

## NANOLASERS

## Goldfinger laser

Coating a semiconductor heterostructure post with a layer of gold enables electrical pumping of nano-sized lasers. This experimental result could dispel the common belief that metallic coatings are too lossy to make good reflectors for tiny emitters.

## Richard K. Chang

is in the Department of Applied Physics, Yale University, New Haven, Connecticut 06520, USA.

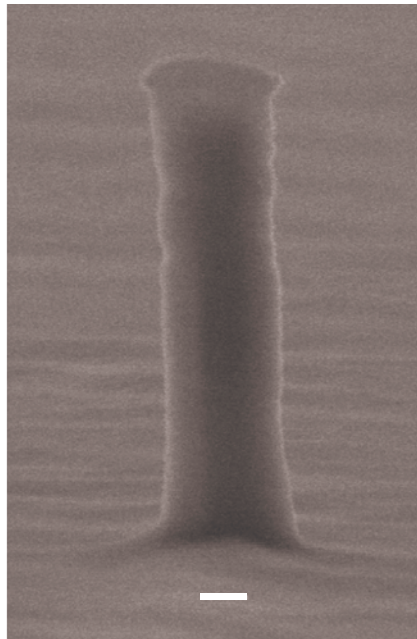
e-mail: richard.chang@yale.edu

**M**artin Hill and colleagues at COBRA Research Institute in the Netherlands and the Korea Advanced Institute of Science and Technology have reported the smallest electrically pumped laser demonstrated so far. On page 589 of this issue<sup>1</sup>, the researchers describe how they encapsulated thin In/InGaAs/InP posts (of various diameters (Fig. 1), where the optimum was found to be 210 nm) with a gold film. The devices lased in the near-infrared at a wavelength of 1,408 nm and featured a low threshold current. This is the first time that an electrically pumped and metal-coated nanocavity semiconductor laser has been fabricated.

The most significant message to other scientists is that metal-coated nanoresonators can have a moderate quality factor ( $Q$ ) for the  $HE_{11}$ -like mode that has a highly localized maximum-intensity distribution. The design provides an excellent overlap between the effective mode volume,  $V_{\text{eff}}$ , and the electrically driven gain region inside the semiconductor. The increased  $Q$  value together with the small  $V_{\text{eff}}$  result in increased radiation rates in accordance with Purcell's seminal prediction, written some 60 years ago<sup>2</sup>. The enhanced radiation rate within the highest-intensity region of the metallic cavity relative to its value in free space is known as the Purcell factor:

$$F_p = (3/4\pi^2)(\lambda_0/n)^3 (Q/V_{\text{eff}}),$$

where  $(\lambda_0/n)$  is the wavelength inside the semiconductor and  $n$  is the index of refraction for InGaAs inside the gold cavity and is equal to 3.4. By using a three-dimensional finite-difference time-domain computer simulation package, the electromagnetic intensity distribution of the semiconductor post with a gold coating was calculated.



**Figure 1** The heart of the nanolaser. An In/InGaAs/InP post prior to being coated with gold. The scale bar represents 103 nm.

Conventional semiconductor lasers are electrically pumped and have sizes in the micrometre range. But for photonics devices to enter the very-large-scale integration arena, basic elements must be submicrometre in size. Semiconductor lasers must also meet the further requirements of low-power lasing threshold and it must be possible to modulate them at high speed. Until now, the optical reflectivity needed for laser operation has come from the interface of two or more dielectric materials. Different examples of reflectivity from dielectrics are included in the following: (1) vertical-cavity surface-emitting lasers, where a series of semiconductor layers form a planar dielectric reflector known as a distributed Bragg reflector; (2) bar-emitting lasers with cleaved ends where the dielectric and air interface act as Fabry–Pérot

reflectors; and (3) microdisk lasers with a high-symmetry shape, such as a disk, toroid or sphere, or the equatorial plane of a sphere with its north pole attached to the end of an optical fibre. In the third type, the optical reflectivity is provided by total internal reflection at the sidewall of the micrometre-sized structure and forms what are known as whispering-gallery modes with  $Q$  as high as  $10^8$ .

Many optical scientists think that metal-coated resonators are too lossy for use as laser reflectors. The important parameter here is the electric permittivity,  $\epsilon$ , which can be expressed in terms of real and imaginary parts as  $\epsilon = \epsilon_1 + i\epsilon_2$ . In the free-electron model,  $\epsilon_1$  is a large negative number and is related to the motion of a single electron in a plasma. In the same model,  $\epsilon_2$  is responsible for irreversible losses to phonons and is created phenomenologically as a viscous parameter in a damped harmonic-oscillator model. Hill and co-workers recognize that  $\epsilon_2$  is associated with electron relaxation involving electron–phonon interaction. By working at low temperatures (10–77 K), the number of phonons will decrease. Hence  $\epsilon_2$  will decrease relative to the room-temperature value, leading to an increase in  $Q$  at low temperatures that enables lasing to occur.

The authors appreciate that instead of gold, silver-coated resonators would have been a better choice for their experiments because silver has a lower  $\epsilon_2$  than gold at room temperature. Replacing gold with silver, Hill *et al.* calculated that the  $Q$  value should improve from 48 to 180. The  $Q$  value could be further increased at a lower temperature.

The challenge ahead is finding a metallic material that has  $(\epsilon_1 + i\epsilon_2)$  values that are appropriate for metallic nanoresonators at any wavelength. To do this, one must look at the band structure of the metals. In particular, let us examine the band structure of silver and gold, which have the following atomic configurations: Ag:  $[\text{Kr}]4d^{10}5s^1$  and Au:  $[\text{Xe}]4f^{14}5d^{10}6s^1$ . The two major contributions<sup>3</sup> to both  $\epsilon_1$  and  $\epsilon_2$  are free electrons making intraband transitions

within the *s*-band and bound electrons making interband transitions from the Fermi level (at the top of the *d*-bands) to the *s*-bands. The free-electron contribution is negative for all frequencies,  $\omega$ , below the plasma frequency,  $\omega_p$ , and obeys the Drude model where  $\epsilon_1 = 1 - (\omega_p/\omega)^2$ : when  $\omega = \omega_p$ , then  $\epsilon_1 = 0$ . The bound-electron contribution is positive and obeys the Lorentz oscillator model. In the case of silver, because of the energy difference between the *s*-band and the Fermi level, there is a near perfect cancellation of the negative and positive contribution to  $\epsilon_1$ . At about 340 nm,  $\epsilon_1$  tends to zero. Often, this is treated as another plasma frequency and the free-electron

model is erroneously applied there. For gold, the separation of the *d*- and *s*-bands is smaller and thus the cancellation of  $\epsilon_1$  is not so perfect leaving it largely negative.

Electron relaxation in the *s*-band contributes to the value of  $\epsilon_2$ . The electrons do not relax by rolling down the parabolic *s*-band, but must obey energy and momentum conservation rules for each downward transition. The only way that the electrons can satisfy these rules is with the absorption and emission of phonon energy and momentum, commensurate with the curvature of the *s*-band. Decreasing the temperature decreases the electron–phonon interaction involving the absorption of

phonons and leaves the emission of phonon processes nearly unchanged. Any decrease in electron–phonon interaction increases the relaxation time and the *Q* value. At telecommunication wavelengths, material engineering might be able to tailor the optimum values for  $(\epsilon_1 + i\epsilon_2)$ . The curvature of the *s*-band could be optimized to have a lower  $\epsilon_2$ . In principle,  $\epsilon_2$  could be minimized along with the ideal  $\epsilon_1$ . The combination of photonics and material science working together could be a real winner.

References

1. Hill, M. T. *et al. Nature Photon.* **1**, 589–594 (2007).
2. Purcell, E. M. *Phys. Rev.* **69**, 681 (1946).
3. Ehrenreich, H. *IEEE Spectrum* **2**, 162–170 (1965).

METROLOGY

# Sampling without synchronization

An electro–optic scheme for sampling the electric field of laser pulses without the need for any synchronization could become a valuable tool for characterizing sources that emit in the infrared and terahertz regions.

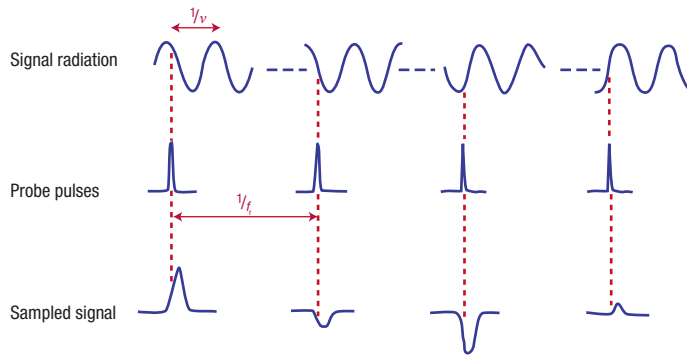
Shunsuke Kono

is at the Nano Electronics Research Laboratories, NEC, 34 Miyukigaoka, Tsukuba, Ibaraki, 305-8501, Japan.

e-mail: s-kouno@cq.jp.nec.com

The spectral region ranging from the mid-infrared to the terahertz (THz) regime is of great interest for spectroscopy of materials, but is hindered by the lack of convenient sources, detectors and analysis equipment<sup>1</sup>. One of the most promising sources of radiation in this region is the quantum-cascade laser (QCL), which is now being commercialized by several firms around the world<sup>2</sup>. However, better tools are urgently required to help analyse the spectral and temporal performance of QCLs and other sources that operate in this regime.

On page 577 of this issue<sup>3</sup>, Peter Gaal and his co-workers have demonstrated a technique that may prove to be a great help. Their experimental method has the potential to measure the emission frequency and time dynamics of a source that emits anywhere between 0 THz and 40 THz by using non-synchronized electro–optic (EO) sampling. The main advantages of the technique are that it can be applied to any wavelength in the terahertz window, can be optimized for a high level of precision and does not require time synchronization between the signal and the probe pulses that make the measurement.



**Figure 1** Schematic representation of the relation between the signal radiation, probe pulse and sampled signal. The electric field of the signal radiation is rescaled at the repetition rate  $f$ , and the sampled signal is used for autocorrelation. Delay of the sampled signal to probe pulses is arbitrarily inserted.  $v$  is the signal frequency.

The study of pulsed THz radiation has become one of the hot topics in spectroscopy, triggered by the invention of the photoconductive (PC) switch<sup>4</sup> and assisted by the development of the mode-locked Ti:sapphire laser. Among the technologies used to investigate this regime, free-space EO sampling is one of the most promising, enabling direct measurement of transients in the electric field in the time domain with a bandwidth as broad as 100 THz (ref. 5).

Electro–optic sampling works by measuring the birefringence in an EO

crystal induced by the electric field of an incident signal beam. The induced birefringence can be measured by detecting the phase shift of probe pulses that mix with the signal beam in the EO crystal. In practice, measurements are made by using a quarter wave plate to split the probe beam exiting the EO crystal into two orthogonal polarization components and then simultaneously measuring their intensities with two identical photodetectors (Senarmont’s method). The difference in the current from the detectors is proportional