Wavelength-Agile LASERS

Scott Sanders

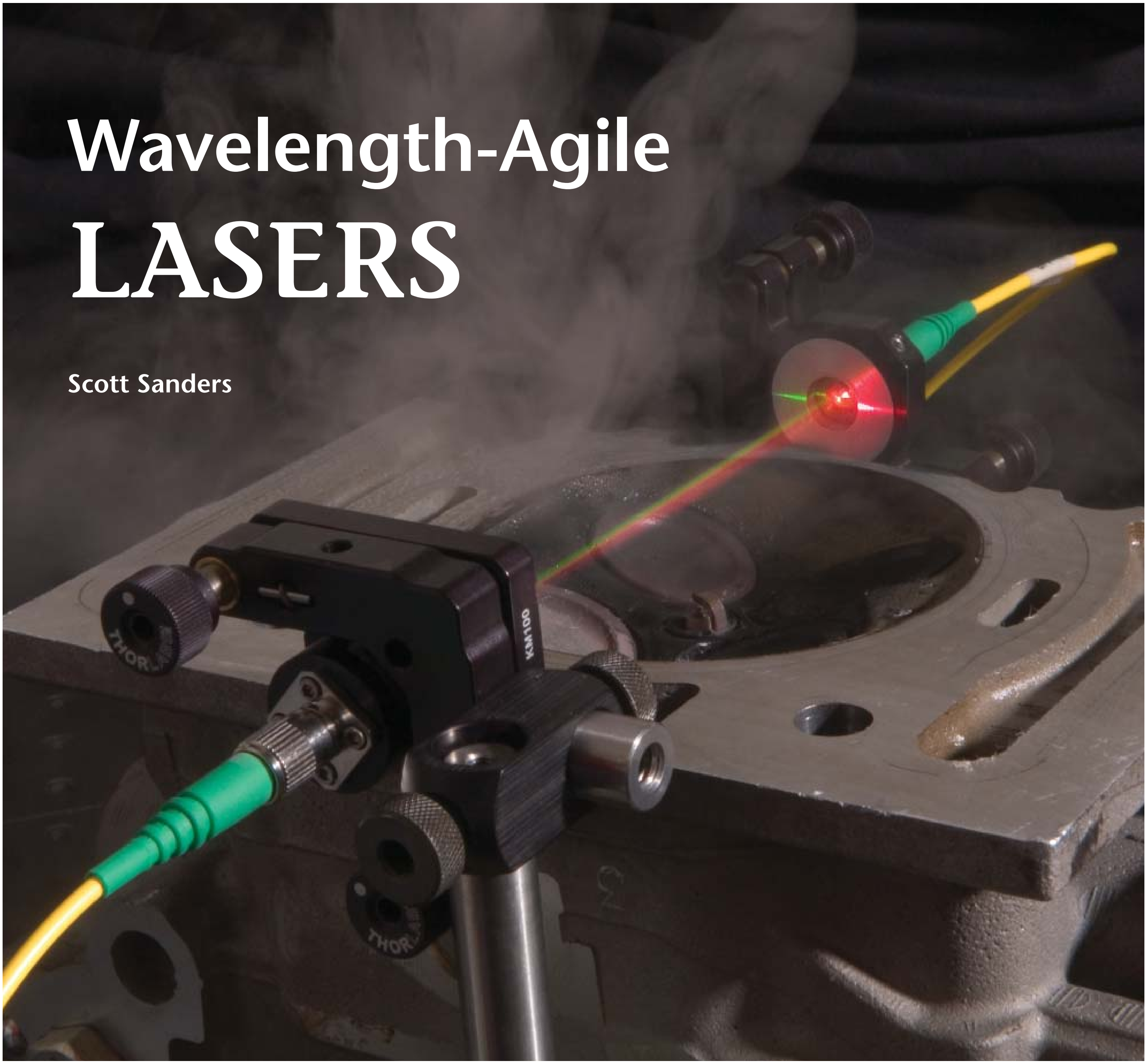

Photo by David Nevala

Lasers that can be rapidly scanned through a broad range of wavelengths are under development, primarily for optical sensing. This article describes the characteristics of these lasers, the history of their development and their potential for future applications.

Imagine a laser pointer that could sweep through an extensive range of wavelengths, from red to orange to yellow to green to blue. My research group would like to energize our presentations with these, at least; we specialize in wavelength-agile lasers, which can scan over a broad wavelength range very quickly.*

More important than gathering attention in a presentation, wavelength-agile lasers are useful in spectroscopy. For example, consider a sensing application: laser light is directed into an unknown gas, liquid or other specimen, and a signal emerges from the test article. The signal could be transmission, reflection, scattering, fluorescence, sound, etc., and could be detected in a number of ways.

Do this at one wavelength, and you may learn something about the specimen. Do it at two wavelengths, and you

* Some scientists have used the term “wavelength-agile” to describe a laser that can rapidly jump to a new wavelength without scanning through the in-between wavelengths; that is not my meaning here. See, for example, Appl. Phys. Lett. **58**, 565-7 (1991).

can probably infer one or two quantitative properties, such as the temperature of the specimen or the concentration of a constituent.

But if you do this over a range of wavelengths, you've measured a whole "spectrum" of information. In short, a specimen's response is generally wavelength-dependent: The more wavelengths you use to monitor a specimen, the more information you will receive, and the more accurate derived quantities will be.

The wavelength-tunability of lasers has long been recognized as a key asset. In his 1986 textbook "*Lasers*," Anthony Siegman noted several laser performance records, including peak power greater than 10^{13} W, continuous average power more than 1 MW, spectral purity less than 0.1 ppq, pulse duration as short as 12 fs, and tuning range greater than 3 percent. Almost 20 years later, lasers exceeding these records would still generally be considered elite.

However, concerning wavelength tuning, considerable progress has been made. Consider the 3 percent tuning range mark of 1986: today, diode lasers tunable over roughly 8 percent of their center wavelength are readily available for less than $20,000. Titanium:sapphire lasers tunable over 35 percent of their center wavelength—ten times the 1986 mark—are not far behind the diodes in terms of availability and cost.

How much wavelength tuning is needed? It depends on the application, but, in general, the more the better. Consider the absorption feature due to molecular iodine vapor shown in Fig. 1(a). This feature was obtained by scanning a laser only 7.7 pm (or 10 parts per million) in wavelength. The shape and amplitude of this one feature contain some potentially useful information. However, if a broader wavelength range is scanned, as shown in Figs. 1(b) and 1(c), a tremendous amount of additional information is revealed.

For instance, detailed examination of the entire spectrum in Fig. 1 reveals several features due to other gases such as oxygen (at 764.2, 764.3, 764.6, 764.7, 765.1 and 765.2 nm) and potassium vapor (at 766.7 and 770.1 nm). In experiments related to these data, we were interested in all three gases.

As shown in Fig. 1, an impressive amount of information can be obtained by a single scan of a wavelength-tunable laser, even one with a modest tuning range of about 2 percent. We could define an information depth as the ratio of the laser tuning range (in this case, 16.5 nm) to the laser's linewidth during the scan (in this case, 0.6 fm). Thus, for Fig. 1, we could assign an information depth of 27.5 million points—an amount of data that is comparable to that contained in a single image recorded by an 8-megapixel digital camera.

Carrying this comparison a bit further, consider an information rate. QuadHDTV delivers 8-megapixel RGB images at 30 frames per second continuously, corresponding to an information rate of roughly 1 billion data points per second. Can a tunable laser deliver spectral data at this rate? The answer is yes: our research group has developed systems capable of approximately ten times this rate. For example, a laser with a spectral resolution of 0.08 nm that scans 230 nm every 385 ns (i.e., a rate of 7.5 billion data points per second).

Evolution of wavelength-agile lasers

Figure 2 illustrates the evolution of wavelength-agile lasers within my laboratories; developments from other laboratories (e.g., cantilever vertical cavity surface emitting lasers, sampled grating distributed reflector lasers) are not depicted. The figure locates various wavelength-agile sources in terms of their scan range and repetition rate. For example, point 4 represents a laser that scans through 1 nm every microsecond (once per microsecond = 1 MHz repetition rate).

The figure is organized chronologically. Each numbered point on the graph corresponds to a reference listed at the end of this article. The repetition rates shown in the figure are defined as the inverse of the scan durations and therefore represent maximum repetition rates. These maximum rates are usually the ones actually demonstrated in the referenced work, with some exceptions (particularly points 11 and 13).

The shaded regions in Fig. 2 represent the approximate limits of operation for

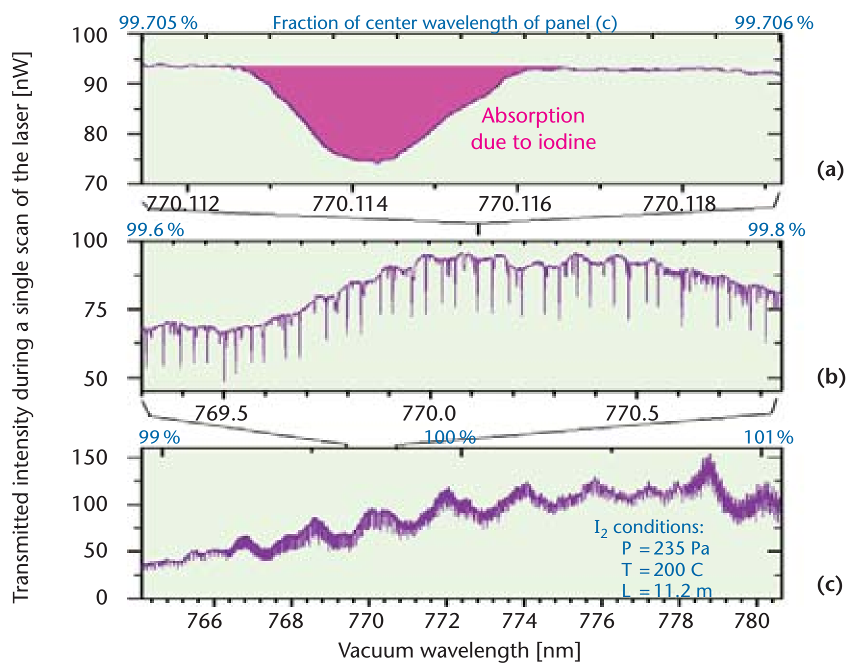

Figure 1. Iodine absorption spectra measured by an external cavity diode laser (single scan in about 10 s). These data were gathered in conjunction with a comparison of slow and fast wavelength scans. [Ref. 11]

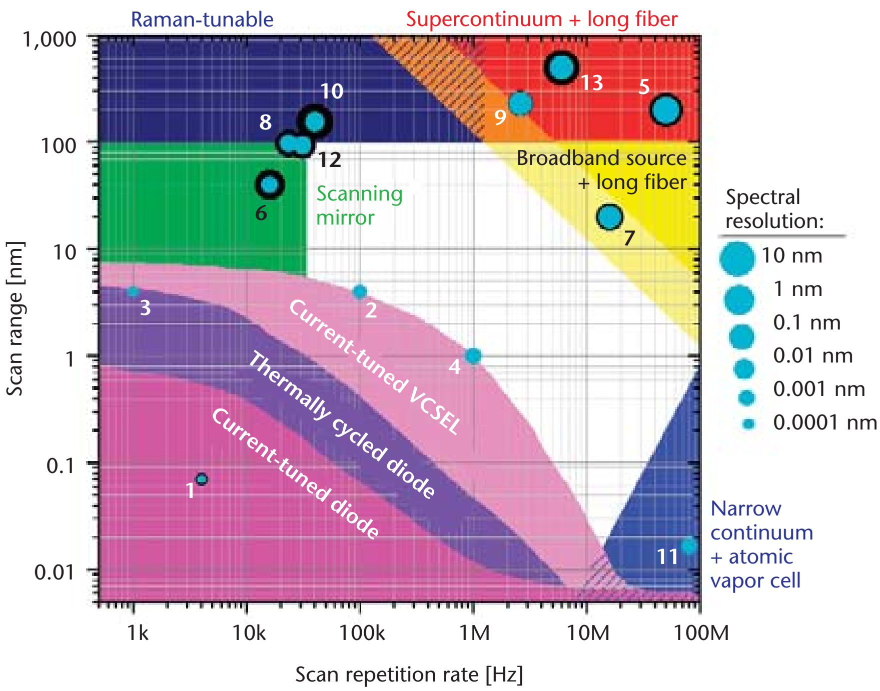

Figure 2. Evolution of wavelength-agile lasers within the author's laboratory. Each numbered point on the graph corresponds to a reference listed at the end of the article. Cyan circles represent ultimate theoretical spectral resolutions. The black circles surrounding the cyan ones represent sprectral resolutions achieved in the referenced works. Because the numbered sources generally operate near 1 μm wavelength, values given in nm correspond approximately to parts per thousand.

each wavelength-agile design. Point 1 on the graph refers to a paper published in 1977; since then, many papers (probably hundreds) have described diode lasers that were wavelength-tuned by injection current modulation. The current modulation, in turn, modulates the wavelength, usually through Joule heating of the active region.

Ordinary diode lasers offered typical information depths of 3,000 points at information rates of 3 million points per second. Beginning at approximately the turn of the century, vertical-cavity surface-emitting lasers (VCSELs) with high series resistance and low thermal capacitance became commercially available, allowing exceptional wavelength-tuning by the same injection-current modulation technique (see points 2 and 4).

These lasers offered typical depths of 5 kpts at rates of 1 Gpts/s, and sparked subsequent developments, including a laser that was rapidly heated by an auxiliary laser to again achieve exceptional thermal tuning (point 3). This thermally cycled diode offered a depth of 44 kpts at a rate of 44 Mpts/s.

Then came lasers that rely on dispersion of pulsed light to generate "chirps" that are useful as wavelength-agile light (see points 5, 7, 9, 11 and 13). In brief, a short, multi-color pulse is directed into a medium in which the various colors travel at different speeds. Typically, a fiber-optic cable with a length of approximately 10 km is used; the red light usually travels faster than the blue light, causing it to emerge first even though all colors entered the fiber at once. At the output of this fiber, then, emerges a rapid wavelength scan from red to blue. These chirp sources offered typical depths of 1 kpts at 3 Gpts/s.

At the same time that chirp sources were being produced, so too were scanners that provide rapid wavelength-tuning simply by rapid mechanical motion of an optical component (points 6, 8 and 12). For example, a vibrating mirror was paired with a diffraction grating to enable wavelength-tuning limited only by structural dynamics. The scanners listed in Fig. 2 offer typical rates of 500 pts at 7 Mpts/s. In terms of depth and rate, they are on par with ordinary current-tuned diodes; the difference is that they are appropriate for broadband spectroscopy because of their increased scan range.

Under certain circumstances, a fiber's output color is a function of the input power, creating a "Raman self-shift" effect (see point 10). In this way, power modulation (which is possible with a host of optical components) can be converted to wavelength modulation. Rapid Raman-tuning was demonstrated in a source that offered a depth of 8 pts at a rate of 300 kpts/s. Although those statistics are unimpressive relative to others cited in this article, the Raman-tunable sources occupy a unique region on Fig. 2 and are therefore attractive for some applications.

The most agile sources appear in the upper-right-hand corner of Fig. 2. An interesting feature of wavelength-agile lasers is that their spectral resolution is limited by the Heisenberg uncertainty principle. Rapidly tuning lasers cannot also be spectrally narrow. The cyan circles in the figure identifying each source represent the minimum possible spectral resolution; the nearer a source is to the upper-right-hand corner, the larger the cyan circles. The surrounding black circles in Fig. 2 are the spectral resolutions actually achieved in practice in each case. Practical resolutions often exceed the corresponding theoretical limit, but in most cases could be engineered to achieve near-theoretical performance.

Wavelength-agile lasers are beginning to be commercialized. For example, Thorlabs part number FTL1300 is based on a source developed for optical coherence tomography [see Opt. Lett. **28**, 1981-3, (2003)]. It has a scan range of about 70 nm and a scan repetition rate of roughly 16 kHz (near point 8 on Fig. 2).

It is helpful to characterize wavelength-agile lasers as shown in Fig. 2 because varying degrees of wavelength-agility are needed for different applications. In short, broad scanning ranges (specifically, a large ratio of scan range to spectral resolution) provide high information depth, and fast repetition rates provide a high information rate. In sensing applications, large depths generally increase the quantity and accuracy of the sensed parameters. Large rates are useful for monitoring high-speed events such as detonations (see Ref. 4), and usually offer increased accuracy because extraneous noise can be essentially frozen in time. Further, large rates generally improve assessment of accuracy by building up measurement statistics while the specimen is "frozen."

These benefits come with a cost. Sensors based on the most agile lasers in Fig. 2 (upper right) often require high-speed (about 20 Gs/s) oscilloscopes and high-speed, small-area (less than roughly 1 mm^2) photoreceivers. These components tend to be expensive and "noisy." In addition, high speed measurements often reveal optical beating that would be negligible in a similar but lower speed experiment.

Thus, I recommend choosing a laser that is only as agile as needed for a given application, aided by plots like Fig. 2. This figure does not include every possible method of generating wavelength-agile light; as more wavelength-agile lasers emerge, the plot is expected to expand to include new colored regions. For example, the vacant space in the middle of the plot does not represent any fundamental limit and is not expected to persist for the next decade.

Figure 2 highlights wavelength-agile laser systems developed primarily for monitoring combustion processes, such as those used in piston engines (points 7 and 9), pulse detonation engines (point 4) and gas-turbine engines (see Fig. 3). A typical target in such measurements would be to record combustion gas temperature and/or composition once per microsecond. Such measurements

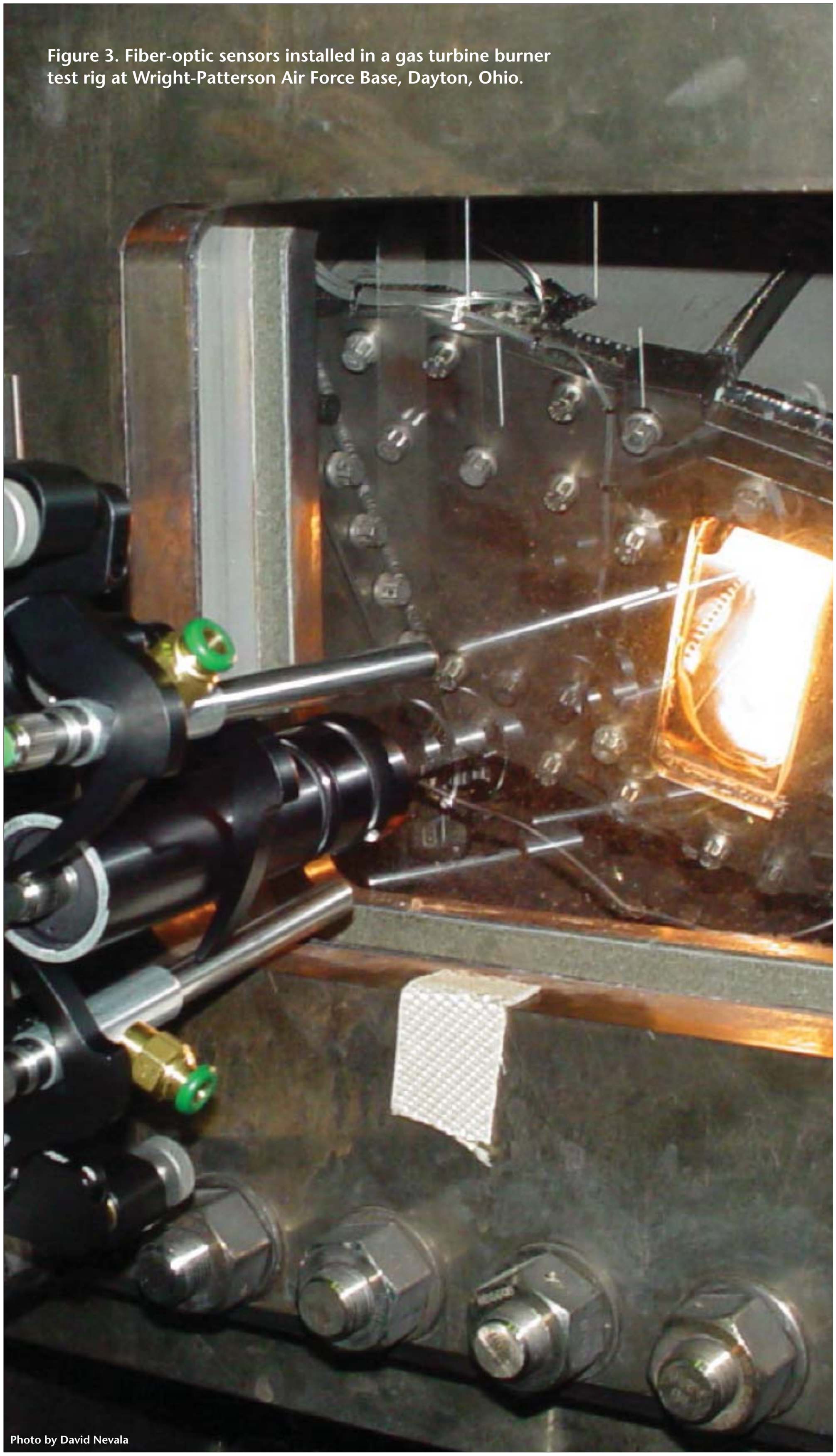

Figure 3. Fiber-optic sensors installed in a gas turbine burner test rig at Wright-Patterson Air Force Base, Dayton, Ohio.

Photo by David Nevala

are typically made using absorption spectroscopy.

Figure 4 shows sample measurements. A chirp is created by injecting pulsed supercontinuua (spanning about 500 to 2,000 nm) into a fiber that is approximately 40 km in length. The wavelength-agile fiber output is then directed through a mixture of combustion gases. In this fashion, the absorption signature was logged in about 6 µs cumulative time (10 shots at roughly 600 ns per shot) using a single high-speed photoreceiver.

Gas temperature is normally inferred from the relative strengths of the individual absorption features. (For example, as temperature increases, some of the features shown in Fig. 4 become more prominent and some diminish.)

New frontiers

Until now, wavelength-agile lasers have mainly been used in absorption or reflection spectroscopy to monitor the properties of a specimen. For example, we have used a laser scanning 1374 to 1472 nm every 85 µs to monitor gas temperature and H_2O mole fraction during the compression stroke of a piston engine (see Fig. 2, point 8), and we used the same laser to monitor the temperature of a piston by fiber Bragg grating reflection thermometry.

Absorption and reflection spectroscopy are valuable techniques, but there are other sensing approaches that stand to benefit from agile operation. For example, laser-induced fluorescence (LIF) can offer spatially resolved measurements, combined with sufficient selectivity to monitor, for example, a trace constituent of a biological specimen.

To demonstrate the potential of wavelength-agile lasers in LIF spectroscopy, we directed a wavelength-agile beam through a cuvette containing dye solution (10^{-6} molar Exciton LD 700 perchlorate in methanol) and monitored the fluorescence using a photomultiplier tube. Figure 5 is an image taken in conjunction with these experiments. The fiber on the left launches wavelength-agile light into a series of cuvettes. The first and third cuvettes contain only scattering media (alumina particles in water).

The first cuvette appears orange, the apparent color of the input light, although a pink spectrum (a white spectrum biased to the red) is actually present. In the second cuvette, dye molecules absorb orange-red components of the beam and fluoresce red.

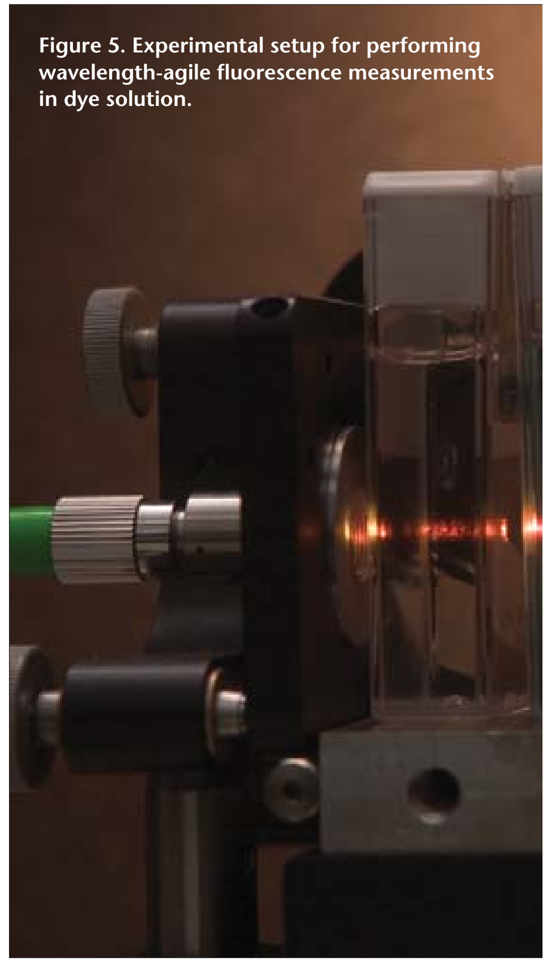

Figure 5. Experimental setup for performing wavelength-agile fluorescence measurements in dye solution.

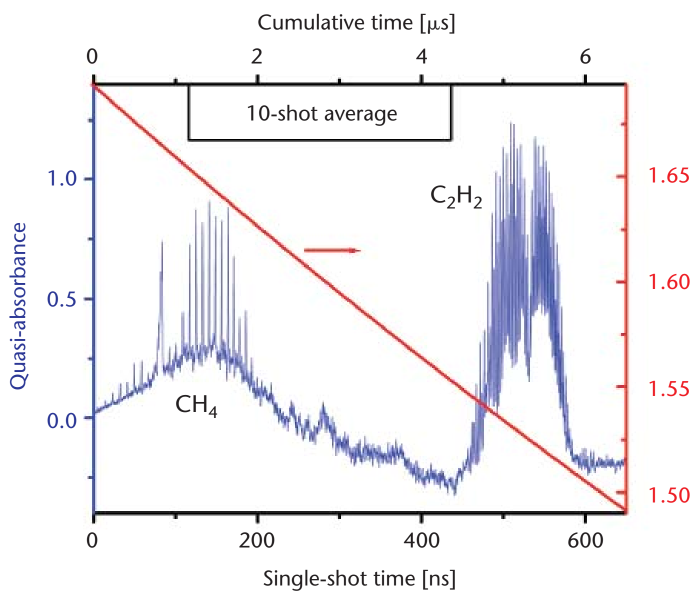

Figure 4. Absorption spectra containing of methane (CH_4) and acetylene (C_2H_2) features, measured in a cumulative time of 5 µs.

Note the intensity decay of the red fluorescence associated with the absorption of the orange-red components. The final cuvette reveals that the remaining portion of the originally pink spectrum is now biased to the green.

In the wavelength-agile LIF demonstration (see Fig. 2, point 13), the wavelength-agile source was essentially the same chirp used to generate Fig. 4 except that the long fiber is "only" 1.7 km. The "I_O" trace in Fig. 6 represents the intensity of the input to the dye cell, detected by the photomultiplier tube. The light blue curve represents a single wavelength scan occurring in about 100 ns, and the dark blue curve shows the average of 1,000 scans occurring in a cumulative time of roughly 100 µs.

The red curve indicates the wavelength-tuning dynamics of the I_O scan. Note the span of approximately 400 nm, with a red-biased spectrum. The green

curves represent the response of the dye solution (again single-shot as well as time-averaged). The dye begins absorbing around t = 60 ns (corresponding to about 700 nm), and continues absorbing the bluer wavelengths as the laser scans.

From the traces shown in Fig. 6, we can produce the excitation spectrum of the dye in much shorter times than is possible with previous approaches. In future applications, wavelength-agile LIF might be applied in order to monitor the presence of one or more substances within a specimen, or for thermometry using a tracer with a temperature-dependent excitation spectrum. Both applications could feature high spatial and temporal resolution.

Other potential applications of wavelength-agile light include those that convert wavelength-scanning into spatial scanning. For instance, by projecting wavelength-agile light through a prism or onto a diffraction grating, a laser beam can be rapidly deflected through a wide range of angles. If a chirp is used as the wavelength-agile source, 45 degrees of deflection in 1 µs would be easily achieved, without any moving parts. Such high-speed repeatable spatial scanning is not possible with ordinary mechanical components like the galvanometers used in laser printers.

There may be applications where high-speed scanning is desirable, such as in data storage. Data storage devices that have a maximum speed that is presently limited by a mechanical motion (e.g., the rotation speed of a CD) might be extended to higher data rates using a wavelength-agile laser to write data.

Finally, focusing a wavelength-agile beam with a Fresnel zone plate enables scanning of the focal point in the axial direction, a scanning motion that is difficult to achieve with common optics at any speed. For any of the spatial scanning ideas listed in this article, spatial addresses can be encoded as wavelength in a remote location far from where the actual scanning takes place.

Wavelength-agile light is just beginning to make the leap from the laboratory into commercial applications. With a variety of potential uses in spectroscopy and high-speed scanning, these colorful lasers are proving to be as functional as they are beautiful.

Acknowledgment

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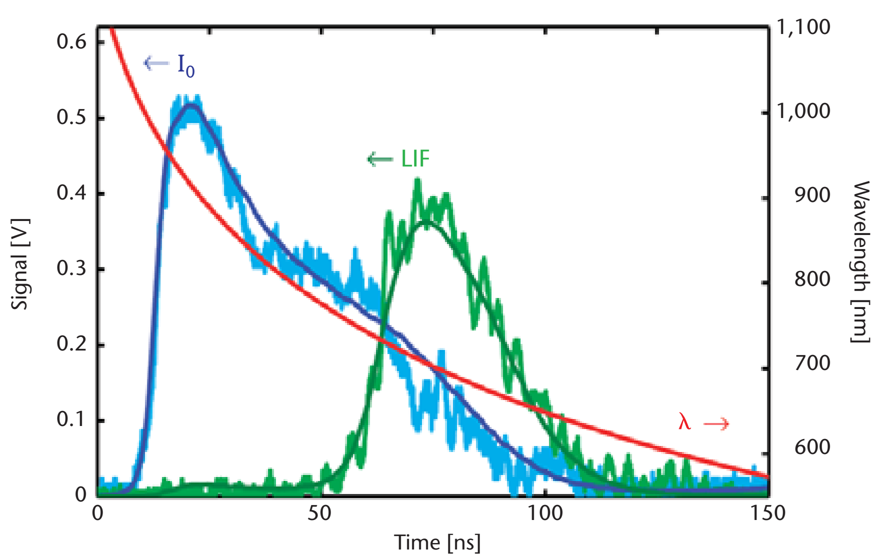

Figure 6. Excitation intensity and fluorescence intensity recorded in a high-speed fluorescence experiment. The light curves are single-shot (150 ns total time), and the dark curves represent 1000 averages (150 µs cumulative time). [Ref. 13]