ics of its constituents are concerned, "the Universe is an unusual system in that it is very slow to forget its initial conditions." Its large-scale structure is one important result of those initial conditions, and we have only just begun to mine the wealth of information it contains. —DAVID J. HELFAND

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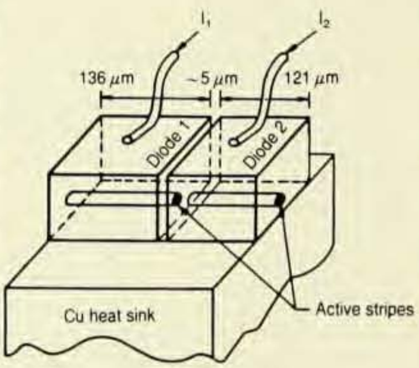
Novel laser for fiber-optic communication

A new kind of semiconductor laser, developed by Won-Tien Tsang and his colleagues at Bell Labs, has demonstrated a number of remarkable capabilities that promise to be of considerable importance for fiber-optic communication. This cleaved-coupled-cavity semiconductor laser, nicknamed the C^3 laser, is able to generate essentially monochromatic pulses of infrared light at repetition rates in excess of a gigahertz. Furthermore, one can electronically switch this pulsed monochromatic output from one wavelength to another on a nanosecond time scale.

In the infrared wavelength regime suitable for long-distance fiber-optic communication (1.3 to 1.6 microns), the pulsed output of conventional semiconductor diode lasers has a wavelength spread of about fifty or a hundred angstroms. This spectral width presents dispersion problems that severely limit the rate of data transmission and the distance over which one can transmit information without reamplification. One is faced with a trade-off. Single-mode silica optical fibers are most transparent at 1.55 microns. But at this wavelength the fibers suffer from considerable dispersion. Different frequency components of the pulse travel at different speeds, eventually washing out the signal structure and thus limiting the rate at which one can send information over long distances. If one chooses, on the other hand, to transmit information at a wavelength of 1.3 microns, dispersion is minimal. But at 1.3 microns the fiber is significantly less transparent, making it necessary to reamplify the signal along its way more often than one would like.

The new C^3 laser, developed by Tsang, Anders Olsson and Ralph Logan, uses[1] a coupled-cavity resonance technique to get rid of all but one of the half dozen or so Fabry–Perot modes that are responsible for the spectral width of a conventional single-cavity diode laser. The result is a pulsed output with a spectral width of less than an angstrom at gigahertz rates of amplitude modulation. With this extraordinarily monochromatic pulsed output one can forget about dispersion and transmit data at a wavelength of 1.55 microns, where the optical fibers are at their clearest. Thus Bell Labs has recently demonstrated[2] the transmission of digital information at a rate of 10^9 bits/second over 104 kilometers of optical fiber, with an error rate of less than 1 in 10^9 and no reamplification along the way. At this rate, Tsang likes to point out, one can transmit the entire text of the *Encyclopedia Britannica* in less than half a second.

This impressive long-distance, high-rate demonstration was done at a fixed



The cleaved-coupled-cavity semiconductor diode laser with which the Bells Labs group demonstrated gigahertz frequency switching in the 1.3-micron wavelength regime. Laser light is reflected back and forth across the 5-micron air gap between the GaInAsP active stripes of the two diodes, so that only the resonant mode common to both cavity lengths is reinforced, producing monochromatic output pulses at gigahertz repetition rates. Fine tuning and frequency switching are accomplished by independently varying the injector currents, I_1 and I_2, in the two diodes.

infrared frequency, with pulse amplitude modulation providing the binary information. But the C^3 laser offers an alternative method of encoding digital data that can enhance the information transfer rate still further. At a gigahertz rate one can switch the output wavelength among as many as a dozen modes spaced about 20 Å apart. Thus, instead of single-frequency transmission with low- and high-power pulses representing binary 0 and 1, respectively, one could simply switch between two frequencies. Switching among four (or eight) frequencies would yield pulses with twice (or three times) the information content of a binary bit.

The cleaved-coupled-cavity laser is made by cleaving a conventional semiconductor diode laser along a crystal plane parallel to its end faces to produce two shorter diode lasers of slightly different length. Starting, for example, with a GaInAsP laser 250 microns long, one might end up with two lasers with lengths of 130 and 120 microns. It turns out, contrary to the pessimistic expectations of many, that the precise difference between the two lengths doesn't matter. One can therefore mass-produce the C^3 laser by conventional fabrication techniques without having to worry about the exact point of cleavage.

Each of these half-length diodes in isolation would behave like a conventional semiconductor laser. Its two end faces would serve as the mirrors of a Fabry–Perot interferometer cavity, supporting only those lasing modes for which the diode's length is an integral multiple of half the wavelength. About half a dozen such Fabry–Perot modes, spaced roughly 20 Å apart, would generate a laser output with a spectral width of more than a hundred angstroms.

The trick of the C^3 laser is to suppress all but one of these modes by coupling the two half-length diodes together optically. The cleaving is done with the original diode fixed on a substrate film, so that the active lasing strips of the resulting short diodes will be precisely aligned, with an air gap of about 5 microns between them. Thus the laser light is reflected back and forth between their active stripes.

Because their lengths are slightly different, the Fabry–Perot mode spacings of the two coupled laser cavities will differ; their lasing modes will not, in general, overlap. If, for example, the lengths of the two diodes differ by 10%, only every tenth Fabry–Perot mode can be the same in both cavities. (Think of a Vernier scale.) The coupled laser system will support only these *common* resonant modes. A lasing mode in one diode that does not correpond to a Fabry–Perot mode of the other will not be coherently reinforced. With common resonant modes thus spaced an order of magnitude further apart than the modes of a single diode laser, the stimulated radiative recombination of electrons and holes in the active lasing medium will generate only a single, monochromatic Fabry–Perot mode in the coupled system.

The idea of coupling laser cavities for single-frequency selection is not new. Herwig Kogelnik and Kumar Patel applied it with a three-mirror system of gas lasers at Bell Labs more than twenty years ago. In 1978, Louis Allen and his colleagues at McDonnell–Douglas achieved single-mode lasing with a cleaved diode laser configuration similar to Tsang's. This single-frequency lasing, however, was reported only for continuous (cw) laser operation, as distinguished from the high-rate pulsed operation necessary for fiber-optic communication. Allen has told us that he had, in fact, succeeded in achieving pulsed single-frequency operation at high modulation rates. But, he explained, this work could not be reported in the open literature at the time, for reasons of commercial and military secrecy.

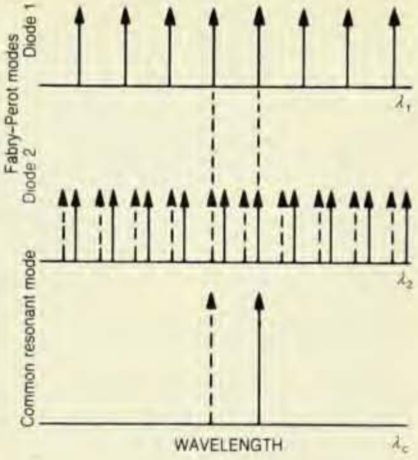
Electrical tuning. The crucial feature that permits the Bell Labs C^3 laser to generate single-mode output in high-rate pulsed operation is the *independent* control of injection current in each of the coupled diodes. The effective index of refraction of a semiconductor diode laser depends on the carrier density, which increases with the imposed injection current. Increasing the current in one of the diodes decreases the internal wavelength of the stimulated emission, thus shifting the Fabry–Perot modes of the cavity.

If one does not have independent electrical control of the refractive indices of the two coupled diodes, the overlap of their Fabry–Perot patterns is fixed by the precise position and orientation of the cleavage, and by the width of the air gap it opens. No practical cleaving technique, Tsang told us, can control these geometric parameters with sufficient precision to assure adequate single-mode coincidence between the two Fabry–Perot patterns. Unless one lasing mode in the first cavity coincides quite precisely with a mode in the second, single-frequency operation will break down in pulsed operation.

The C^3 laser has therefore been designed as a three-terminal electro-optical device, permitting one to control separately the injection current in each diode. Thus electrical fine tuning can easily adjust the effective optical lengths of the coupled cavities to optimize common-mode resonant overlap, compensating for the vagaries of mass production. "We didn't know about the earlier work," Tsang told us. "If we had, we probably wouldn't have tried." The prevailing opinion, he explained, was that the fabrication precision required to make a successful C^3 laser would be prohibitive.

Allen's 1978 coupled-cavity laser had been a two-terminal device, permitting only a common injection current to flow through both diodes. But, he told us, the temperature changes generated by this current did afford some degree of fine-tuning capability.

In 1981, a Bell Labs group led by Larry Coldren developed a three-terminal, coupled-cavity diode laser, using chemical etching rather than cleavage. Last year the group reported[3] that they had achieved single-mode, 1.3-micron pulses of sub-nanosecond duration. Coldren cautions, however, that his device is a high-current-threshold, gain-guided laser—a laboratory device with dimmer prospects for immediate practical application than the index-guided laser of Tsang. Furthermore, he adds, the chemical etching technique produces a less reliable yield of good reflecting surfaces than one gets with cleavage.



Frequency switching in the C^3 laser. The solid arrows in the top two rows represent the wavelengths of the Fabry–Perot lasing modes in each diode. Because their lengths are slightly different, there can be only one mode in the high-gain region common to both diodes. This common mode (bottom row) is the only one reinforced in the coupled-cavity configuration. A small change in the injection current of diode 2 shifts its Fabry–Perot pattern (dashed arrows), producing a much larger shift of the common output mode.

Frequency switching. Separate control of the two injection currents has another crucial consequence. It lets one switch the C^3 laser from one single-mode frequency to another in about a nanosecond. To achieve this gigahertz frequency modulation, Tsang, Olsson and Logan maintain the injection current in one of the coupled diodes above lasing threshold while its coupled partner is kept below threshold to serve as a Fabry–Perot etalon, suppressing all but the one frequency common to both diodes. If one now increases the injection current in the etalon slightly, its Fabry–Perot pattern will shift slightly, yielding a much larger jump in the common resonant mode. If, for example, the Fabry–Perot modes are about 20 Å apart and the two diodes differ in effective length by 10%, one need shift the mode pattern by only 2 Å to get a full 20-Å shift in the frequency of the common mode. (Again it is helpful to think of a Vernier scale.)

By this technique, which they call cavity-mode-enhancement frequency modulation, the Bell Labs group has recently been able to tune a 1.55-micron C^3 laser over fifteen Fabry–Perot modes—a range of 300 Å. The frequency shifting responds very sensitively to the etalon injection current; it requires little more than a milliamp to shift the common mode by 20 Å. Spectral analysis of the output pulses indicates that they remain quite monochromatic and stable even at frequency-modulation rates in excess of a gigahertz.

Replacing the usual binary amplitude modulation of digital fiber-optics communication by four-frequency modulation would double the amount of information carried per pulse. Using only two frequencies, Tsang points out, a C^3 laser can serve as an optoelectronic logic gate, performing the full set of logic operations (and, or, exclusive or, inversion).

Another scheme for exploiting the frequency tuning capabilities of the C^3 laser to enhance fiber-optic digital communication capacity is referred to as wavelength-division multiplexing. One would couple several C^3 lasers to the same fiber, each tuned to a different frequency. They could then transmit several independent messages simultaneously along the single optical fiber. Such a scheme requires stable, monochromatic pulses of a quality that only the C^3 laser has thus far demonstrated. —BMS

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