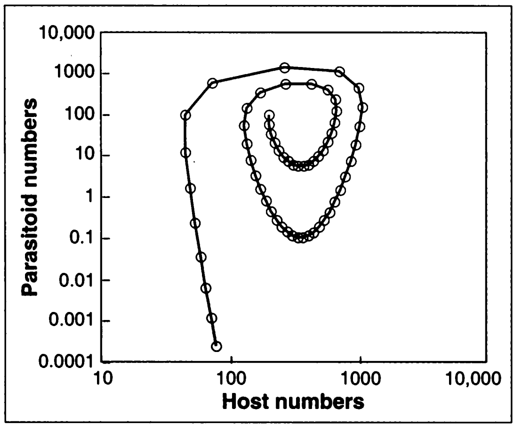

The death spiral. Dynamics of the Nicholson-Bailey model of interactions between an enemy (parasitoid) and victim (host) species. This enemy-victim interaction where the parasitoid lays its eggs in the developing host is very common among insects. The number of parasitoids and hosts over a defined time period demonstrates that this enemy-victim interaction is highly unstable.

figure). Nicholson and Bailey were among the first to look for stabilizing influences, mentioning as one possibility the importance of space (extinctions of hosts or parasitoids in one location could be compensated for by individuals at other locations).

Recent work on spatial heterogeneity in ecology has pointed out the importance of stochastic factors, in particular the dynamics that arise because the local environment faced by an organism differs from the average environment (*7*). Ecological interactions are inherently nonlinear because they depend on the combined densities of the interacting species. With spatial heterogeneity, the average of the local interactions is not the same as the interaction in the average environment. These kinds of dynamics can be easily explored by means of stochastic spatial simulations, but developing analytical descriptions of spatial stochastic models is very difficult. Similar problems arise in many other areas of biology, and have been carefully studied in the physics literature as well.

The obvious first step—taking spatial averages—yields what is known as the mean field approximation. Not surprisingly, a predator-prey version of this model does produce regional stability even if the local interactions are unstable (*8*). The next step in approximating the dynamics of a spatial model is to look at descriptions that take into account the spatial correlations of the species distributions. Unfortunately, this is a very difficult problem, and current methods rely upon approximations that are not easy to apply in general, nor easy to justify (*9*). Yet, these methods have begun to provide important ecological insight (*10*).

Keeling *et al.* begin with either of the two classic models: the Lotka-Volterra model or the Nicholson-Bailey model. They formulate equations for the dynamics of the averages of a stochastic version of the model and show that the key quantity is the covariance term describing the joint occurrence of enemy and victim. As already noted, this covariance is not a constant, but a variable whose dynamics must be included in any description of the system. Using a moment-closure approach (where the dynamics of a full spatial model are approximated by just the spatial average and variance-covariance terms), Keeling *et al.* derive approximations for the covariance term that clearly show that this term is negative. This essentially says that enemy and victim are found together less often than by chance, and therefore that this effect is stabilizing. They also show that the approximations they derive are in agreement with their simulations.

There are other interpretations of the covariance term that provide unification of explanations (both theoretical and observational) for stabilizing influences. The covariance term depends on past behavior of the system, and so it acts like a time lag. This explains observations of delayed density dependence. Alternatively, the covariance term can be interpreted as competition between parasitoids, which has been suggested as a stabilizing factor.

The Keeling *et al.* work is not the final answer, but does point the way to a better understanding of stabilizing influences in enemy-victim interactions. It also demonstrates the importance of spatial stochastic dynamics in ecology. A next step, which may require statistical advances, will be to relate work like this more closely to observations of enemy-victim interactions in large spatial scale natural systems and in smaller scale experimental work. Future progress will depend on the development of better methods for describing analytically the dynamics of spatial stochastic systems. Then, approaches like those used by Keeling *et al.* to study enemy-victim interactions can be applied to larger communities with more species, perhaps providing a better explanation of the relation between diversity and stability.

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PERSPECTIVES: APPLIED PHYSICS

Smaller, Faster Midinfrared Lasers

Jerome Faist

Semiconductor lasers are used widely as optical sources in telecommunication systems and CD-ROM and DVD optical memory drives. According to conventional wisdom, these very small, efficient devices are good for almost any task, although to date they cannot emit efficiently at very short (blue) and very long (midinfrared) wavelengths or achieve very short pulse emission. On page 1739 of this issue, Paiella *et al.* (*1*) expand the range of operation of these devices substantially by demonstrating midinfrared lasers that emit picosecond pulses at wavelengths of 5 and 8 μm. Perhaps the most interesting aspect of this work is the innovative technique used to achieve this goal.

In a simple picture, the active medium of a laser is a two-level system in which the population of the upper energy state is kept larger than the population of the lower one. Because of this population inversion, stimulated emission (transition from the upper to the lower state) is more likely than absorption. Light is amplified by passing through the active medium, resulting in optical gain. In a semiconductor laser, the active medium (the semiconductor itself) is shaped into an optical waveguide that captures and guides the light between the edges of the semiconductor. The resonant optical frequencies of this cavity are called the modes. In a mode-locked laser, the individual modes

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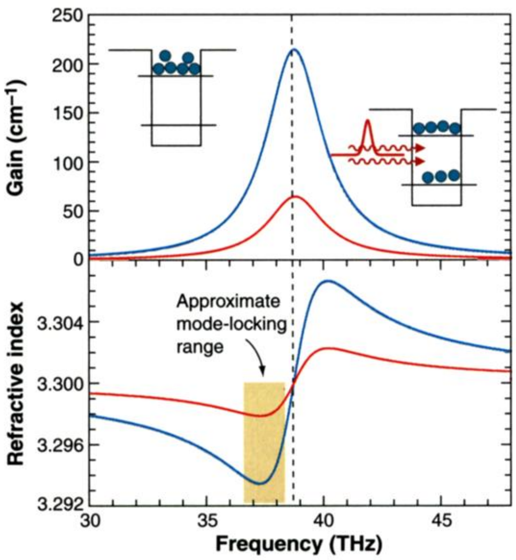
of the laser cavity are locked in phase. As a result, the output intensity is time-dependent and a train of very short optical pulses is emitted, whose period is equal to the roundtrip time in the cavity. In an ideal case, the pulse duration is limited by the uncertainty principle of wave mechanics, which means that it cannot be shorter than the inverse of the spectral gain bandwidth.

To understand mode-locked operation, think of a long rope stretched between two fixed points. The modes of the optical cavity are equivalent to the vibrating frequencies of the rope. Active mode-locking is analogous to periodically hitting one end of the rope as the pulse travels back and forth between the edges of the rope. Passive mode-locking is more difficult to illustrate with an acoustic equivalent, although it does naturally occur in some musical instruments.

A laser will operate when the gain equals the cavity losses. Passive mode-locking is based on having, through the use of a nonlinear material, a lower cavity loss for mode-locked operation than for continuous wave operation. This approach is attractive because of its simplicity and has enabled the generation of the shortest optical pulses from solid-state lasers to date (*2*). It has been difficult to implement in semiconductor lasers, however, mainly because their high intrinsic losses make it difficult to engineer a large enough loss difference between mode-locked and continuous wave operation to ensure mode-locked operation.

Paiella *et al.* have applied a passive mode-locking scheme to midinfrared quantum cascade lasers, which are relative newcomers in the semiconductor laser family (*3*). Two important features set them apart from more conventional semiconductor lasers: They are unipolar (transport is based on either electrons or holes and not both) and cascading (the lasing region consists of repeating identical cells). Quantum cascade lasers exploit the atom-like nature of laser transitions in semiconductor multilayer structures, where each layer is as thin as a tenth of a nanometer each. These "intersubband transitions" proceed between confined electronic states in the conduction band. Because they can be tuned across most of the midinfrared spectrum (from 3 to 19 μm) and emit strongly, quantum cascade lasers are now widely used for molecular spectroscopy and chemical sensing applications.

Intersubband transitions have been studied extensively for their nonlinear optical properties. A nonlinear optical material converts one optical frequency into another: For example, the near-infrared emission from a Neodymium Yag laser can be converted into blue light by frequency doubling in a nonlinear crystal. Nonlinear susceptibilities many orders of magnitude larger than in the bulk have been achieved using intersubband transitions (*4*–*6*) by tuning the transition energies to the various emission frequencies involved. However, the major drawback of this strategy is its low conversion efficiency because the generated signal is strongly attenuated by reabsorption before a useful amount of power can be emitted.



How to achieve passive mode-locking. The origin of the nonlinearity in the lasers described by Paiella *et al.* (*1*) is shown schematically. The curves were computed with the parameters given in (*1*). The laser frequency is assumed to be centered on 38 THz. We assume a 70% bleaching of the transition.

The authors use an elegant trick to circumvent this problem. In their system, the very transition that provides the laser gain is also the source of the nonlinearity, eliminating the problem of reabsorption. A simple two-level system is used by the authors to explain their data (see the figure). Under electrical excitation, the intersubband gain at the laser frequency (blue curve, top graph) changes in the refractive index on both sides of this center frequency (blue curve, bottom graph). This relation between absorption and refractive index is universal. During the intense optical pulse, the transition is bleached because the upper and lower populations equalize and the gain is depressed (red curve, top graph). The refractive index change is also strongly reduced (red curve, bottom graph). This means that below the resonant frequency, the refractive index increases with optical intensity.

The active medium thus acts like a lens and "self-focuses" the beam. Because the waveguide used by the authors was designed to exhibit some controlled amount of losses from the side walls of the waveguide, the self-focusing effect, which will decrease the overlap between the optical mode and those side walls, will effectively decrease the overall losses of the laser. The peak optical intensity, and therefore the self-focusing effect, is greater in mode-locked operation, which is therefore favored over continuous wave operation.

Given that this mechanism is so general, it may seem surprising that it has not been used previously in semiconductor lasers. For the mechanism to be efficient, however, the nonlinearity must recover extremely fast. In intersubband transitions, recovery within about a picosecond is assured by optical phonon scattering. In contrast, conventional semiconductor lasers exhibit very long gain recovery times of hundreds of picoseconds.

The very short pulse duration available from mode-locked lasers, particular solid-state ones (*2*), allows the very short time dynamics of excitations in semiconductors or chemical reactions to be studied. The device demonstrated by Paiella *et al.* could replace, for some midinfrared spectroscopy applications, the commonly used large pulsed laser systems, which consist of near-infrared solid-state lasers followed by nonlinear optical frequency down-conversion. More importantly, this experiment demonstrates the engineering potential of intersubband transitions. In their experiments, the authors exploited many of their features: quantum cascade laser activity, giant optical nonlinearities, and ultrafast quantum well intersubband detection.

Yet the engineering capability from intersubband transitions is still far from exhausted. It is conceivable that the nonlinearity in the gain medium can be tailored not only to achieve mode-locking, as demonstrated by Paiella *et al.*, but also to generate new frequencies. Direct generation, inside the laser cavity of terahertz radiation is a particularly attractive option because there are very few terahertz sources. In addition, the development of new materials based on nitrides and antimonides would allow the implementation of these concepts at telecommunication wavelengths ($\lambda = 1.55$ μm).

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