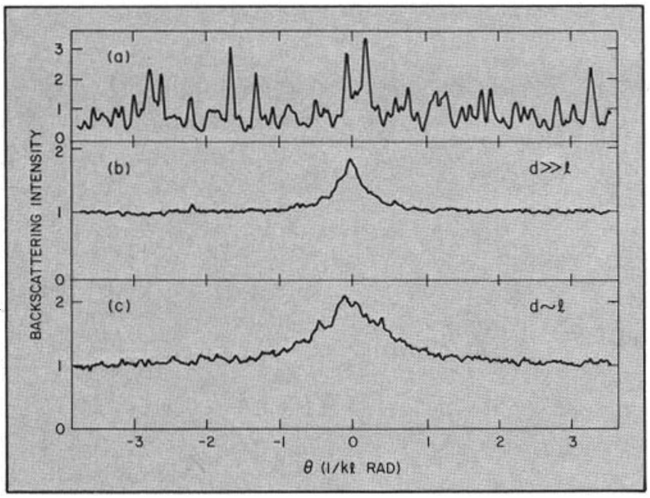

FIGURE 1. (a) Reflected intensity from a rigid network of colloidal silica. The "speckle" reflections from the surface are removed with an isolator.[8] The "sample specific, noise like" trace comes from multiple scattering in the bulk. (b) Ensemble averaging of many traces like (a) by rapidly moving the sample. (c) Backscattering peak broadens as the diffusion becomes quasi-two dimensional.

Recently, researchers have become aware of the existence of rather strict analogies between electron and photon coherent backscattering. Van Albada et al.[5] and Wolf et al.[6] have independently reported experiments that revealed coherent backscattering peaks from dielectric spheres suspended in a fluid medium and have pointed to the close analogy with weak electron localization.

There remains one glaring omission in the experimental studies of photon localization, especially as they mirror the properties of electrons. No one has reported a disordered media, without loss, that scatters sufficiently such that the mean free path for photons will become comparable to the wavelength. Such a medium is required for the strong localization of photons.

Nonetheless, the observation of the photon backscattering peak, the appreciation of the critical role of ensemble averaging, and the rigorous analogy with electron transport in disordered conductors has both broadened and unified our view of wave phenomena in disordered materials.

References

1. A.F. Ioffe and A.R. Regel, Prog. Semicond. **4**, 237 (1960).
2. G. Bergman, Phys. Rep. **107**, 1 (1984).
3. Y. Kuga and A. Ishimaru, J. Opt. Soc. Am. A **1**, 831 (1984).
4. L. Tsang and A. Ishimaru, J. Opt. Soc. Am. A **1**, 836 (1984).
5. M.P. van Albada and A. Lagendijk, Phys. Rev. Lett. **55**, 2692 (1985).
6. P.E. Wolf and G. Maret, Phys. Rev. Lett. **55**, 2696 (1985).
7. P.A. Lee and A.D. Stone, Phys. Rev. Lett. **55**, 1622 (1985).
8. S. Etemad, R.A. Thompson, and M. Andrejco, Phys. Rev. Lett. **57**, 575 (1986).

Tunneling and photoconductivity

FEDERICO CAPASSO
AT&T BELL LABORATORIES
MURRAY HILL, N.J.

Recently a striking new type of photoconductivity based on quantum mechanical tunneling in superlattices has been reported by Capasso et al. The underlying physical cause of this phenomenon is effective mass filtering. Since the tunneling probability of carriers through the barrier layers of a superlattice increases exponentially with decreasing effective mass, electrons are transported through a superlattice much more easily than through the heavy holes. When light is shined on the superlattice, the photogenerated holes essentially remain localized in the wells while the electrons can tunnel through the barriers. Thus the superlattice acts as a filter for effective masses.

This gives rise to a new photoconductive mechanism controlled by tunneling. Since the electron mobility perpendicular to the layers depends exponentially on the supperlattice gain thickness, it follows that the electron transit time, the photoconductive gain, and the gain-bandwidth product can be artificially varied over a wide range. This allows greater versatility in device design than is available with standard photoconductors.

High-performance infrared photoconductors utilizing effective mass filtering were recently demonstrated.[3] The devices, grown by molecular beam epitaxy, consisted of 100 periods of AlInAs (35 Å)/GaInAs (35 Å) between two contact layers and responded to wavelengths in the 1.6–1.0 μm region. These detectors exhibit high current gain (up to 2×10^4) at very low voltage (≤ 1 V), with response times in the 10^{-4} sec range. The low bias operation cuts down on the device noise, which was only $\approx 3 \times 10^{-14}\,\mathrm{Watt(Hz)}^{1/2}$. These are the highest gain and lowest noise photoconductors operating at such low voltage.

Another important advance is the first observation of sequential resonant tunneling through a superlattice.[4] If the quantum wells are weakly coupled (relatively thick barriers), the state of a superlattice is well described by the quasi-eigenstates of the individual wells. Suppose now that a uniform electric field is applied to the superlattice. As the bias is increased, at some point the energy potential drop across the superlattice period equals the energy difference between the first two levels of the quantum well. At this point, resonant tunneling occurs between the groundstate of the nth well and the first excited state of the well, followed by intrawell energy relaxation by phonons.

This process is repeated sequentially through the superlattice. Two pronounced peaks were observed in the photocurrent of a reverse-biased molecular-beam-epitaxy grown p^+in^+ diode. The low-doped i region had 35 periods of AlInAs (135 Å)/GaInAs (135 Å). The voltage position of the two peaks divided by the number of periods (35) gave exactly the calculated energy difference between the first two excited states and the ground states of the quantum wells. This provides direct evidence of sequential resonant tunneling through the superlattice.

There are some potentially important device applications of this effect, including a semiconductor laser, proposed by Kazarinov et al., [5] which will emit in the infrared region of the spectrum, from 5 μm to 10 μm, depending on the well thickness.

References

1. A. Rose, *Concepts in Photoconductivity and Allied Problems* (Wiley, New York, 1983).
2. F. Capasso, K. Mohammed, A.Y. Cho, R. Hull, and A.L. Hutchinson, Phys. Rev. Lett. **55**, 11152 (1986).
3. F. Capasso, K. Mohammed, A.Y. Cho, R. Hull, and A.L. Hutchinson, Appl. Phys. Lett. **47**, 420 (1985).
4. F. Capasso, K. Mohammed, and A.Y. Cho, Appl. Phys. Lett. **48**, 478 (1986).
5. R.F. Kazarinov and R.A. Suris, Sov. Phys. Semicond. **5**, 707 (1971).

Improved calibration standards in laser-Stark spectroscopy

W.H. WEBER
PHYSICS DEPARTMENT, RESEARCH STAFF
FORD MOTOR CO., DEARBORN, MICH.

Two recent developments promise major improvements in both the electric field strength calibration and laser frequency standardization of Stark-tuned Lamb-dip spectroscopy, a technique developed over 15 years ago which has become a widely used tool for high-resolution studies of molecular vibration-rotation spectra.

In its simplest form, Stark-tuned Lamb-dip spectroscopy involves measurement of the absorption of a laser beam in an optical cavity versus the measured electric field strength produced in a Stark cell, in the same cavity, containing the molecule being studied. Narrow resonances (Lamb dips) are observed whenever a molecular transition is Stark-tuned into coincidence with the laser frequency.

In principle, the precision of the measurements should approach the 10-kHz to 20-kHz linewidths obtainable from a typical infrared gas laser, but in practice the precision is much worse. The laser center frequency is often uncertain by several MHz. Since the positions in field strength of the Lamb dips depend upon this frequency, its uncertainty precludes using them for accurately calibrating the electric field strength measurements against known standards such as the oxygen carbonyl sulfide (OCS) dipole moment.

Promising improvement in electric field strength calibration is the discovery of accidental three-level cascade-type double resonances in several ammonia-type molecules: in the 10-μm region of PH_3 (Ref. 2) in the 6-μm region of $^{15}NH_3$ (Ref. 3), and in the 5-μm region of PD_3 (Ref. 4). These resonances are narrow sub-Doppler features that can be characterized as two-photon absorptions with an exactly resonant intermediate state. When observed in an optical cavity, they occur in pairs. One is associated with co-propagating absorption (both photons from one beam), and the other is its counter-propagating partner (one photon from each of two opposed beams).

The co-propagating resonances are particularly significant since they can be observed under single-pass conditions (no cavity) and their resonant field strengths are independent of the laser frequency. In this regard, they are similar to level-crossing and anticrossing resonances seen earlier in the laser-Stark work, but are stronger and narrower and thus more suitable for calibration standards.

A laser-microwave double resonance method has been used to calibrate two of these three-level resonances against the widely-used OCS dipole moment standard.[4,6] Relative accuracies of 10 ppm for the 10-μm PH_3 resonances and 25 ppm for the 5-μm PD_3 resonances were obtained. These exceed the precision of 50 ppm with which the OCS dipole moment is known.

On the laser frequency standardization front, it has been demonstrated that the saturation Lamb dips in an intracavity Stark cell can be used to frequency-sta-