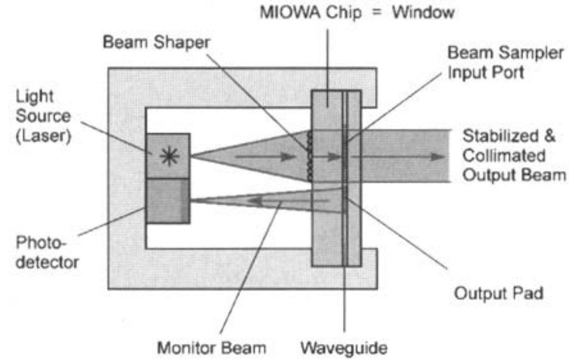

Wiki Figure 1. Miniature light source with "smart window" combining spectral beam control (wavelength tuning and stabilization) and beam shaping in one single optical element.

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]

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MICROCAVITIES

Microlasers with Chaotic Resonators and Bow-tie Lasers

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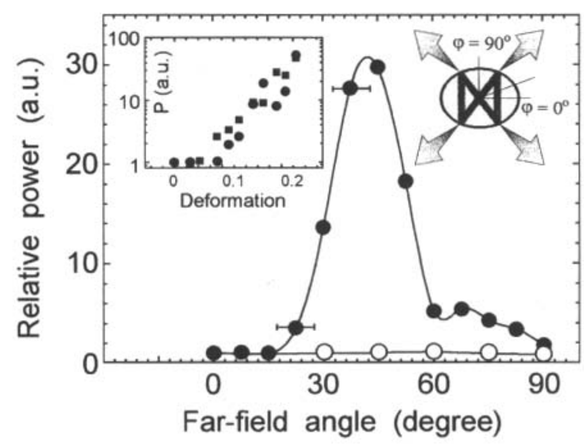
High quality micro-resonators are of particular interest for semiconductor lasers as they allow a smaller volume of the active material with concomitant moderate energy requirements and the ability to pack the lasers in a small space.[1] Micro-disk lasers operating on whispering gallery modes are an 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.)

of a ray in a whispering gallery mode to fluctuate in time. Eventually a ray trapped by total internal reflection impinges on the boundary below the critical angle and escapes by refraction.

However, at higher deformations (*i.e.*, above ~10%) a different type of laser resonance emerges and is responsible for highly directional (~45° off the major axis, see Fig. 1) and high-power emission. Unlike the chaotic whispering gallery modes of smaller deformations, these bow-tie resonances are stable resonator modes surrounded on all sides (in phase space) by chaotic motion. Their modal path and emission pattern is shown in the right inset to Figure 1. In the favorable directions of the far-field, the "bow-tie" laser shows a power increase of up to three orders of magnitude over the conventional circularly symmetric laser. A peak output power of 10 mW (one quadrant) is measured for a laser with minor and major axis diameters of 40- and 60-μm, respectively, waveguide thickness 5.4 μm, at 100 K heat sink temperature. The lasers are operated in pulsed mode and show laser action up to 270 K.

Acknowledgments
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Coupled Microcavities in Light-Emitting Porous Silicon

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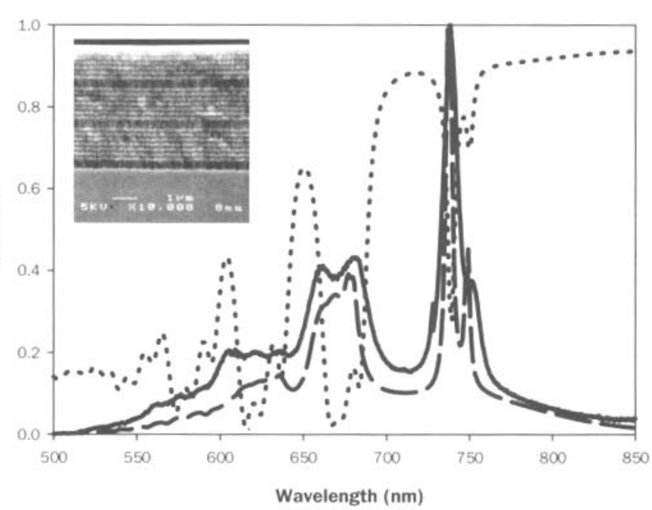
Although porous silicon (p-Si) can be easily, rapidly, and cheaply produced in electrochemical cells without the need for lithographic or epitaxial techniques, the emitted light has an undesirably broad spectrum (FWHM ~150 nm) and long (microsecond) decay times.[1] If the spectrum can be narrowed, the response time reduced, and the efficiency improved, p-Si light emitters are likely to rapidly find their way into advanced Si-based optoelectronic chips. A potential way of overcoming these limitations is to place the p-Si in a resonant environment—but how best to produce a high quality micro-resonator? An attractive feature of the anodic etching process is that the porosity is a strong and reproducible function of current density. This means that multilayer stacks with precisely controlled refractive index profiles can be produced. This has been used to produce passive filters and microcavities that enhance the p-Si luminescence.[2,3]

We have produced a range of multilayer structures in p-Si and for the first time successfully modeled their emission spectra using only the macroscopic optical properties of the layers (refractive index, absorption coefficient, layer thickness, emission spectrum) without detailed knowledge of their microscopic physical and electronic structure. Figure 1 shows the intricate optical properties of a 42-layer porous silicon coupled-microcavity system. The sample (SEM inset) consists of two cavities bounded by 13-layer mirrors comprised of 0.11-μm (41% porosity) and 0.08-μm (69% porosity) layers. The figure shows the measured reflectivity and photoluminescence spectrum—both strongly modified compared to a bulk porous silicon layer. As expected, the luminescence peaks at the transmission maxima for the unpumped structure (*i.e.*, at the reflectivity minima). The cavity modes at 740 nm dominate and are narrower than the first transmission mode on the low-wavelength side of the stop-band. Both the reflectivity and the emission spectrum show mode splitting arising from the coupling of the microcavities. Clearly, the emission has been enhanced and channeled into a few modes of the structure.

The emission spectrum is modeled using a modified transfer matrix technique, which includes the effect of porosity on the complex refractive index.[4] Emission effects are included using a gain spectrum derived from bulk emission properties. The results of the calculation closely match the details of the measured spectrum, illustrating the power of the approach.[5]

In summary, high performance multilayer microcavities can be produced rapidly in porous silicon with great precision and reproducibility. These structures considerably enhance the light emission from p-Si, allowing narrower bandwidths, higher efficiencies, and faster modulation rates, as well as making possible a wide range of useful passive devices.



Snow Figure 1. Spectra from a porous silicon 42-layer coupled microcavity system. The dotted spectrum is the sample reflectivity. The solid line shows the measured photoluminescence spectra after excitation by a 488-nm pump beam. The long-dashed line shows the modeled emission spectrum assuming constant excitation of all luminescent p-Si in the structure.