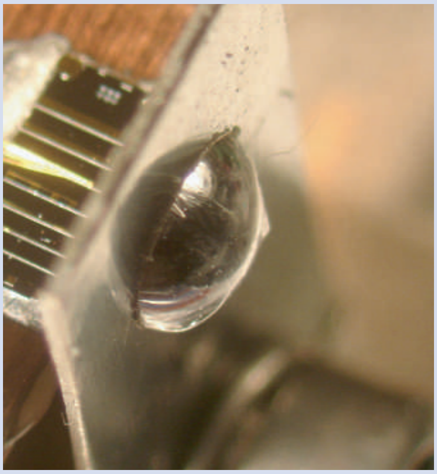
Box 1 A selection of QCL achievements reported at CLEO/QELS 2007

- A US collaboration from labs in Florida, Princeton, Wisconsin and the firm BRIDGELUX reported a narrow-stripe design of high-power QCL that operates at 5.3 µm. At a temperature of 80 K it provides an output of 12 W, peak power, at a drive current of 14 A.

- A team from the universities of Texas A&M, Princeton, Rice and Harvard described a new design of nonlinear QCL that they expect will offer ultrabroad spectral tuning and allow QCLs to reach the 2.5–4-µm window.

- By integrating a hemispherical lens with a terahertz QCL, researchers from the Massachusetts Institute of Technology and Sandia Labs demonstrated a QCL (pictured) that emits up to 145 mW (pulsed at 5 K), 100 mW (pulsed at 77 K) and can operate at lower powers up to a temperature of 160 K.



MIT

A terahertz QCL with an integrated hemispherical lens, just one of the latest results presented at CLEO/QELS by researchers from Sandia and MIT.

- Researchers from the University of Neuchatel in Switzerland reported a QCL that operates at frequencies as low as 840 GHz. The laser is based on a so-called bound-to-continuum lasing scheme that combines high injection efficiency with low intersubband absorption.

- As a strategy to achieve room-temperature operation for a terahertz QCL, scientists from Sandia Labs are investigating optically assisted electrically driven designs of QCL. By recycling pump photons these offer the potential to overcome the Manley–Rowe efficiency limit for QCLs.

window and pulsed powers of a few watts. Much of the increase in performance is down to improvements in growth of the materials."

Indeed, commercial devices with this kind of performance were on display at the CLEO exhibit hall by a US start-up firm called Daylight Solutions, which is targeting applications in gas sensing and spectroscopy. And Daylight isn't the only firm muscling in on the area, Hamamatsu is allegedly about to launch products, although datasheets are still being finalized, and Laser Components, Cascade Technologies and Alpes Lasers are all now offering commercial products, besides others.

According to Williams, the big push now for mid-infrared QCLs is to increase the wall-plug efficiency and create devices with emission wavelengths shorter than 4 µm. DARPA is now sponsoring a research project with the ambitious aim of pushing efficiency figures up from the current level of around 5% to 50%.

At the other end of the spectrum, terahertz QCLs are still a nascent field, confined to relatively low output powers and temperatures, and very much planning catch-up with their mid-infrared cousins. "It took seven years after the first mid-infrared QCL to get the first terahertz QCL," commented Williams. "Today the record temperature for operation is 170 K, and getting up to room temperature is a big challenge."

MODULATION

Plasmons lend a helping hand

Optical modulators typically rely on weak nonlinear light–matter interactions to modulate light with light. But using surface plasmons to excite quantum dots, researchers at the California Institute of Technology have now demonstrated an efficient approach to chip-based all-optical modulation.

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Modulation conveys information by adding a data signal to a signal carrier. Native Americans modulated the flow of smoke to communicate with one another, and telegraphy was made possible by virtue of a modulated voltage, for example in the form of Morse codes. Modulating one light signal with another could be useful for data storage, information processing and communication, but the key to integrated optical modulation is to build a compact, fast device that consumes little power. All-optical modulation has been achieved in the past using nonlinear materials, which require large interaction lengths (centimetres) and high power levels to achieve fast modulation. On page 402 of this issue[1], Dominico Pacifici and co-workers from the California Institute of Technology (Caltech) present a different approach. They exploit the properties of a structured metal surface to demonstrate, for the first time, a compact, low-power and fast (less than 40-ns modulation time) all-optical modulator.

How can light affect light? Various approaches to all-optical modulation have been explored, for example by harnessing the Kerr effect in a silicon polymer waveguide[2], or using photonic circuits on a silicon chip[3]. In a silicon chip, low powers in the picojoule range and fast modulation on the order of picoseconds were reported.

Under ordinary conditions in an optical medium (that is, typically within a linear regime, with moderate power levels and without the use of 'exotic' materials), a photon cannot be used to affect another photon directly, owing to weak photon–photon coupling, which rules out the possibility of modulation. But in the presence of a metal nanostructure, such as a thin film or a grating, the excitation of an intermediary surface plasmon (SP) may enable this light-by-light modulation.

In 1957, Rufus Ritchie at the Oak Ridge National Laboratory (ORNL) in the USA predicted the existence of SPs (ref. 4). Surface plasmons and their associated electromagnetic waves result from collective oscillations of the electrons at a metal–dielectric interface, and researchers have since realized that coupling mechanisms involving SPs could be promising for optical modulation.

Recently, the petahertz capability of SPs, such as fast field enhancement and energy confinement, has garnered interest as a potential means for modulation and thus a way of boosting the information transmission speeds in optical communication systems and computer chips. The concept of SP-assisted optical modulation was first explored by Ali Passian, myself and colleagues[5–7] at the Nanoscale Science and Devices Group of the ORNL. In 2004, we performed experiments in an attempt to change the attributes of one beam of photons using another at the same or a different energy in a pump–probe arrangement. Light-on-light modulation was demonstrated at low rates using coupling to SPs and their associated thermal effects in a thin gold foil. In addition, the ORNL team proposed using SP interference and plasmon standing waves to accomplish high-frequency modulation[6].

As a step along the path to fast, all-optical modulation, Pacifici and colleagues[1] have demonstrated all-optical modulation using SP polaritons (SPPs) and active quantum dots for the first time (Fig. 1). They bring together the electronic properties of CdSe-based quantum dots and the

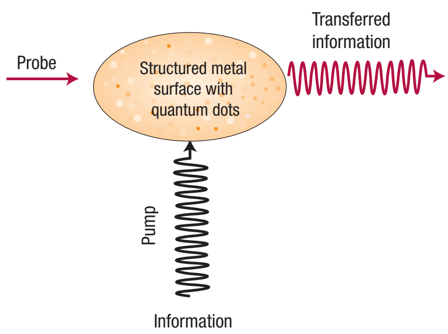

Figure 1 A schematic of the all-optical modulation approach adopted by Pacifici and colleagues[1]. Grooves and slits in a metal surface aid the generation of SPPs from the probe and pump beam, and interaction with the quantum dots modulates the amplitude of the probe SPP.

SPP-launching abilities of a silver film (in which microscale slits and grooves are milled[8]) to achieve high-frequency all-optical modulation. By introducing an abrupt discontinuity, such as a groove, into a metal surface (in this case a silver film), an incident light beam can be coupled to SPs. Grooves are subwavelength scatterers of light and they can provide the momentum needed to couple an incident light beam to an SPP. This is how photons can directly couple to plasmons through subwavelength structures, such as holes, gratings, islands, dimers and other nanostructures. It has been suggested that this effect plays a role in the enhancement (and suppression) of light transmission through subwavelength apertures[9]. Nanoparticle-based structures also offer useful electronic properties. For example, nanoparticles made from CdSe exhibit fluorescence that can be tuned as a function of the particle size.

The Caltech group uses CdSe-based quantum dots that absorb green light but are transparent to infrared waves. The quantum dots are placed between 10-μm-long parallel grooves and slits (with a typical separation of about 3 μm) in a silver film. Diffractive scattering at a groove converts two incident beams into co-propagating SPPs. The quantum dots, with an energy bandgap of 600 nm, are then made to interact with the two co-propagating SPPs. A probe SPP in the infrared range (a wavelength of around 1,500 nm) propagates along the silver metal surface and through the thin film of quantum dots without being absorbed, because its energy is lower than the quantum-dot bandgap. A 'green' (a wavelength of 515 nm) pump SPP with an energy greater than the energy bandgap of the quantum dots can then be used to generate quantum-confined electron–hole pairs (excitons) in the quantum dots. In the presence of the pump SPP, the co-propagating probe SPP can be absorbed by promoting an intraband transition in the quantum dots, that is, by re-exciting the electron to a higher energy level. As soon as the pump SPP is turned off, the probe SPP is no longer absorbed, as the quantum dots quickly (in less than 40 ns) return to their ground state. By externally modulating the control SPP, the team was able to demonstrate a rapid induced modulation in the amplitude of the probe SPP.

In practice, the approach may be seen as being equivalent to a two-arm interferometer, where one of the arms is the quantum-dot-coated path between the groove and the slit in the silver film. The modulated amplitude of the probe SPP determines a change in the interferometer output state ('on' and 'off'). Thanks to the highly confined nature of the SPP field and the large quantum-dot absorption cross-section, Pacifici *et al.* achieve fast (less than 40 ns) all-optical plasmonic modulation at very-low power densities, in micrometre-scale planar devices.

Photons are widely touted as a potential solution to the interconnect bottleneck problem of electronics. But perhaps this work and that of others in the field shows us that SPPs could be important too. Of course, further work is needed to optimize this modulator scheme. One can envisage, for example, stacking the device in a vertical multilayered array and exploiting the planar, compact nature of the device in a three-dimensional way. Moreover, it may be possible to engineer a more CMOS-compatible active medium to replace the quantum dots used at present. If issues such as these can be addressed, SPPs might become an important part of the all-optical modulation landscape.

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