RESEARCH: OPTICAL COMMUNICATIONS

Chaos Has Come Again

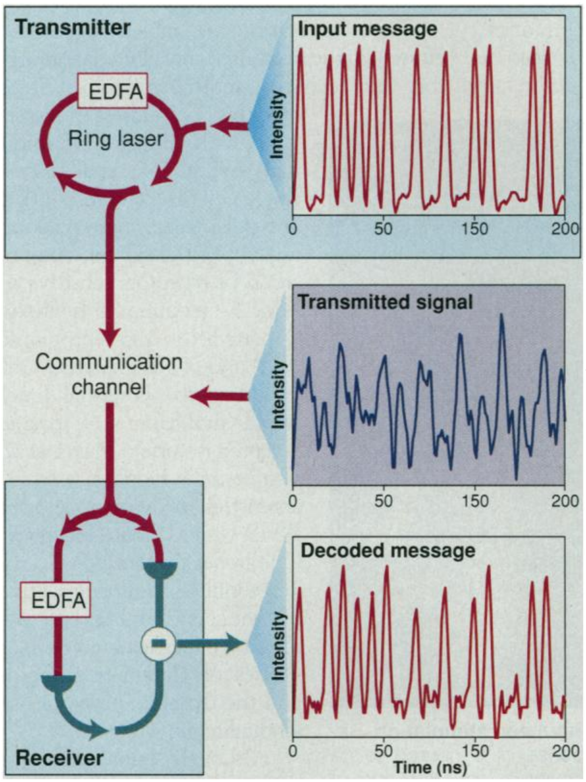
Daniel J. Gauthier

Most laser users would rush to contact their friendly service representative if the intensity or frequency of their high-priced device began fluctuating in an erratic manner. In some cases, what appears to be random behavior is a manifestation of deterministic chaos arising from the fundamental interaction between light and matter. Noise-like fluctuations, a broad optical power spectrum, and extreme sensitivity to initial conditions are hallmarks of chaotic lasers, characteristics that usually limit the performance of the device (1). On page 1198 of this issue (2), VanWiggeren and Roy put a new twist on this story by demonstrating that optical chaos is not bad for all applications: it may be ideally suited for communicating information at high data rates.

VanWiggeren and Roy are members of a nascent group of nonlinear-dynamics researchers who believe that chaos can be harnessed for a variety of applications, many of which are yet to be discovered. This new industry of sorts is based on the discovery that it is possible to control and synchronize chaos in optical as well as biological, chemical, electrical, and mechanical systems (3). Communicating information at high speeds by means of chaos is one step toward realizing the potential of this approach.

Pecora and Carroll (4) first suggested the possibility of modulating messages in a chaotic carrier and decoding them with a properly designed receiver in the early 1990s. In their scheme, a tiny-amplitude message is added to a strong chaotic signal generated by a transmitter before it is sent on its way down the communication channel. This technique offers some level of privacy from eavesdroppers because the tiny message is hidden in the broad, noise-like spectrum of the chaotic carrier. The receiver is an identical subassembly of the transmitter (a collection of a few transmitter components).

The tiny message is decoded by exploiting the fact that the receiver tends to synchronize its behavior to the chaotic part of the transmitted wave form but not to the message. Subtracting the wave form created in the receiver from the transmitted signal yields the tiny message. Soon after their suggestion, Cuomo and Oppenheim (5) demonstrated chaos communication using a low-speed electronic-circuit implementation of the transmitter and receiver; the bandwidth of their system was less than tens of kilohertz. Chaos communication with an electro-optical setup with a potential for high-speed operation has also been reported by researchers at the University of Franche-Comté (6).



Hidden messages. Injecting a message into the transmitter laser "folds" the data into the chaotic frequency fluctuations. The receiver reverses this process, thereby recovering a high-fidelity copy of the message. EDFA, erbium-doped fiber amplifier.

VanWiggeren and Roy (2) have demonstrated data transmission rates of 10 Mbits s^{-1} with the use of an optical setup that has the potential for significantly higher rates. Their transmitter is a ring laser consisting of a commercially available optical-fiber amplifier doped with erbium ions—a mainstay of the commercial optical communication industry—producing chaotic light with a broad spectrum and a center wavelength of 1.53 μm when operated far above the laser threshold.

The message, a 10-MHz square wave, is encoded in the chaotic light beam with a three-step process. First, the intensity of an auxiliary (well-behaved) laser with a similar center wavelength is modulated in proportion to the message amplitude. Next, this modulated beam is injected into the chaotic ring laser with an optical coupler. Injecting the message into the lasers is a much more complex process than just adding the message to the chaotic signal as in the Pecora and Carroll scheme. The message is "folded" into the chaotic fluctuations as it circulates many times around the ring laser. In addition, the chaotic laser and message fields are mixed in a nonlinear fashion as they propagate through the highly saturated erbium-doped optical fiber. Finally, a fraction of ring-laser power is coupled out of the resonator and sent on its way along the communication channel.

They decode the message using an optical generalization of technique originally introduced by Volkovskii and Rulkov for electronic circuits (7). The incoming optical signal is split equally and directed to two separate parts of the receiver. One half is sent to a moderate-speed optical square-law detector whose response is proportional to the intensity of the chaotic fluctuations with the encoded message; the second half is sensed by a similar detector after the beam passes through an erbium-doped optical-fiber amplifier whose properties are precisely matched to the optical fiber in the chaotic transmitter. This identical fiber amplifier in the receiver "unfolds" precisely the message from the chaotic carrier so that a high-fidelity copy of the original message is obtained by subtracting and low-pass filtering the electrical signals generated by the two optical detectors.

In principle, it is possible to communicate information at ultrahigh data rates with the use of this scheme because the spectral width of the ring-laser chaotic fluctuations is very large (of the order of tens of gigahertz). VanWiggeren and Roy realized that the main data-rate limitation in their current setup is the speed of the optical detectors. They suggest that it is possible to subtract the signals in the receiver optically by a heterodyne technique, opening up the possibility of exploiting the full bandwidth of the chaotic fluctuations for modulating

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information. In the mean time, they have modified their setup and can now communicate random bits of information at data rates in excess of 150 Mbits s^{-1} (8) (see figure). The theory for this experiment was developed by Abarbanel and Kennel (9), building on the ideas suggested earlier by Rulkov and Volkovskii (7).

These preliminary but intriguing results suggest that chaos-based applications may be more than just a laboratory curiosity, although substantial research must be undertaken to transfer such discoveries to the commercial sector. For example, the level of security afforded by this scheme and the effects of communication channel distortion and fading must be fully addressed. In addition, nonlinear-dynamics researchers have yet to develop a general, systematic method for designing new nonlinear systems suitable as chaos transmitters and receivers. In light of the interest expressed by corporations and governments in such laboratory demonstrations, I expect that many of these issues will be tackled in the near future.

References and Notes

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CONDENSED MATTER PHYSICS

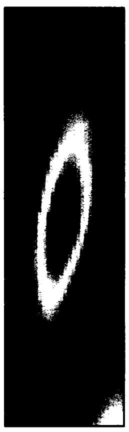
Superconductivity Compatibility

Anthony J. Leggett

Twelve years after the original discovery of superconductivity above 30 K in a cuprate material, and despite its subsequent achievement at temperatures ranging up to 160 K in a vast number of different materials of this class, the mechanism of superconductivity remains as contentious as ever. The cuprates are characterized by the existence of relatively well-separated planes consisting of copper and oxygen atoms (CuO_2 planes), and the general belief is that the electrons which carry the superconducting current reside at least primarily in these planes.

Most current theories of the mechanism are intraplane models, that is, they assume that the essentials can be understood by focusing on the mutual interactions of the electrons within a single CuO_2 plane and that any interplane contact, either by tunneling or through the Coulomb interaction, is secondary. An important exception is the interlayer tunneling (ILT) model of Anderson and his collaborators (1), whose essentials I outline below; this theory is further distinguished from many of its competitors by the fact that it makes at least one quantitative and parameter-free prediction. Two research reports in this issue make important if prima facie contradictory inputs into the debate on the compatibility of this prediction with the experimental data: On page 1196, Anderson (2) discusses the relation of the ILT model to some key superconducting materials, and on page 1193, Moler *et al.* (3) present data on one of the compounds.

In the ILT model, the tunneling of single electrons between neighboring CuO_2 planes (along the *c* axis) in the normal state is postulated to be blocked. (In Anderson's original version of the model, the blockage was caused by the unusual nature of the electron states within each plane, but this feature is not essential to the present discussion.) As in the traditional theory of superconductivity, the onset of this phenomenon corresponds to the formation of Cooper pairs (bound pairs of electrons resembling extended "di-electronic molecules"). However, in the ILT model, the energy saving that drives the formation of the pairs does not come, as in the traditional theory, from an effective electron-electron attraction mediated by exchange of virtual lattice vibrations, but rather from the fact that the pairs, as distinct from the single electrons, can tunnel much more readily between neighboring CuO_2 planes; as a consequence of the uncertainty principle (if perhaps counter to one's initial intuition), the effect of this easy motion along the *c* axis is to decrease the associated kinetic energy and therefore make the formation of Cooper pairs energetically favorable.



Around and around. Image of an interlayer Josephson vortex in $Tl_2Ba_2CuO_{6+\delta}$ [from Moler *et al.* (2)]. The width of the vortex is determined by experimental resolution and so is not of fundamental significance; the height, on the other hand, is a measure of the London penetration depth λ_c.

Now, Cooper pairs tunneling along the *c* axis can carry a supercurrent in this direction, and one might therefore expect that in the ILT model there should be some relation between the "strength" of the supercurrent and the energy that is saved by the tunneling and thus available for pair formation (in other words, for condensation into the superconducting state). This is true; in fact, for single-plane cuprates—that is, those in which all pairs of neighboring CuO_2 planes are equivalent—the model in its current version predicts that the energy of condensation E_{cond} should be directly proportional to the inverse square of the so-called London penetration depth for currents flowing along the *c* axis (usually denoted λ_c): $E_{cond} = A\lambda_c^{-2}$, where the constant *A* depends only on known geometrical factors. A check of this prediction for the various single-layer cuprates should thus constitute a critical test of the ILT model.

In the ideal experiment, a single sample of each known single-plane cuprate would be measured directly for both E_{cond} and λ_c. In real life, for practical reasons, the experiments are usually done on different samples, and of the half-dozen-odd single-plane cuprates currently known, many display a degree of intersample variability, such as to make the result of such a procedure meaningless; in addition, existing measurements of λ_c are often indirect and mutually inconsistent. However, at least three single-plane materials are usually believed to be sufficiently well-characterized and reproducible that intersample comparisons may be legitimate, and moreover may allow relatively direct measurements of λ_c, namely $HgBa_2CuO_{4+\delta}$ (Hg-1201), $Tl_2Ba_2CuO_{6+\delta}$ (Tl-2201), and $La_{2-x}Sr_xCuO_4$ (LSCO), where the oxygen doping δ or strontium dop-

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