Tunable Diode Lasers

Tunable diode lasers are increasing their market penetration via rapid evolution — a new generation of products every year or so.

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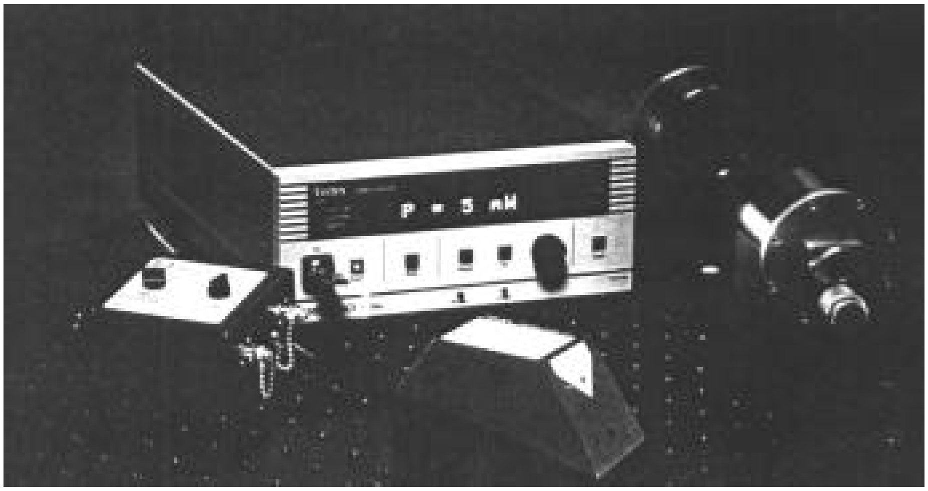
At the recent Photonics West and Optical Fiber Conferences, companies presented many new products, ranging from mechanical products to instruments to complex laser systems. As a product engineer, there is nothing quite like the feeling of standing in the booth, talking to potential customers about the product You've designed or built. But the real success happens when customers buy the product

Customers decide to buy for a number of reasons. The product may let them do something that was difficult or even impossible before. Or the product might make their experiments simpler by creating a better-designed or easier-to-use instrument than was previously available. For this to happen, the product must clearly satisfy a real need of the customer, the product should have some sustainable competitive advantage over other companies' offerings, and the company should be able to make a profit by selling the product. This last item is important since the product can survive only if it can be justified economically both to the customer and the manufacturer.

The tunable diode laser is a product that has satisfied all of the above requirements to become a successful product. Since the first commercial introduction of this type of laser about five years ago, it has found numerous applications, ranging from telecommunications to spectroscopy to metrology. While each of these applications places slightly different requirements on the laser and the user interface, each of them requires a narrow-linewidth, continuously tunable, reliable source. (As examples, Figures 1 and 2 depict two somewhat different system that will be described in greater detail in upcoming sections.)

The technical capabilities and features of the tunable diode laser played a major role in the success of the product. But the ease-of use of the product also contributed to its success. For example, a room-temperature, 2-μm tunable diode laser was recently used by researchers at Stanford University and Focused Research to obtain a survey spectrum of CO_2 in a matter of minutes. With this type of technology these researchers can imagine a very sensitive diode-laser-based sensor for combustion monitoring.



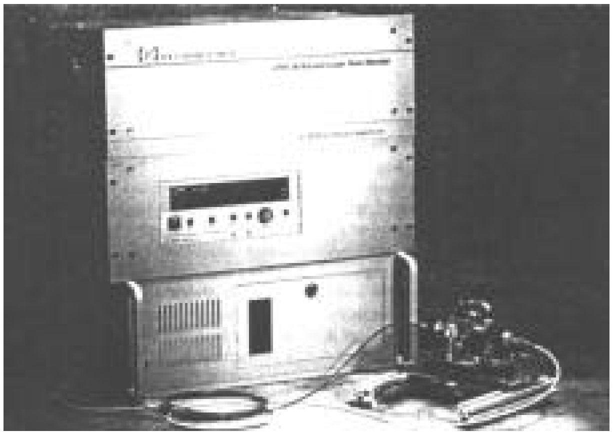


Figure 1. (top) The Vortex laser (New Focus' newest) is built to the customer's specific wavelength specification and offers robust, narrow-linewidth source for atomec spectroscopy, environmental monitoring, and metrology applications.

Figure 2. (below) Atomic absorption monitor based on a New Focus Vortex tunable laser and built by Orca Photonics. This system was designed to monitor barium deposition rates and has been deployed with an industrial customer.

Some History

Before the tunable diode laser was introduced, the workhorse of the tunable laser market was the liquid dye laser. This laser was developed in the 1960s and was used in a number of fundamental discoveries in spectroscopy. Different dyes allowed users to cover a wide spectral region. However, the dye laser had a number of drawbacks, such as the need for an expensive pump laser and the inconvenience of using and changing the liquid dyes. The Ti:sapphire laser was developed in the late 1980s and offered a solid-state replacement for the dye laser in the 600- to 1000-nm range. But the Ti:sapphire laser still required an expensive pump laser and water cooling, yet did not directly offer the wavelength diversity (roughly 350 to 1200 nm) of the dye laser.

At the same time, semiconductor diode lasers were also widely available. A diode laser can be tuned over its large gain spectrum by adjusting

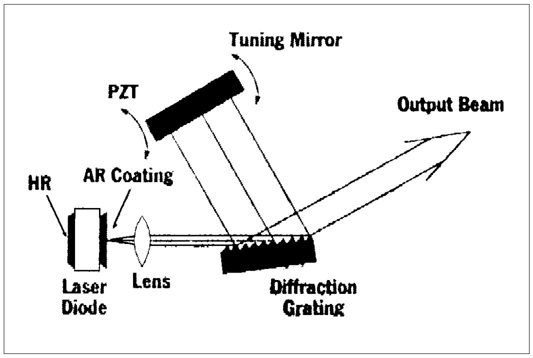


Figure 3. Schematic drawing of a Littmann-Metcalf laser cavity. The angle of the tuning mirror selects the output wavelength and the diffrection grating acts as a frequency-selective output coupler. The location of the pivot point is critical to obtaining continuous tuning without mode hops.

its operating temperature. However, because of the semiconductor's inherently broad spectrum, more than one mode will often operate simultaneously. This produces multiple output wavelengths and, therefore, a broad spectral linewidth.

Adapting The Diode Laser

Adding an external optical cavity forces the diode laser to operate in a single longitudinal mode by creating a wavelength-dependent loss within the laser cavity. In practice, this cavity can be either a Littman-Metcalf or a Littrow design — two cavity designs widely used in dye lasers. Both of these cavities consist of a diode laser gain element with one facet antireflection (AR) coated for very low ($<10^{-4}$) reflectivity. The output from the AR-coated facet is collimated and directed onto a highly dispersive diffraction grating,

In the Littrow cavity, the angle of incidence is such that the beam is diffracted back on itself. The grating therefore serves as one mirror in the cavity; tuning is achieved by controlling the angle of the grating. In the more common Littman-Metcalf design, shown in Figure 3, the grating diffracts the light toward a tuning mirror, which reflects the desired wavelength back towards the grating and gain medium. This double-pass scheme, coupled with the grazing incidence on the grating, results in a very narrow spectral passband, and therefore excellent wavelength sensitivity, without the use of additional intracavity filters such as an etalon. Tuning is achieved by adjusting the angle of the mirror which selects a unique diffracted wavelength. The reflected zero order from the diffraction grating has constant direction and forms the output beam. These external cavity designs yield continuous tuning over the wide gain curve of the diode laser element with a very narrow linewidth!

The tuning range depends on the gain element used in the cavity; at 630 nm the tuning range is 10 nm, while at 1550 nm the tuning range can be greater than 70 nm. In both cases, the linewidth is less than 300 kHz. The inherent efficiencies in the already mature diode laser market helped make the external-cavity diode laser an attractive replacement for conventional dye and solid-state tunable technologies. As a result, these lasers have quickly found use in the applications mentioned above.

Some Recent Applications

One of the benefits of the tunable diode laser is the wavelength diversity that can be obtained. Almost any wavelength that is available in a semiconductor diode laser can be made into a tunable diode laser. The most recent example is in the 2-µm region. In a partnership with Focused Research (a subsidiary of New Focus), researchers at the Sarnoff Corporation (Princeton, N.J.) have demonstrated strained InGaAs/InP quantum well lam with center wavelengths near 2.02 µm. These semiconductor diode lasers were AR coated and placed in a specially designed external cavity by a team at Focused Research. This laser operated at room temperature and demonstrated continuous tuning from 1.96 to 2.06 µm with an output power as high as 18 mW. The tuning curve for this laser is shown in Figure 4.

The 2-µm region and beyond Is of particular interest in environmental monitoring, since these wavelengths allow access to strong ground-state vibrational overtones of many major pollutants. Professor Ron Hanson and his group at the High Temperature Gasdynamics, Laboratory in the Mechanical Engineering Department at Stanford University (Palo Alto, Calif) have been investigating flame dynamics in combustion chambers for a number of years. Their aim is to produce a compact, reliable sensor for CO_2 and other combustion gases to measure the efficiency of burn chambers and incinerators. They have focused on sensors based on diode lasers due to the robustness, reasonable cost, and relative ease-of-use of these lasers. Because of this focus on compact sources, their work has always been dictated by the available wavelengths of the diode lasers. In the past, this constraint has limited their sensors to detection of the relatively weak transitions associated with vibration-rotation bands. For comparison, the CO_2 linestrengths in the 2 µm region are 70 times stronger than at 1.58 µm. This group has recently collaborated with Focused Research and has used a 2-µm tunable diode laser to obtain survey spectra of CO_2 and H_2O at various temperatures and pressures. A representative CO_2 survey spectrum is shown in Figure 5. From these survey spectra, they have selected a strong CO_2 ab-

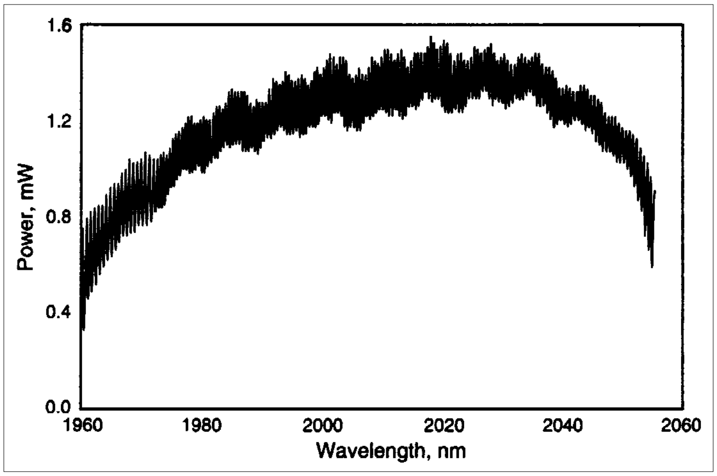


Figure 4. Tuning range of an external-cavity tunable diode laser using a strained InGaAs/InP quantum well as the gain element. This 2-µm laser was operated at room temperature.

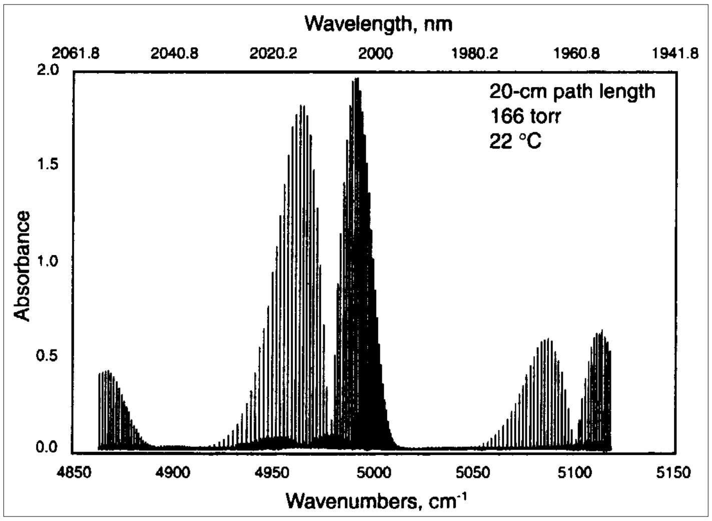


Figure 5. Measured survey spectra of CO_2 between 4866 cm^{-1} (2.055 µm) and 5118 cm^{-1} (1.954 µm) taken using a room temperature external cavity diode laser.

sorption band relatively free from background absorptions that offers the best opportunity for sensitive CO_2 measurements.

As mentioned briefly earlier, each application tends to require a different set of features. It is tempting to continue adding features to a product in an attempt to satisfy everyone. But this approach often leads to an overly complex and expensive instrument that satisfies no one. In many instances, the product with the fewer features is the better product.

This is the approach New Focus decided to use when designing the newest tunable diode laser; the Vortex (Figure 1). There are a number of applications where the full tuning range of the tunable diode laser is not needed or used. Examples include studying a single atom or molecule, such as rubidium, with a well-known atomic transition. Or, as in the work described above, an optimum wavelength can be selected after obtaining an initial survey spectrum with a broadly tunable laser and identifying a wavelength free from background sources. Or you could imagine a metrology application needing a stable, narrow-linewidth source but with a narrow tuning range that would allow FM measurements to be made, something not possible with a HeNe laser.

To satisfy such needs, New Focus uses the same Littman-Metcalf external cavity design as in their other tunable diode lawn but removes the coarse tuning feature.

One example of an industrial application of this laser is the collaborative work of Focused Research and Orca Photonics Systems. Physical vapor deposition techniques such as electron beam, sputtering and molecular-beam epitaxy (MBE) are critical to the manufacture of semiconductor devices, high-performance alloys, and high-temperature superconductors. The product yield depends on precise control of the flux of the different elements during manufacture. Historically, techniques such as quartz crystal monitors, quadrupole mass spectrometers, and ion gauges have been used in process control for such applications.

Atomic absorption monitoring offers species-specific measurement of the deposition process, including flux velocities and spatial and temporal homogeneity. In an atomic absorption monitor, the vapor absorbs light at the wavelength corresponding to an atomic transition; measurement of the incident and transmitted light yields the evaporation rate. While tunable diode lasers are more expensive than other light sources such as hollow cathode lamps, the higher spectral intensity translates into faster data acquisition. In addition, the laser's modulation capability is useful for the development of a more sensitive, drift-free sensor (Figure 2). The narrow linewidth of a laser source enables spatial, temporal, and velocity mapping of the flux and creates a more complete understanding of the deposition process. This improved understanding can then be used to increase the process yield.

While the pace of development in the tunable laser field has been quite fast, with a new laser system available almost every year, each new generation has offered customers additional benefits. Additional wavelengths such as the 2-µm tunable diode laser and products focused on customers needs have allowed customers to do what they could not have done before and provided simpler, easier-to-use tools for them. This focus on customer needs that continue to expand the market for the already successful tunable diode laser.

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