about innovator biologics themselves. When competitors face major hurdles in fully understanding a biologic's production and characterization, the trade secrecy–protected monopoly on that biologic can continue indefinitely. Would-be biosimilar applicants have incentives to develop stronger analytical tools, but do not have access to the extensive information possessed by innovator firms and the FDA. This lack of fundamental knowledge weighs down the industry, blocking both competition and further innovation.

Regulation could, however, provide a potential solution. The FDA could play an important role in mediating disclosure by originator manufacturers. Even without congressional action, the FDA may be able to offer incentives for disclosure such as accelerated review. Congressional action could provide the FDA the ability to offer other incentives, such as longer exclusivity periods, or to mandate disclosure in limited circumstances.

Additional procedural burdens would be small. Although trade secrecy, particularly in complex areas like biologics manufacturing, often involves tacit knowledge—difficult to codify and thus transfer (*12*)—originator manufacturers must already codify and submit the relevant manufacturing details to the FDA. Disclosure of these regulatory submissions would not only drive competition but would also provide a rich source of knowledge to support additional work, including fundamental research into the science of how to develop and manufacture biologics. ■

REFERENCES AND NOTES

1. S. Tavernise, A. Pollack, FDA Approves Zarxio, Its First Biosimilar Drug, *New York Times*, 6 March, 2015.
2. B. Falit, S. Singh, T. Brennan, *Health Aff.* **34**, 294 (2015).
3. H. Grabowski, R. Guha, M. Salgado, *Health Aff.* **33**, 1048 (2014).
4. *The Global Use of Medicines: Outlook Through 2016* (IMS Institute for Healthcare Informatics, 2012).
5. S. Ozturk, W.-S. Hu, *Cell Culture Technology for Pharmaceutical and Cell-Based Therapies* (CRC Press, Boca Raton, FL, 2005).
6. H. Li, M. d'Anjou, *Curr. Opin. Biotechnol.* **20**, 678 (2009).
7. B. Sharma, *Biotechnol. Adv.* **25**, 325 (2007).
8. U.S. Food and Drug Administration, Scientific Considerations in Demonstrating Biosimilarity to a Reference Product (2012); www.fda.gov/downloads/Drugs/GuidanceComplianceRegulatoryInformation/Guidances/UCM291128.pdf.
9. U.S. Food and Drug Administration, Quality Considerations in Demonstrating Biosimilarity to a Reference Protein Product (2012); www.fda.gov/downloads/Drugs/GuidanceComplianceRegulatoryInformation/Guidances/UCM291134.pdf.
10. M. McCamish, G. Woollett, *Clin. Pharmacol. Ther.* **90**, 405 (2011).
11. M. McCamish, Global Health Biopharm and Oncology Injectables Development, Sandoz, Presentation to the Oncologic Drugs Advisory Committee, 7 January 2015.
12. D. J. Teece, *Economic Performance and the Theory of the Firm* (Edward Elgar, Cheltenham, UK, 1998).

10.1126/science.aab1684

OPTICS

A chaotic approach clears up imaging

A laser that emits bright, incoherent light provides an ideal light source for imaging

By **Harald G. L. Schwefel**[1] *and* **Hakan E. Türeci**[2]

Lasers appear to be ideal light sources for a variety of projection and imaging systems because of their spectral brightness and their ability to produce a beam of light that can be tightly collimated to travel long distances. Lasers owe these extraordinary properties to a quality called coherence. Yet, lasers are not widely used in imaging and projection applications, because the coherence of laser light is just too extreme. Spatiotemporal coherence of the imaging source leads to artifacts such as speckle, caused by the uncontrolled scattering of laser light and multipath interference that degrade the image considerably. Redding *et al.* (*1*) now report how a semiconductor laser based on a chaotic cavity can offer a "compact" solution to this problem. The availability of such low-cost, on-chip semiconductor lasers and the possibility to electrically modulate them make such lasers attractive light sources for a variety of applications, ranging from compact projectors to optical coherence tomography.

Most modern-day sources for imaging and projection are low-coherence sources, either thermal sources or light-emitting diodes (LEDs). However, their low power is an obstacle for application in high-speed imaging and wide-area projection. The ideal illumination source would combine high output power of a laser with the lower spatiotemporal coherence of an LED.

Chaotic microcavity lasers can fill this gap. In these lasers, the feedback is provided by the specular reflection of rays at the boundary of a micrometer-sized dielectric body (see the figure, panel A). This principle for trapping light rays is the same as in the better-known whispering-gallery resonators, except that because of the deformation of the boundary from a rotationally symmetric shape, the motion of light rays in chaotic microcavities exhibits chaos, similar to the dynamics of a billiard ball bouncing in a deformed pool table.

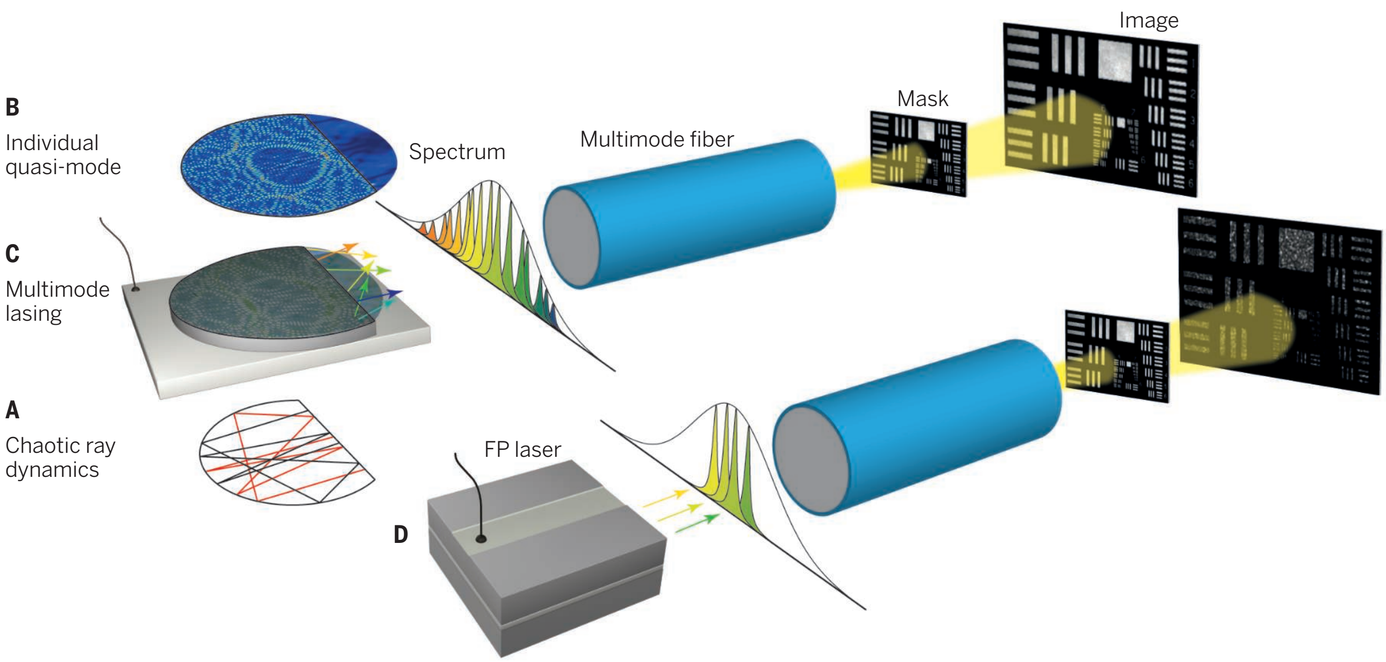
Such chaotic resonators, introduced as model systems to study quantum manifestations of classical chaos (*2*), have spurred the extension of optical resonator theory to complex resonators (*3*). The findings of Redding *et al.* represent a beautiful example of basic science ultimately providing an elegant solution to a technologically relevant problem. In that sense, the chaotic laser has been a "solution looking for a problem."

The key idea (*4*, *5*) is to use a highly multimode laser source to partially suppress coherence. In the proof-of-principle demonstration, Redding *et al.* pumped the laser cavity to oscillate in about 1000 modes. Usually a vast amount of engineering and fabrication effort is spent in designing robust single-mode sources for various applications such as spectroscopy and optical communications. Thus, getting a laser to oscillate in many modes may appear to be a simple matter. However, for a compact laser source like the one used in (*1*) to lase in not just a few but in hundreds of modes, the laser cavity must create a distribution of laser thresholds that is as narrow as possible, so that the number of lasing modes can be maximized before the useful range of the injection current is reached.

> ***"The key idea is to use a highly multimode laser source to partially suppress coherence."***

There are three critical requirements to accomplish this goal. The first is a large cavity so that the mode density is high, and as a consequence, a large number of modes are within the gain bandwidth of the active medium. Second, these modes must have comparable lifetimes. Both of these requirements can be satisfied with certain designs of chaotic (*1*) and random microcavities (*4*). Redding *et al.* opted for the former because of its simplicity of fabrication and lower in-

[1]*Max Planck Institute for the Science of Light, 91058 Erlangen, Germany and Department of Physics, University of Otago, Dunedin, New Zealand.* [2]*Department of Electrical Engineering, Princeton University. Princeton, NJ 08544 USA. E-mail: harald.schwefel@mpl.mpg.de; tureci@princeton.edu*



Imaging without the speckle. The D-shaped resonator of Redding *et al*. emits thousands of modes of slightly different wavelengths that are not phase-coherent, but deliver high power. (**A**) The ray motion in such a resonator is chaotic. The individual linear quasimodes [one example is shown in (**B**)] display quasirandom fluctuations above a uniform background. These patterns may contain additional structure that arise from "scars" (*14*) of periodic ray orbits. (**C**) For above-threshold operation, this device displays multimode emission from hundreds of modes, a few of which are shown in the spectrum of emission. The total emission has substantially reduced phase coherence, resulting in an image for which speckle formation is suppressed, over and above that of an edge-emitting (Fabry-Perot, FP) laser (**D**) that lases in a few modes.

trinsic losses. The third and far more subtle requirement is to suppress spatial hole burning as much as possible. In homogeneously broadened sources, once a mode turns on, it depletes the gain where it has high intensity and suppresses other modes with similar spatial patterns. A lasing mode may never turn on because of such interactions (*6*), thus suppressing highly multimode lasing.

To narrow down the design space, Redding *et al.* resorted to a recently developed theoretical framework, the steady-state ab initio laser theory (SALT) (*7*). This approach was originally developed to address spatial hole burning interactions in a way that provides direct physical insight and is computationally efficient. SALT accurately describes characteristics of lasing in a variety of spatially complex nanostructured photonic media (*6*, *8–10*).

Not all chaotic laser cavities are alike, and the "degree of chaoticity" can vary. Only a few well-studied cavity shapes are known to be maximally chaotic. For a generic cavity shape, the phase space for ray dynamics (a map of allowed trajectories) is neither fully regular ("integrable") nor fully chaotic ("ergodic"), but somewhere in between ("mixed"), with certain initial conditions resulting in quasi-integrable ray trajectories and others in quasi-chaotic, phase-space filling motion. It is a general expectation of quantum chaos theory that in the semiclassical limit, where the wavelength of lasing is much smaller than the size of the cavities, the resulting wave patterns of an ergodic cavity are pseudo-random, filling the entire cavity uniformly up to Gaussian fluctuation for the field amplitude and random phases (*11*).

Redding *et al.* hypothesized that a maximally chaotic cavity should satisfy all three requirements set forth for maximally multimode lasing. Carrying out numerical calculations with SALT, they show that a candidate microcavity is D-shaped. Such a shape is known to be chaotic (*12*), and the maximally chaotic phase space is achieved with a segment cut at exactly half the radius. The individual modes of such a cavity (see the figure, panel B) are fully delocalized over the entire cavity area, suppressing spatial hole burning interactions. The resulting highly multimode laser is demonstrated to have substantially reduced speckle noise in imaging a test pattern (see the figure, panel C), as compared to a ridge waveguide Fabry-Perot cavity (see the figure, panel D).

Finding microcavity designs to maximize the number of lasing modes in a given pump power range is a fascinating theoretical problem. The mathematical complexity derives from three aspects. First, the phase space is generically nonintegrable for ray dynamics in the semiclassical limit (panel A). Second, the resulting modal patterns are spatially complex in a driven and dissipative wave system (panel B). Third, there is competition between the modes to monopolize the gain medium in which they reside (panel C). Even when the ray dynamics is maximally chaotic, however, the resulting spatial mode patterns can have structure. Well-known examples include "quantum scars" (*13*), fascinating remnants of quantum interference in the semiclassical limit, that were a central theme in quantum chaos theory in 1990s and first observed in microcavity lasers in the early 2000s (*14*). Another dimension of this problem is that a steady state, explicitly assumed in this work, may not exist. It is to be expected that this optimization problem may offer a rich playground for theoretical physicists and photonic engineers at the crossroads of quantum chaos theory, nonlinear dynamics, and nonlinear optics, with great potential benefits for future novel sources with engineered coherence that may provide the next generation of battery-powered handheld or wearable personal projectors. ■

REFERENCES AND NOTES

1. B. Redding *et al*., *Proc. Natl. Acad. Sci. U.S.A.* **112**, 1304 (2015).
2. J. U. Nöckel, A. D. Stone, *Nature* **385**, 45 (1997).
3. H. Cao, J. Wiersig, *Rev. Mod. Phys.* **87**, 61 (2015).
4. B. Redding *et al*., *Nat. Photonics* **6**, 355 (2012).
5. M. Nixon *et al*., *Opt. Lett.* **38**, 3858 (2013).
6. L. Ge, O. Malik, H. E. Türeci, *Nat. Photonics* **8**, 871 (2014).
7. H. E. Türeci *et al*., *Phys. Rev. A* **74**, 043822 (2006).
8. H. E. Türeci *et al*., *Science* **320**, 643 (2008).
9. S. L. Chua *et al*., *Opt. Express* **19**, 1539 (2011).
10. P. Stano, P. Jacquod, *Nat. Photonics* **7**, 66 (2013).
11. M. V. Berry, *J. Phys. Math. Gen.* **10**, 2083 (1977).
12. V. Doya *et al*., *Opt. Lett.* **26**, 872 (2001).
13. E. J. Heller, *Phys. Rev. Lett.* **53**, 1515 (1984).
14. N. B. Rex *et al*., *Phys. Rev. Lett.* **88**, 094102 (2002).

10.1126/science.aaa7409

A chaotic approach clears up imaging

Harald G. L. Schwefel and Hakan E. Türeci

Science **348** (6231), 189-190.
DOI: 10.1126/science.aaa7409