OPTICAL SIGNAL PROCESSING

Hybrid success

Despite two decades of work geared towards improving the nonlinear optical properties of organic molecules, practical organic light modulators have not yet reached the market in large numbers. New organic–inorganic hybrid approaches may revolutionize the field.

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High-speed optical communication and signal processing depend increasingly heavily on devices known as optical modulators. These devices impart information to light beams as they zip through kilometres of optical fibres at the heart of telecommunication and data-sharing networks. When a light wave passes through a modulator, its polarization state, intensity or phase can be changed simply by applying an external electric or magnetic field. These fields can be encoded with information ranging from a single telephone conversation to thousands of channels of high-definition television programmes.

Today's modulators, however, have come up against a problem familiar to modern technology — speed. Current market technology relies on fast-switching lasers or inorganic electro–optic (EO) modulators — which control the light passing through them using electrical signals — based on lithium niobate ($LiNbO_3$), to impart information on optical circuits. Owing to limitations in the EO coefficient of the inorganic materials in these devices (<30 pm V^{-1}) and their large dielectric constants, current modulation speeds are limited to a few gigabits per second. On page 180 of this issue[1], Yasufumi Enami and colleagues from the Universities of Arizona and Washington report an approach that combines organic and inorganic materials to produce high-performance EO modulators. Their work could open doors to the information superhighway (Fig. 1).

The performance of an EO modulator can be expressed in terms of its EO coefficient. Knowledge of this number allows the change in the refractive index of the modulator material, induced by application of an external voltage, to be predicted. For high-speed, broadband applications, a material must have a large EO coefficient that does not depend strongly on the frequency of the applied voltage.

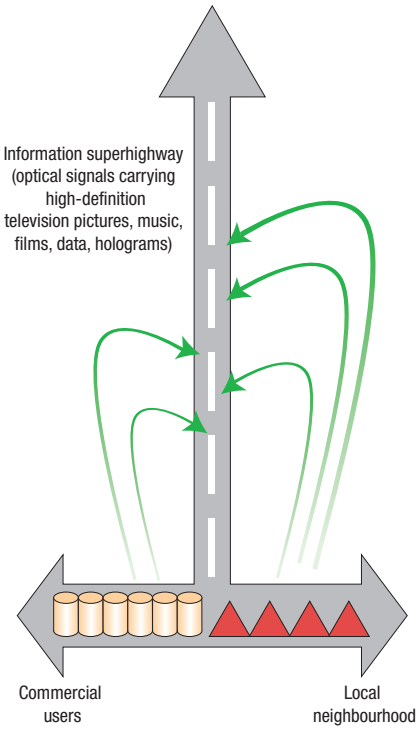

Figure 1 Optical signals are altered by electro–optic modulators as they travel along the information superhighway. By applying an electrical signal to the light beam inside it, an electro–optic modulator can 'encode' the light with all sorts of useful information: phone conversations, high-definition television programmes, music and more. The key is to find an electro–optic modulator that provides that information quickly enough. Enami *et al.* report on a hybrid organic–inorganic waveguide device that might fit the bill.

For 20 years researchers have been working to develop alternative modulators based on organic molecules incorporated into polymer hosts, in the hope that organic systems will offer better EO properties than the benchmark inorganic $LiNbO_3$ modulators. By exploiting the nonlinear optical characteristics of organic molecules, researchers have produced two-dimensional organic–polymer films[2] that exhibit EO coefficients greater than 260 pm V^{-1}, when operating at telecommunication wavelengths (1.3 μm and 1.55 μm). The EO behaviour of such films is also reasonably stable to changes in temperature, with more than 75% of the nonlinearity retained when the films are stored at 85 °C.

Nevertheless, one of the major stumbling blocks in bringing these materials to market has been the successful integration of EO polymer materials into practical devices. For efficiency, simplicity and network-maintenance purposes, modulator waveguides must be coupled to standard optical fibres or other optical interconnects that form part of photonic circuit boards. And for efficient optical coupling at the fibre–waveguide interface, the size and shape of the light beam needs to be similar in both media. Unfortunately, EO polymer waveguides, with their high refractive index and typically very thin structure, give rise to a much smaller and less circular beam profile than is usually found at the output of standard optical fibres, leading to inefficient coupling.

This problem is cleverly addressed by Enami and co-workers who have constructed a hybrid organic–inorganic waveguide instead[1]. Their approach borrows from the best of both worlds: the large nonlinearities offered by an organic polymer layer and the good optical coupling derived from an inorganic sol–gel (catalytic silicon oxide gel) cladding of the waveguide.

In order to induce EO behaviour in an organic molecule and polymer mixture, the polymer composite has to be heated above its glass-transition temperature. The polymer chains

then become mobile enough to allow the organic dopants (chromophores) embedded in the host polymer to rotate under the influence of an applied electric field, thus enabling EO behaviour. This procedure is known as 'poling' as the resulting arrangement of (normally highly dipolar) chromophores is a polar, azimuthally symmetric alignment. After cooling the polymer host back down to room temperature and removing the external field, the molecular configuration becomes 'frozen' in place.

Although this molecular arrangement is not thermodynamically stable, there are ways to reduce the decay of the polar order so that devices can be made to last for several years. What the US team brings to the table are fabrication tricks that boost the stability of the polar order. They introduce a noteworthy self-assembly method — whereby fluorinated and non-fluorinated dendrons provide a molecular-level scaffold that enhances the poling efficiency of the chromophores and increases the temporal stability.

This is not the end of the story, however. Constructing devices from EO polymer composites brings other challenges: namely, how can we preserve the strong EO properties offered by single thin films once those films become integrated into a multilayered waveguide structure? Again, the approach of Enami *et al.* is unique in that they use the high conductivity of the sol–gel cladding to ensure that virtually all of the external poling voltage is applied across the thin EO polymer layer. The result is that the EO coefficients of the hybrid modulator match those measured in thin-film versions of the same materials.

In my opinion, the two major achievements of this work are the near-perfect poling efficiency (due to the conductivity of the sol–gel) and the optical-mode-matching properties of the organic–inorganic structure, which lead to lower device-insertion losses and improved compatibility with optical fibres. The EO coefficient obtained by the team, 170 pm V^{-1}, represents a record for these types of modulators. This record is likely to be broken very quickly now that a prescription exists for translating the high EO coefficients measured in thin films to those obtained in actual working devices.

The question still remains: will these hybrid modulators ever become commercially viable? Other technologies are being developed that may supplant both existing devices and potential EO polymer-based ones, such as direct optical generation, modulation and detection in silicon[3]. In addition, organic modulators face the possibility of light-induced degradation of the chromophores themselves during extended operation. Although careful lattice-hardening techniques and encapsulation methods that prevent the in-diffusion of damaging oxygen molecules can help, they involve extra fabrication roadblocks that must be overcome. However, this is nothing new to those developing EO polymer modulators. Their field has taken a marked turn up in the past few years, witnessing very large increases in EO coefficients (and correspondingly, decreases in the modulation voltages that are needed). This latest work shows that feasible devices may be just around the corner.

References

1. Enami, Y. *et al. Nature Photon.* **1,** 174–177 (2007).
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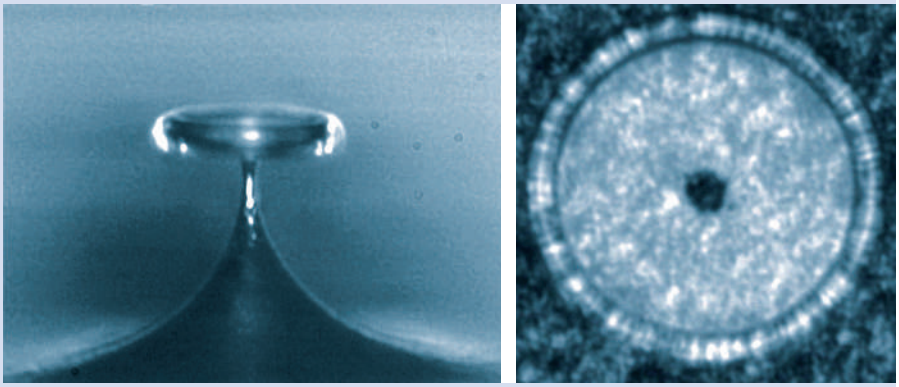
MICRORESONATORS

Optical doughnuts

Portable tiny doughnut-shaped glass structures with exceedingly smooth surfaces and high *Q*-factors of around 30 million have now been made by scientists in California. The 'microtoroidal silica resonators' allow light to circulate around their outer ring with low loss and are potentially ideal for creating high-performance optical filters and exploring cavity quantum electrodynamics (QED) (*Opt. Express* **15,** 166–175; 2007).

Fabricating and handling the 50-micrometre diameter microtoroids is a tricky business. Mani Hossein-Zadeh and Kerry Vahala, from the California Institute of Technology, first deposit a thin disk of glass (2 μm thick) onto a silicon wafer. They then etch away the silicon substrate with XeF_2 to create a small pillar beneath the silica disk. The glass disk is then irradiated with a CO_2 laser beam, which melts its edges, and surface tension causes the glass to flow with exceptional smoothness into a doughnut shape that features a very thin membrane of glass in its centre. Finally, the silicon pillar is etched to a point and the tip of a tapered optical fibre is used to break the microtoroid from the pillar and detach it.



Although detaching the toroid creates a small hole (4–6 μm in diameter) in the central silica membrane, the researchers say that this does not adversely affect the optical properties or *Q*-factor in any way because the light is confined within the ring part of the structure.

As any contamination or physical damage to the microtoroid would degrade its *Q*-factor, the team from Calfornia have also designed and fabricated so-called silica microforks to help make the detachment and handling much easier and safer. As for its future plans, the team is now gearing up to integrate several such microtoroids together on a silicon–silica bench and couple them to waveguides.

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