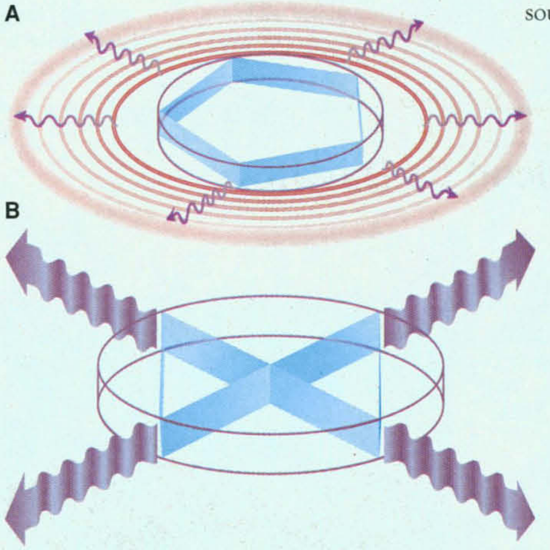
RESEARCH: LASER PHYSICS

Geometrical Shaping of Microlaser Emission Patterns

Erich Gornik

Optoelectronics—the conversion of electronic signals into light and back again—is part of our everyday lives. Though unnoticed when we pick up the phone, listen to a compact disk player, or touch the television remote control, optoelectronics is based on highly refined technology, a well-balanced combination of transistors, semiconductor lasers, and detectors. Although enormous effort is still going into the improvement of these "standard" devices in major laboratories and university institutions, significant breakthroughs have been achieved in the area of laser sources. The field is experiencing an explosion of fresh and unconventional ideas; the control of threshold currents and emission patterns make many new applications possible. The research article by Gmachl *et al.* (*1*) on page 1556 in this issue represents a milestone in this respect. It not only provides a concept for lasing at extremely low currents but also for directionality control; it provides an example in which an active optical system has entered a regime where the boundary to chaos can be controlled by geometrical design.

Micrometer-size lasers are of enormous interest as they promise to satisfy the demands for ever smaller and more power-efficient systems. Nevertheless, these devices still face several difficulties. One concept that offers an extremely low current threshold is the "whispering-gallery" disc laser (*2*); unfortunately this design still has problems with low power output and uncontrollable directionality [see (A) of figure]. Gmachl *et al.* (*1*) have developed a new type of semiconductor microlaser that is a dramatic improvement over earlier related lasers by using better resonator optics, chaos theory, and semiconductor quantum-engineering. The authors demonstrate a power increase by several orders of magnitude (from ~10 μW to ~10 mW) and output directionality of miniature cylinder lasers by fabricating them in a geometry that is smoothly deformed from circular symmetry. The lasers are, in fact, quadrupolar; that is, they have a circular cross section that has been elongated in one direction and squeezed in the perpendicular direction. At small deformations this results in chaotic whispering-gallery resonances, which are explained below. At larger deformations the lasers operate on bow-tie-shaped modes that are completely new to these little resonators and are highly advantageous. The nature of these resonances becomes quite clear from the lower part of the figure. In contrast to the circular lasers and those with very small deformations, these resonances use only parts of the cylinder laser's perimeter as resonator mirrors. This is responsible for the strongly directional light output. The reflectivity of the boundary is very high, but not quite unity, allowing the laser to have a low threshold and reach a high output power.



A la mode. (**A**) Schematic diagram of a whispering-gallery resonance in a circular symmetric cylinder laser; the light remains trapped within the laser resonator by continuous specular reflection from the boundary that essentially circles along the cylinder perimeter. Light only weakly leaks out from the resonator. (**B**) Schematic diagram of a bow-tie resonance in a smoothly deformed cylinder laser of the kind described by Gmachl *et al.* (*1*); the light bounces back and forth across the resonator emitting strong light (by refraction) into narrow angles.

The authors applied this technique to mid-infrared lasers, an important class of devices because of their many applications, such as pollution monitoring, medical diagnostics, and combustion or process control. Nevertheless, the demonstrated concept is universal to resonators made of high–refractive index material and as such is applicable to a much broader range of materials, in particular to semiconductor lasers of all different wavelength ranges.

The gain medium is an electrically pumped semiconductor cylinder laser. When the cross section is circular, laser action takes place on so-called whispering-gallery resonances. This old and well-known concept comes from medieval churches, where sound was known to travel along the curved inner surfaces of arches and domes. Whispering-gallery lasers are some of the tiniest monolithic lasers. The resonator operates by confining the light through total internal reflection within a spherical or cylindrical dielectric medium. In such a case the long-lived (low-threshold) resonances can be described by light rays that reflect repeatedly from the boundary with the same angle of incidence, which is greater than the angle for refracting out of the medium; hence, the light circulates around the boundary, perpendicular to the symmetry axis, trapped indefinitely (top part of figure). Light leaks out very weakly and equally in all directions by a process that may be described as quantum-mechanical tunneling of photons. In principle this circular symmetric design allows one to make a very compact resonator. However, the very long lifetime and particularly the isotropic emission from the optical resonances of such symmetric dielectric resonators make them unsuitable as laser resonators for technological applications because such lasers produce very low power and require additional components to direct the emitted light.

Some time ago Nöckel, Stone, and Chang (*3*) suggested that by substantially deforming the resonator from perfect circularity, resonators with highly directional emission could be achieved. The interesting point is that the motion of rays in such asymmetric resonant cavities is not simple, but instead extremely complex. In fact, if one puts aside for the moment the possibility that such rays can escape from the resonator eventually and applies the familiar law of specular reflection from a boundary,

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the problem of ray motion within such a resonator becomes identical to a classic problem in nonlinear dynamics: that of the motion of an elastic billiard ball on an oddly shaped billiard table. For most table shapes the motion is chaotic, which means that the trajectories of two balls (or rays) with almost identical initial conditions would diverge from one another exponentially. One can think of this as arising from the slightly different "kicks" each ray is given at the boundary, the effect of which is amplified by the nonlinear dependence of the angle of incidence on the previous angle of incidence. This is quite remarkable since it opens the door for chaotic studies with light rays.

This analogy has initiated experimental searches for chaotic effects in deformed quantum cascade lasers. These lasers (*4*) are nearly ideal two-dimensional optical billiards because light propagates in the plane of the semiconductor layers polarized perpendicularly to the layers.

Although the existence of chaotic billiard motion means that the trajectory of any one ray is in practice impossible to predict, it does not imply that the emission of light from such a resonance is unpredictable. The electromagnetic resonance is equivalent to an ensemble of such rays, and it is possible to predict where the rays are most likely to escape and in what directions. The escape process as described by Nöckel *et al.* (*3*) involves a diffusive "spiraling in" of the angle of incidence of the trapped rays until this angle falls below the critical angle for total internal reflection and escapes by refraction. This has a strong tendency to happen at or near the points of highest curvature on the boundary, leading to highly directional emission in the far-field. This approach was used to explain the highly anisotropic emission of laser light from deformed liquid droplets containing a lasing dye (*5*), a long-observed but poorly understood effect. A quantitative theory of the emission directionality for these materials with a relatively small index of refraction has been developed (*6*).

In contrast, the new lasers are based on the stable ray motion that survives when the resonator is substantially deformed: a "bow-tie" resonance (lower part of figure) develops as the remaining stable mode. However, the chaotic behavior in the rest of phase space (surrounding the bow-tie) plays an important role as it suppresses competing lasing resonances, which are still present from lower deformations. This is an important point: the chaotic resonances basically feed the stable orbit, and the gain is only limited by diffusion processes within the pump medium. In addition, this lasing principle opens new possibilities for injection control in lasers. By changing the lateral distribution of the injection current through special contact geometry the interplay between the chaotic region and the stable mode can be controlled and dynamic processes within the nonlinear medium can be studied.

A new parameter for laser design is thus introduced with this work: deformation of the resonator. In conventional lasers, the output power depends on the resonator length, whereas here the power increases exponentially with deformation. It is remarkable that the transition from whispering-gallery modes to bow-tie modes appears at certain deformations where simultaneously the spectral properties are also improved.

These new laser-resonators provide a system for fundamental studies of mode behavior at the boundary to chaos, thus creating a playground for mesoscopic physics in optical systems. The theoretical concepts do not directly relate to optical physics but to the field of quantum chaos. This field, which has been an active branch of theoretical physics for about two decades, seeks to understand the consequences of chaotic classical motion for the associated quantum dynamics. The same concepts apply to the wave equation for light in the short wavelength limit where ray optics apply: light rays exhibit chaotic motion. Quantum or "wave" chaos theory allows one to classify and understand the possible solutions of the wave equation, which are hard to find with numerical methods because of unsymmetrical boundary conditions.

References

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PLANETARY SCIENCE

Deuteronomy?: A Puzzle of Deuterium and Oxygen on Mars

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Mars is covered by ancient channels which strongly suggest the existence of a warmer past climate that supported liquid water near the surface (*1*). This is very different from the current cold and arid conditions. It is difficult to reconstruct this early, potentially life-sustaining, climate, or to determine how it evolved into the current extremely hostile climate. One of the few clues we have to the evolution of the martian climate is the isotopic signature left by the various processes that have modified the atmosphere over time. Two reports in this issue, one by Krasnopolsky *et al.* (*2*) on page 1576, the other by Farquhar *et al.* (*3*) on page 1580, add new data to the search for answers.

If we understand the fractionation caused by the various processes that may have affected the atmosphere and know the current isotopic values of the various reservoirs, it should be possible to reconstruct the early climate and its evolution to the present climate. One of the key issues in understanding the martian climate and how it changed is to understand the history and size of the water reservoirs.

It is quite clear that the current mean column-integrated 8.8 μm of H_2O in the martian atmosphere is much too little to have created the features seen on the surface. This amount of atmospheric water is controlled by planet-wide low surface temperatures. The summer polar cap temperatures and seasonal changes in the atmospheric water vapor imply that much more water is frozen at the poles and possibly in the regolith or interior of the planet (*1*). Another "reservoir" was pointed out in a classic paper by McElroy (*4*) in 1972. Using a combination of Mariner 9 observations of the corona of hydrogen atoms (*5*) and a model for the aeronomy of Mars, McElroy indicated that there is an escaping flux of hydrogen (1×10^8 to 2×10^8 atoms cm^{-2} s^{-1}), which is matched by a corresponding escape of oxygen atoms at half the hydrogen rate, so that the net result is the loss of H_2O from Mars. Over geological time, the present escape rate implies a total loss of water equal to 280 mbar in the atmosphere, or 3 m of water uniformly spread over the martian surface. This is a lower limit because there was probably more water in the early atmosphere and the young sun may have driven a

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