, and device integrators will probably continue to blur.

Similarly, charge-coupled-device (CCD) sensors and complementary metal-oxide semiconductor sensors, both of which use silicon photodiodes, have broad use cases in spectroscopy, machine vision, and defense applications.

As another example, industrial cutting lasers used in manufacturing are beginning to gain new capabilities through the integration of precision optics and sensors. Initially, machine operators set parameters, and the laser completed the cut exactly as ordered, with no midprocess adjustments. More recent devices include sensors that detect parameters, such as surface finish, density, depth of cut, and thermal stress on materials. Such devices not only provide for real-time adjustments but also contain precision optics, often beam-splitting filters, to enable both laser cutting and laser measurement in the same optical path (Exhibit 7).

Next steps for companies in the photonics sector

As industry stakeholders pursue opportunities within photonics and integrated devices, M&A merits increased attention. Despite the recent wave of deals, the laser-device industry remains fragmented, with many small players with less than $250 million in revenues focusing on specialized niches. This fragmentation suggests that operators, board members, and investors may find many opportunities for synergistic combinations or partnerships.

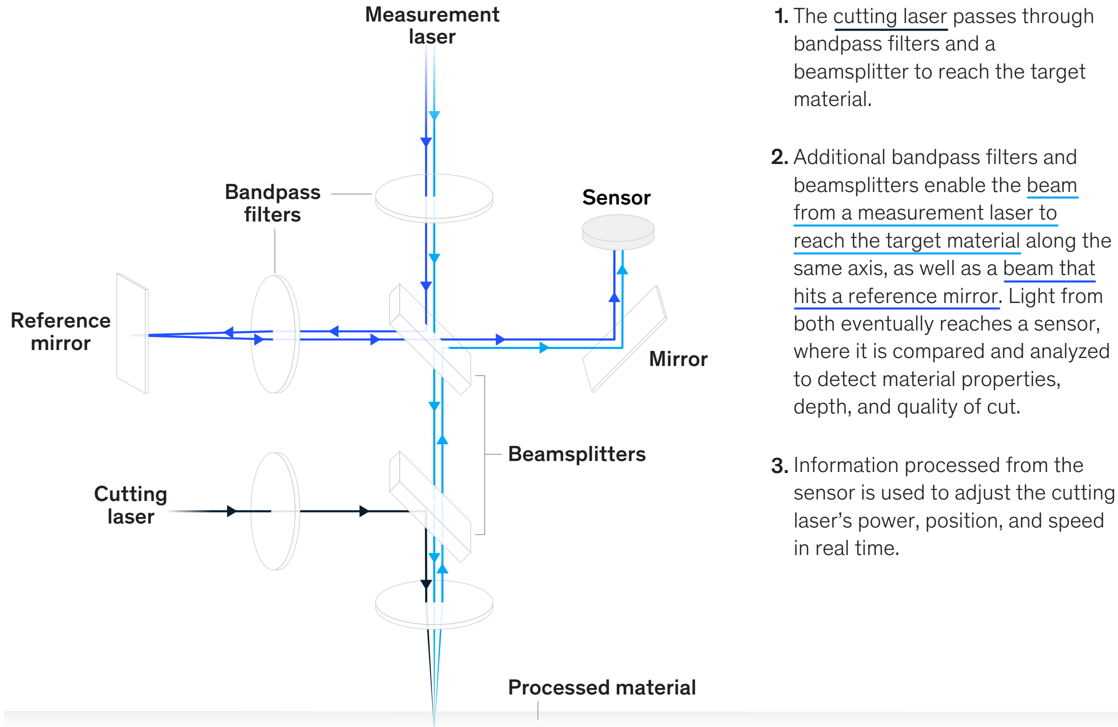
Some laser manufacturers and end customers are already pursuing such deals to facilitate the creation of devices that integrate precision-optics, sensors, and lasers. For instance, a major supplier of lithography systems recently acquired a precision-optics company to gain additional capabilities for extreme-ultraviolet and deep-ultraviolet products. Another leading industrial-applications company acquired minority stakes in some laser-technology firms to boost its capabilities in materials-processing applications. It also acquired a company that manufactures many of the photonics components and products used in sensors for autonomous driving, smartphones, and digital data transmission.

As integration among lasers, sensors, and optics becomes increasingly important for creating value in next-generation systems, operators and board members must rethink their product strategies and reposition themselves along the value chain. For instance, the need for effective integration and real-time monitoring is likely to increase the importance of software in this traditionally hardware-driven industry. New serviceability requirements, such as remote diagnostics, adjustments, and calibration, could also create additional opportunities to provide services over the life of each system. And as OEMs across market segments increasingly turn to photonics systems to address customer needs, the lines between component suppliers, subsystem providers, and device integrators will probably continue to blur.

Exhibit 7

New quality-monitoring systems use sensors to improve precision in laser cutting.

Paths of cutting and measurement lasers in an industrial-cutting machine



1. The cutting laser passes through bandpass filters and a beamsplitter to reach the target material.
2. Additional bandpass filters and beamsplitters enable the beam from a measurement laser to reach the target material along the same axis, as well as a beam that hits a reference mirror. Light from both eventually reaches a sensor, where it is compared and analyzed to detect material properties, depth, and quality of cut.
3. Information processed from the sensor is used to adjust the cutting laser's power, position, and speed in real time.

Source: Discussions with experts; McKinsey analysis

Like any high-tech sector, photonics must innovate to survive. Although the speed of innovation in laser technology has been dropping, the creation of integrated devices combining lasers, sensors, and optics could usher in a new age of opportunity. Companies that develop such devices now could have a first-mover advantage, since end customers are likely to seek strategic partnerships to explore new applications and build product offerings. The move to integrated devices might require new capabilities, but opportunities abound for rapidly sourcing them within the fragmented industry landscape.

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