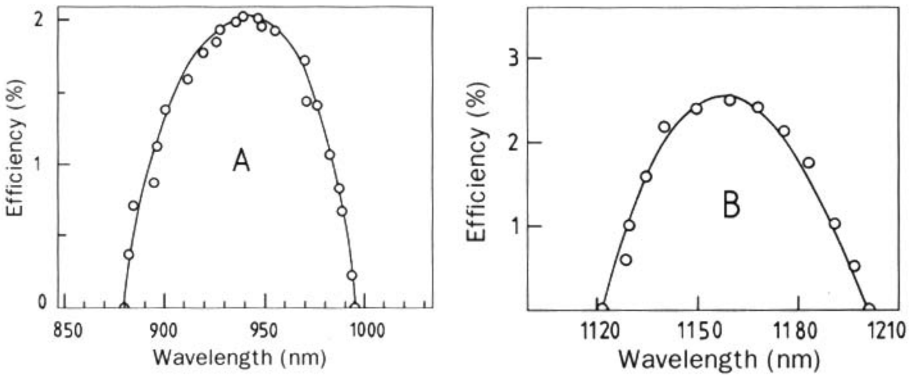
lay between pulses of different spectral components during tuning. (The last circumstance makes it possible to use LiF:F_2^+ and LiF:F_2^- laser radiation successfully for nonlinear wavelength conversion technology where good overlapping between pumping and lasing pulses is required.)



Ter-Mikirtychev Figure 1. Tuning curves of the diode-pumped (A) LiF:F_2^{+*} and (B) LiF:F_2^- laser.

There is considerable interest in the use of direct diode pumping of these highly efficient and unique room-temperature stable solid-state lasers. The diode pumping technique provides high amplitude stability, high efficiency with respect to the electrical power source, easy handling, and compactness. Such diode-pumped mid-IR lasers have a number of potential applications in optical communication, information processing spectroscopy, and evanescent-field in-line fiber amplifiers.[1]

Recently demonstrated diode-pumped LiF:F_2^{+*} and LiF:F_2^- lasers are the first room-temperature diode-pumped color center oscillators.[2, 3] Achievement of the diode-pumped room-temperature tunable lasing creates a new class of all solid-state tunable systems. Color center lasers described in References 2 and 3 were pumped by two different laser diode arrays that could be driven by the same pulsed laser diode driver. A commercial 60-W SDL-6231-B1 InGaAs diode laser array, which provided maximum pulse energy of quasi cw 976-nm radiation of 24 mJ with a pulse width of 400 μs was used for the LiF:F_2^- laser pumping. Another commercial 3-W SDL-7470-P5 InGaAlP fiber-coupled linear array laser diode, which emitted 680-nm light, was used for the LiF:F_2^{+*} laser pumping. To create nanosecond light pulses from laser diodes (as the room-temperature excited state lifetime of the F_2^{+*} and F_2^- centers are 19.5- and 100-ns, respectively) close to the F_2^{+*} and F_2^- excited state lifetime in LiF, the SDL lasers were impedance-matched to a Melles Griot DLD 701 pulsed diode laser driver. Finally the diode laser sources were able to produce reliable pulses with pulse width from 25 ns to 1 μs and a pulse repetition rate of 10 Hz.

Tunable oscillation was achieved by inserting the birefringent plate into the color center laser cavity. The oscillating pulse energy threshold corresponding to the free running (nonselective cavity) of the LiF:F_2^{+*} laser was 0.0085 μJ, and the laser demonstrated 3% optical-to-optical conversion efficiency. A minimum pulse energy threshold of 0.0125 μJ was measured at the maximum of the tuning curve, corresponding to a 940-nm wavelength. The maximum tunable laser efficiency was determined to be 2% at this wavelength. The tuning range of the LiF:F_2^{+*} laser is shown in Figure 1a. The color center laser operated over the 880–995 nm range. For the LiF:F_2^- laser, a minimum pulse energy threshold of 2 μJ was measured at the maximum of the tuning curve, corresponding to a 1160-nm wavelength. The maximum tunable laser efficiency was determined to be 2.5% at this wavelength. The tuning range of the LiF:F_2^- laser (1122–1201 nm) is shown in Figure 1b.

It is expected that further optimization of the diode laser technology (including the development of the efficient fiber-coupled laser diode arrays and fiber-optic pumping scheme), pumping geometry and cavity configuration (toward the better mode to pumping beam waist matching), as well as the optimization of the color center crystals preparation will lead to higher output energy characteristics, increased efficiency, and expanded tuning range.

References

1. V.V. Ter-Mikirtychev and T. Tsuboi, "Stable room-temperature tunable color center lasers and passive Q-switchers," Progr. Quant. Electron. **20**, 219–268 (1996).
2. V.V. Ter-Mikirtychev, "Diode-pumped LiF:$F2^{+*}$ color center laser tunable in the 880–995 nm region at room-temperature," IEEE Photon. Techn. Letts. **10**, 1395 (1998).
3. V.V. Ter-Mikirtychev, "Diode-pumped tunable room-temperature LiF:F_2^- color center laser," Appl. Opt. **37**, 6442 (1998).

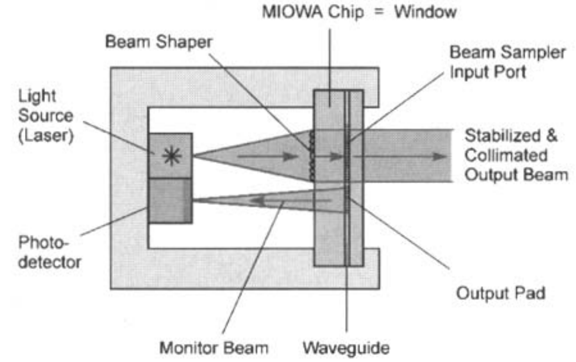
Tuning and Stabilization of Laser Diodes by a Planar Optical Wavelength Analyzer

M. Wiki and R.E. Kunz, CSEM Centre Suisse d'Electronique et de Microtechnique SA, Zürich, Switzerland.

For many applications of narrow-band light sources such as edge-emitting laser diodes or VCSELs, it is important to know the spectral properties of the optical beam, and it is required that we be able to control the spectrum actively. However, conventional solutions such as tunable lasers or thermal light sources in combination with monochromators are expensive and, in the latter case, very bulky.

The novel approach presented here makes use of the spectral information obtained by a miniature integrated optical wavelength analyzer (MIOWA) chip[1] in an active optoelectronic feedback loop to control the light emitted by laser diodes. The MIOWA chip acts as a smart integrated optical beam splitter that performs the beam splitting and spectral analysis by one single planar optical element without the need for any further optical components.

The feasibility of active spectral beam control is demonstrated for two different types of laser diodes. For VCSELs, the wavelength is controlled by regulating the case temperature by means of a Peltier element. Details on wavelength sampling and stabilization of VCSELs are given in Reference 2. For VCSELs with a single-mode and mode-hop free tuning range of about 3 nm,[3] the wave-



Wiki Figure 1. Miniature light source with "smart window" combining spectral beam control (wavelength tuning and stabilization) and beam shaping in one single optical element.

length dependence of the transducer response is stored in a lookup table and used for stabilizing and controlling the desired wavelength. To evaluate the performance of the active beam control, the spectrum and peak wavelength of the laser diode are simultaneously observed using a commercial high-resolution spectrometer.

Experimentally, the performance of the stabilization is demonstrated by varying the temperature of the VCSEL mount between 11°C and 29°C and comparing the wavelength of the VCSEL for non-stabilized and stabilized operation. For the non-stabilized operation mode, a thermal wavelength drift of about $\partial\lambda/\partial T_{VCSEL} =$ 0.056 nm/°C is measured, while for stabilized operation, a wavelength accuracy of 0.008-nm rms is achieved.

Figure 1 shows how miniature, compact light sources are realized by means of a single planar optical element that replaces the window of conventional laser packages. This "smart window" combines beam shaping optics with the spectral beam sampling capability. This approach has great potential for realizing miniature tunable light sources, due to the suitability of mass production of these elements by replication techniques.[4]

References

1. R.E. Kunz and J. Dübendorfer, "Miniature integrated optical wavelength analyzer chip," Opt. Lett. **20,** 2300 (1995).
2. M. Wiki *et al.*, "Spectral beam sampling and control by a planar optical transducer," Sensors and Actuators A **67,** 120–124 (1998).
3. K. Gulden *et al.*, "High performance deep-red AlAs/AlGaAs VCSELs for applications in sensing," *Laser Diodes and Applications II,* Kurt J. Linden and Prasad R. Akkapeddi, eds., SPIE Proc. **2682,** 125–135 (1996).
4. R.E. Kunz *et al.*, "Replicated chirped waveguide gratings for optical sensing applications," Sensors and Actuators A **47,** 482–486 (1995).

MICROCAVITIES

Microlasers with Chaotic Resonators and Bow-tie Lasers

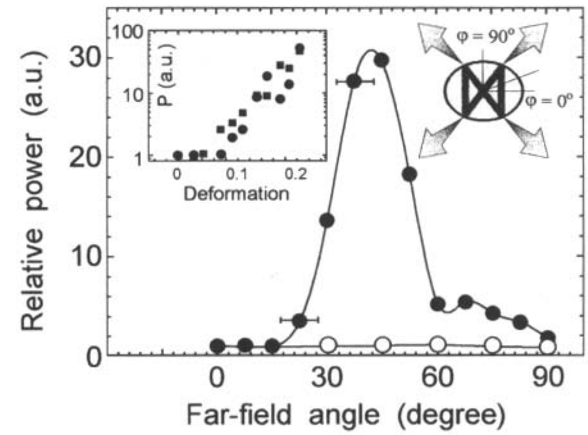
Claire Gmachl, Federico Capasso, Deborah L. Sivco, and Alfred Y. Cho, Bell Laboratories, Lucent Technologies, Murray Hill, NJ; E.E. Narimanov and A. Douglas Stone, Applied Physics, Yale Univ., New Haven, CT; Jens U. Nöckel, Max-Planck-Institut für Physik Komplexer Systeme, Dresden, Germany; Jérôme Faist, Université de Neuchâtel, Neuchâtel, Switzerland.

High quality micro-resonators are of particular interest for semiconductor lasers as they allow a smaller volume of the active material with concomitant moderate energy requirements and the ability to pack the lasers in a small space.[1] Micro-disk lasers operating on whispering gallery modes are an excellent example. In these lasers, light circulates around the curved inner boundary of the resonator, reflecting from the resonator walls with an angle of incidence always greater than the critical angle for total internal reflection, thus remaining trapped inside the resonator.

The work presented here reports on deformed disk lasers with significantly improved performance as they overcome the drawbacks of conventional disk lasers, low-output power, and lack of directionality.[2]

Micro-cylinder lasers have been fabricated from quantum cascade laser material designed for laser emission at 5.2-µm wavelength and grown by molecular beam epitaxy in the InGaAs/AlInAs (InP) material system.[3] Their cross section is deformed from circular symmetry into an approximately quadrupolar shape (see Fig. 1, right inset). Lasers with different deformations ranging from 0% (circular) to ~20% have been characterized (the percentage of deformation refers to elongation and compression of the major and minor axis, respectively, compared to a circular cylinder with equal area).

In the low-deformation regime (< 10%), whispering gallery modes dominate and show an increase in output power with increasing deformation and weak directionality with increased output into the direction of the minor axis. This behavior can be understood from the ray dynamics in these deformed resonators, which is known to be either partially or fully chaotic in the generic case:[4] The deformed boundary causes the angle of incidence



Gmachl Figure 1. Measured angle-resolved far-field pattern (one quadrant) of a circular (open symbols) and a deformed (16%) micro-cylinder laser (filled symbols). The measurements were taken at a constant current level, at which the deformed laser displayed pure single-mode emission. However, the far-field shows qualitatively the same characteristic directionality at a current level corresponding to peak optical power. The data-sets are normalized to the value measured at 0°. Data points are connected by splines for clarity. Left inset: Maximum peak optical power from various lasers as function of their quadrupolar deformation. The aperture with width 15° is centered around 0°. A peak power of ~10 mW was measured for a laser with 20% deformation (collected over one quadrant, at 100 K heat sink temperature). Right inset: Schematic cross-section of a deformed disk laser with the "bow-tie" shaped modal path and emission pattern (arrows). The polar coordinate system is oriented such that φ = 0° indicates the direction along the elongated (major) axis, and φ = 90° denotes the direction of the compressed (minor) axis. (See color image, page 15.)