

Tunable Lasers and Fiber-Bragg-Grating Sensors

For years, the tunable laser remained confined to the laboratory as a spectroscopist's tool to investigate the spectral characteristics of atoms and molecules. Today, it is being tested in many industrial applications, including optical remote sensing, where laser-based systems can provide improved performance over electronic means of measuring strain, temperature, and pressure.

One reason for the movement of tunable lasers into uses beyond the laboratory is the external-cavity diode laser (ECDL). Before the ECDL, the workhorse of the tunable-laser market was the organic liquid-dye laser—a cumbersome system that requires an expensive pump laser and messy liquid dyes. In the late 1970s and early 1980s, Michael Littman, Harold Metcalf, and Karen Liu pioneered broadly tunable ECDLs, which were considerably less complex than their forerunners.

The gain medium of an ECDL consists of a laser diode chip in which one of its end facets is coated with an antireflection layer. This coating arrangement forces these diodes to act only as gain media. The other components that make up the ECDL cavity include wavelength-selective devices, such as diffraction gratings or etalons, and other optical elements such as mirrors and lenses. However, ECDLs did not evolve from quirky laboratory apparatuses to rugged and reliable turnkey test-and-measurement instruments until the past decade. Two conditions enabled tunable ECDLs to come of age: the development of inexpensive, high-performance laser diodes and the tremendous demand—driven by the dot-com/telecommunications economic boom—for high-performance benchtop tunable lasers.

ECDLs became commercially available in the early 1990s, a few years before the telecommunications boom. They were centered at 670 nm and targeted at the spectroscopy market. These systems delivered 1 mW of continuous-wave output power

and had 6-nm/s tuning rates over 12-nm wavelength ranges. Their side-mode suppression ratio (the ratio of the carrier to the nearest side mode expressed in decibels) was 40 dB. Unlike their laboratory-built

the industry's test-and-measurement market. Wavelength-division-multiplexed (WDM) network component manufacturers used ECDLs to test the spectral characteristics of their products, whose spectral performance is essential to the overall performance of WDM network systems. In a WDM network, a single fiber carries many wavelength channels simultaneously (see *The Industrial Physicist*, February/March 2002, pp. 18–21). Thus, optical filters, wavelength multiplexers, and demultiplexers must help direct the information to its correct destination.

WDM components revolutionized the information superhighway by dramatically increasing bandwidth capacity, which led to next-generation networks and the maturation of the photonics industry. Because companies needed these network components in large volumes and at narrower channel spacings, testing and measuring these devices required ever-faster, lower-noise tunable lasers. ECDLs were developed that could tune continuously at speeds of up to 100 nm/s over a wavelength range of 1520 to 1620 nm and with side-mode suppression ratios as high as 70 dB, which resulted in extremely low-noise performance. Because the lasers operated 24 hours a day, 7 days a week on the manufacturing floor—often overseas—they had to be rugged, reliable, and stable and meet strict shock and humidity standards.

Intense competition among laser companies resulted in significant advances in the cost-effective manufacture of the lasers.

Because ECDLs reduced testing times from hours to seconds, they revolutionized the manufacture of passive network components, which led to higher efficiencies and yields. Moreover, many telecom companies

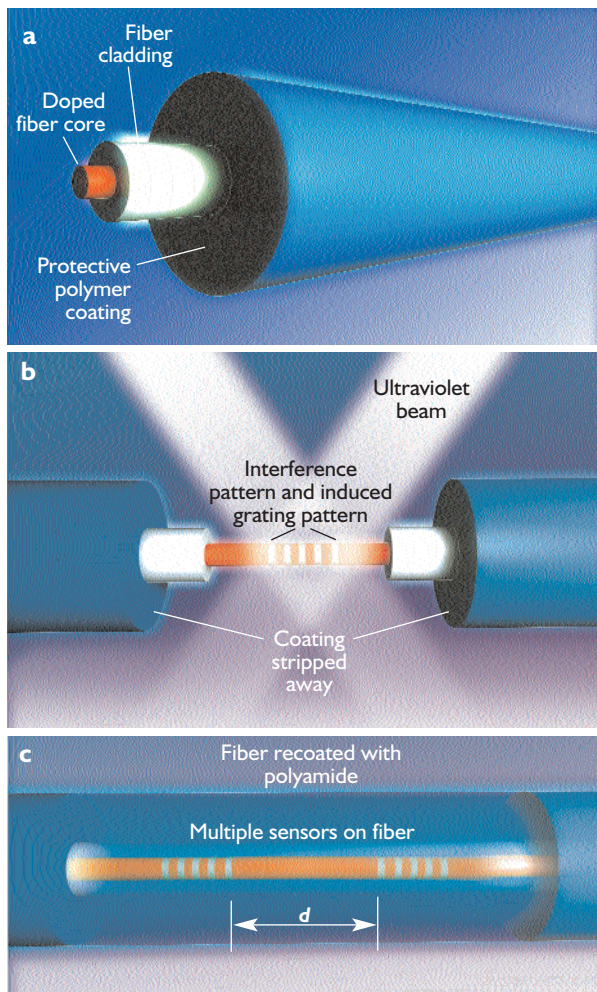


Figure 1. Multiple fiber Bragg gratings may be written at discrete distances (d) on a doped optical fiber by stripping away the protective coatings, using the interference patterns of ultraviolet beams, and recoating the fiber.

counterparts, which required constant adjustment to maintain precise tuning, commercial ECDLs were more rugged, and some achieved continuous tuning over their entire tuning range without the wavelength hopping to a side mode.

As telecommunications companies thrived in the late 1990s, ECDL companies targeted

realized that tunable lasers could ultimately lead to increased network intelligence, functionality, and efficiency. Technological advances made these devices compact and so inexpensive that they would soon compete with the single-wavelength distributed-feedback (DFB) lasers that are used in WDM networks.

Today, with the dot-com bubble burst and a bandwidth glut worldwide, telecom spending has fallen dramatically. The industry's cash squeeze has affected all of its components, from giant corporations to the smallest companies—many of which went out of business or survived only by significant layoffs. In this new economic climate, photonics companies are seeking opportunities in nontelecom markets—including semiconductor, biotechnology and industrial-sensing applications—to help them ride out the slump.

On the flip side, nontelecom markets have taken advantage of photonics manufacturing companies' expertise, product innovation, and business maturity that resulted from the explosive growth and development of the telecom industry. Today, ECDL modules are relatively low in cost and high in performance, provide output power up to 10 mW, can be tuned across a wavelength range of 400 to 1620 nm, and are compact enough to fit in the palm of the hand. However, a lack of awareness about the technology among nontelecom companies has hampered its adoption in other arenas. Often, decision-makers in nontelecom industries are unaware of how photonics can be applied in their areas.

Fiber Bragg gratings

Sensing provides one example of applying tunable lasers to a nontelecom market. These lasers can serve as the optical source in fiber-Bragg-grating (FBG) sensing systems to provide faster, more accurate, and more sensitive systems. The progression to telecom tunable lasers in FBG systems was natural because FBGs typically are centered in the 1550-nm region. These devices provided dense wavelength-division

demultiplexing, dispersion compensation, and erbium-doped fiber amplifier (EDFA) gain flattening for telecommunication networks.

Because the temperature and strain states of FBGs directly affect their reflectivity spectrum, they can also be used for a variety of sensing applications. As the fiber-optic analogue to conventional electronic sensors, FBGs can serve as strain-gauge sensors to provide structural engineers with measurements not previously possible. Emerging applications include detecting changes in stress in buildings, bridges, and airplane bodies; depth measurements in streams, rivers, and reservoirs for flood control; and temperature and pressure measurements in deep oil wells. The advantages of FBG sensors include

- considerably improved accuracy, sensitivity, and immunity to electromagnetic interference, radio-frequency interference, and radiation.
- the ability to be made into a compact, lightweight, rugged device small enough to be embedded or laminated into structures or substances to create smart materials that can operate in harsh environments—such as underwater—where conventional sensors cannot work.
- the ability to be multiplexed and an

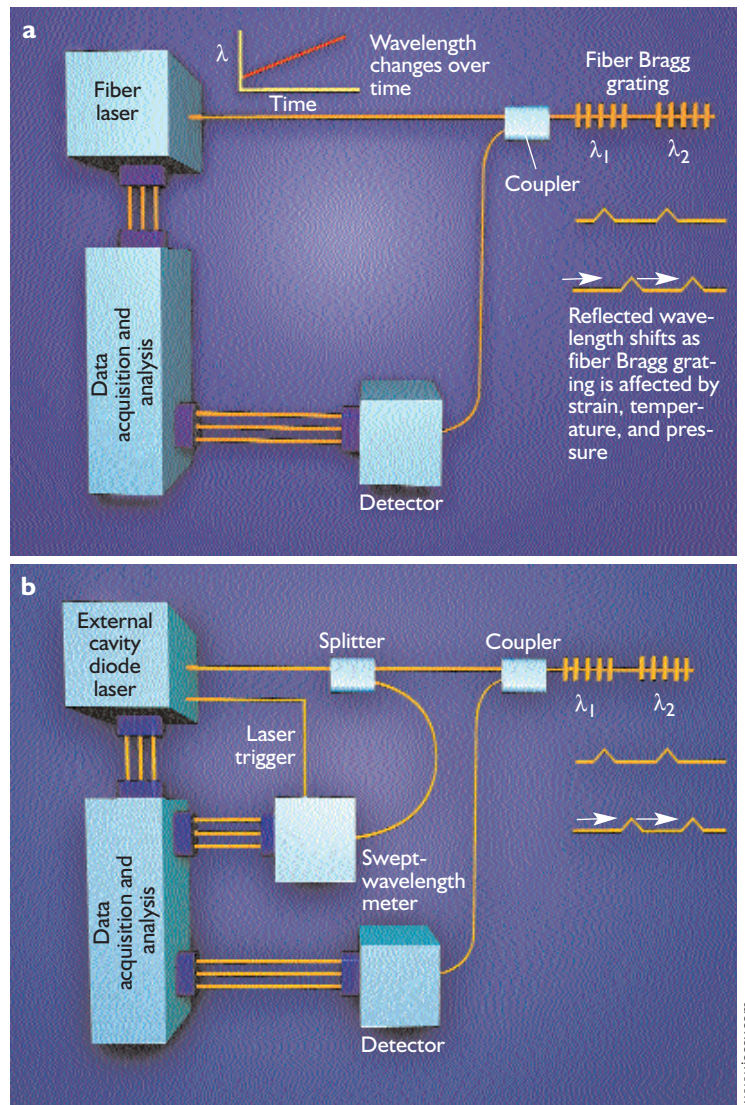


Figure 2. Two laser/detection systems that measure the wavelength shifts in fiber Bragg gratings resulting from strain, temperature, or pressure changes—the fiber laser (a) and the ECDL tunable laser (b).

inherent low transmission loss at 1550 nm. These features enable using many sensors on a single optical fiber at arbitrary spacing. Using WDM technology, including tunable lasers, one can interrogate each sensor independently and obtain a distributed measurement over large structures.

- ease of installation and use. Because the gratings are multiplexed on a single fiber, many sensors can be accessed with a single connection to the optical source and detector. Conventional electronic strain-gauge sensors require each sensor to have its lead wires attached and routed to the sensor readout.
- potential low cost as a result of high-volume telecommunications manufacturing.

How it works

The physical principle behind the FBG sensor is that a change in strain, stress, or temperature will alter the center of the wavelength of the light reflected from an FBG. A fiber's index of refraction depends on the density of the dopants it contains. FBGs are made by redistributing dopants to create areas that contain greater or lesser amounts, using a technique called laser writing. The FBG wavelength filter consists of a series of perturbations in the index of refraction along the length of the doped optical fiber. This index grating reflects a narrow spectrum that is directly proportional to the period of the index modulation (Λ) and the effective index of refraction (n).

The wavelength at which the reflectivity peaks, called the Bragg wavelength (λ_B), is expressed by $\lambda_B = 2n\Lambda$. Because temperature and strain directly affect Λ and n , any change in temperature and strain directly affects the λ_B . In the 1,550-nm (C-Band) window, the main telecommunications transmission frequency, a change in mechanical or thermal strain on the FBG results in a wavelength/strain sensitivity of 1.2 pm/ μ strain (microstrain is a change in dimension that is one millionth of the original) and a wavelength/temperature sensitivity of 10 pm/ $^\circ$ C. The gauge lengths of FBGs are up to 5 mm, although lengths of up to 100 cm are being developed for civil-engineering applications.

FBGs are fabricated by writing an index grating directly on a doped optical fiber. Two intense ultraviolet beams are angled to form an interference pattern with the desired periodicity, which is written on one side of a bare fiber after the external coatings have

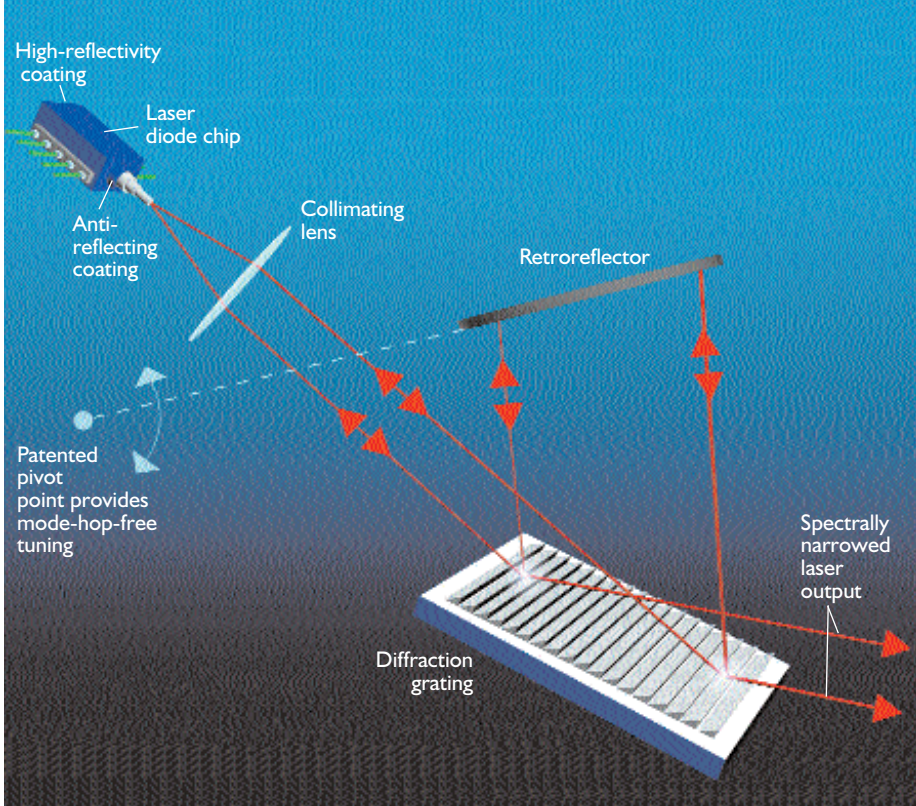


Figure 3. In this ruggedized Littman-Metcalf tunable laser design, the light diffracted to the retroreflector returns to the external cavity diode laser in a resonance effect that outputs a spectrally narrowed beam.

been stripped away. The pattern's intense bright and dark bands cause local changes in the index of refraction by the migration of the dopants in the fiber. After the grating is written on the fiber, it is recoated with polyamide (Figure 1).

Writing many sensors on a single optical fiber requires careful consideration of each FBG's specifications. For example, the allowable strain range for any given FBG sensor depends on the available optical bandwidth. When placing many FBG sensors on a single fiber, each sensor must have its own wavelength segment so that various signals do not overlap. As the FBGs undergo strain, they shift in wavelength within their allotted optical bandwidth range. This situation is similar to wavelength-division multiplexing, in which each channel is allotted a specific wavelength. In general, there should be a 0.5-nm wavelength buffer between sensor channels. The maximum change in wavelength of each sensor—and thus, the distance between each channel—depends on the application.

To measure wavelength shifts that result directly from changes in temperature or tension, FBG sensor systems must consist of an optical source that continuously interrogates

the reflection spectrum and a detection module that records the shifts in the peak reflectivity versus wavelength. A system's overall sensitivity depends directly on the wavelength accuracy of the source and detection module—the better the accuracy, the higher the sensitivity. However, higher wavelength accuracy often results in slower update rates, or scan frequencies, and less-frequent monitoring of sensors.

The system scan frequency is a combination of the speed of the optical source, the bandwidth of the detectors, the data acquisition rate, and the rate at which the analysis of the wavelength shift can be performed. For applications such as maintenance checks of an airplane's structural integrity, the slower—but more accurate—systems are desirable. In other applications for which in situ monitoring is required, high update rates are more important.

The simplest FBG sensor system uses a broadband light source, such as an amplified-spontaneous-emission (ASE) white-light source, with a tunable filter and a detector. Because detectors are wavelength-insensitive, a tunable wavelength filter is required to scan the wavelength range of the FBG sensors, typically 40 nm, to determine the sensors' Bragg wavelength. The main advantage of these systems is their lower cost. However, because the output power from the ASE white-light source is low, only a limited number of in-line gratings can be measured, and with a limited dynamic range. Moreover, the requirement of an external wavelength filter limits the accuracy and scan frequency of these systems.

A fiber laser provides higher output

Company	Location	Web site
Blue Road Research	Fiber-optic sensing consulting; education; products	www.bluerr.com
Luna Innovations	Fiber-optic sensors	www.lunainnovations.com
Micron Optics, Inc.	Fiber lasers; fiber-Bragg-grating interrogation systems	www.micronoptics.com
New Focus, Inc.	Tunable diode lasers; fiber-Bragg-grating systems	www.newfocus.com

power and, thus, an increase in the number of FBG sensors that can be monitored and the available dynamic range. In addition, a laser emits only a narrow spectrum of optical radiation, which eliminates the need for a tunable filter and thus allows faster update rates (Figure 2).

ECDLs provide even higher output power than fiber lasers, which increases the number of sensors and the dynamic range. The narrow linewidths, fast sweep speeds, higher output power, and high side-mode suppression ratios of ECDLs improve the accuracy and dynamic range of FBG sensor systems. Moreover, incorporating a swept-wavelength meter improves system accuracy. Although the laser-based FBG systems have lower scan frequencies than those using fiber lasers, developments in ECDL technology will soon provide ultrafast tuning rates of up to 10,000 nm/s, enabling both high-speed and highly accurate sensing systems (Figure 3).

Planes, floods, oil

Currently, ECDL-based FBG sensing systems are being investigated for monitoring stress in airplanes, flood control, and efficient oil-well recovery—just to name a few applications. FBG sensors embedded throughout the body of an aircraft can monitor structural stress. In flood control, FBGs are placed in rivers upstream of populated areas, where they serve as early warning systems that constantly monitor changes in water pressure. If large changes occur, the systems provide enough warning to allow safe evacuation of areas downstream.

FBG systems used in oil recovery have the potential to provide geophysical data enabling more efficient exploitation of oil fields, and continuous real-time data on well-bore conditions. Currently, approximately two-thirds of the oil in a field goes unrecovered because it is not easy to access.

As companies move to higher-cost and higher-risk exploration areas, conditions in the well bore must be monitored more closely, and FBG sensors will play an increasing role by providing more reliable and less expensive methods of collecting well-bore and geophysical data. With the development of robust and responsive FBG sensors that can withstand extremely high temperatures and downhole environments, the main hurdle to adoption is the low awareness by the industry that these telecom technologies have sensing applications.

FBG sensor systems have the potential for low-cost, robust, and reliable monitoring in the harshest of conditions—where conventional sensors cannot operate. They provide improved accuracy and sensitivity over existing systems and are immune to electromagnetic interference. And with the cost-effective manufacturing of FBGs and tunable ECDLs that resulted from the telecom era, FBG sensors using tunable ECDLs will become cost-competitive with existing remote sensing systems.

Further reading

Grattan, K. T. V.; Meggitt, B. T., Eds. *Optical Fiber Sensor Technology: Advanced Applications—Bragg Gratings and Distributed Sensors*; Kluwer Academic Publishers: Dordrecht, Netherlands, 2000; 385 pp.

Littman, M. G.; Metcalf, H. *Appl. Opt.* 1978, 17, 2224.

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B I O G R A P H Y

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Sunday, October 26, 2003
 Academic–Industrial Workshop (pre-conference) "Undergraduate research" IPF opening reception and buffet dinner

Monday, October 27, 2003
 "Historical perspective," Jim Hollenhorst, director, electronics research lab, Agilent Labs
 "DNA microarrays," Steve Laderman, manager, molecular diagnostics, Agilent Labs
 "Microfluidics for chemical analysis," Kevin Killeen, manager, polymer and structured materials, Agilent Labs
 "Nanopore DNA sequencing," Jene Golovchenko, professor of physics and applied science, Harvard University
 "Single molecule biophysics," Steve Chu, professor of physics and applied physics, Stanford University
 "Nanoscale photosynthesis, the photophysics of neural cells and artificial sight," Elias Greenbaum, corporate fellow, Oak Ridge National Laboratory
 Tours of Agilent Labs
 Banquet and tour of Tech Museum

Tuesday, October 28, 2003
Policy session: Industrial R&D in a rapidly changing world
 "From electronics to new markets," Tom Saponas, chief technology officer, Agilent Labs
 "From hardware to software," Rick Lytel, vice president, advanced system development center, Sun Microsystems
 "From technology to systems," Hans Coufal, manager, science and technology, IBM Almaden
Frontiers in Physics Session
 "Life in extreme environments," Jody Deming, professor of biological oceanography and astrobiology, University of Washington
 "3D quantum biomicroscopy," John Sidles, professor of orthopedics, University of Washington
 "Molecule cascades," Don Eigler, Fellow, IBM Almaden

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