

like beamsplitters and modulators, will also be highly challenging. But research in this direction will certainly open up these promising quantum systems to nanoscale photonic engineering.

The physics behind Luttinger liquid plasmonics is at an early stage and located at the interface between condensed-matter theory and nanophotonics. As such, it will no doubt be a very fruitful area for researchers in the coming years. For instance, as Luttinger liquid plasmons have resonances in the optical domain they could also be used as elements in quantum-engineered metamaterials. They may even find applications as information carriers

in quantum information processing, as researchers look to miniaturize optical circuitry for building compact and scalable quantum photonic processors^{10,11}. It will also be interesting to see how well these liquid-based waveguides couple to emitter systems, such as quantum dots and nitrogen–vacancy centres, or even use them as emitters themselves¹². There is clearly a great deal of potential for these novel nanophotonic quantum systems. □

*Mark Tame is at the School of Chemistry and Physics, University of KwaZulu-Natal, Durban 4001, South Africa.
e-mail: markstame@gmail.com*

References

- Hoddeson, L., Baym, G. & Eckert, M. *Rev. Mod. Phys.* **59**, 287 (1987).
- Takahara, J., Yamagishi, S., Taki, H., Morimoto, A. & Kobayashi, T. *Opt. Lett.* **22**, 475–477 (1997).
- Gramotnev, D. K. & Bozhevolnyi, S. I. *Nature Photon.* **4**, 83–91 (2010).
- Marder, M. P. *Condensed Matter Physics* 2nd edn. (Wiley, 2010).
- Deshpande, V. V., Brockrath, M., Glazman, L. I. & Yacoby, A. *Nature* **464**, 209–216 (2010).
- Shi, Z. *et al. Nature Photon.* **9**, 515–519 (2015).
- Moradi, A. *Photon. Nanostruct. Fund. Appl.* **11**, 85–88 (2013).
- Kane, C., Balents, L. & Fisher, M. P. A. *Phys. Rev. Lett.* **79**, 5086 (1997).
- Loudon, R. *The Quantum Theory of Light* 3rd edn. (Oxford Univ. Press, 2000).
- Tame, M. S. *et al. Nature Phys.* **9**, 329–340 (2013).
- O'Brien, J. L., Furusawa, A. & Vuckovic, J. *Nature Photon.* **3**, 687–695 (2009).
- Hartmann, N. *et al. Nano Lett.* **12**, 177–181 (2012).

VIEW FROM... SPP7

A colourful future?

As the plasmonics community meets in Jerusalem, the hunt to make it a more practical technology continues. The use of new materials and applications in colour printing could be part of the answer.

Oliver Graydon

Given that plasmonics is widely considered to have been one of the hot topics in photonics in recent years it seems apt that SPP7 — the Seventh International Conference on Surface Plasmon Polaritons — should take place in the summer heat of Israel. The 2015 event, held in Jerusalem from 31 May to 5 June, was chaired by Uriel Levy, from the nearby Hebrew University of Jerusalem, who proudly proclaimed that the conference had managed to attract over 400 attendees and a total of 450 submitted oral papers and posters.

Despite the scientific achievements and progress in the area, a common concern expressed by several leading figures at this year's event was that the field may soon lose its popularity and decline unless some real-world practical applications for the technology are found.

"The only real practical application to date is highly sensitive biosensing and we need to find other applications or the field will start to die," commented a member of the conference's steering committee.

Vladimir Shalaev from Purdue University shared a similar view. "The field has been promising a lot for a long time and it now needs to deliver," he said. Shalaev says that a big part of the problem is the gold and silver materials used to excite plasmonic resonances in the optical region, which have many limitations, beyond just their expense.



O. GRAYDON

The Seventh International Conference on Surface Plasmon Polaritons was hosted in the historical city of Jerusalem from 31 May to 5 June 2015.

"We need to broaden the materials platform for plasmonics beyond silver and gold. The problem is that they have large optical losses in the visible and near-infrared regions, are not tunable and not suitable for integration as they are not CMOS compatible."

Shalaev and his compatriot at Purdue, Alexandra Boltasseva, are exploring the use of alternative materials for plasmonics such as transition metal nitrides (TiN, ZrN or TaN) and doped transparent conductive oxides such as ZnO, AZO, GZO and ITO. The latter have the advantage of lower losses, operating in the near-infrared telecom window, and the potential for tuning their wavelength of operation by controlling the level of doping. At longer wavelengths, in the mid-infrared, there is also a lot of research exploring the use of graphene for plasmonics, largely spear-headed by Frank Koppens and Javier Garcia de Abajo at ICFO in Barcelona.

Interestingly, Arseniy Kuznetsov's Nanophotonics group at the Data Storage Institute in Singapore have turned their back on metal-based systems completely and are now exploring resonant dielectric systems instead.

"There are three major advantages of using high refractive index dielectric or semiconductor nanostructures compared with plasmonics," explained Kuznetsov. "First, very low losses, which can be almost zero in the transparency range of the dielectric material. Second, a strong magnetic dipole resonance that can be several times higher than in typical plasmonic systems and third, the possibility to work with CMOS-compatible materials such as silicon."

Kuznetsov says that his team is now working to design and develop workable nanophotonic devices for industry. “I believe that resonant dielectrics, in contrast to plasmonics, have a strong chance to reach real-world industrial applications in the very near future,” he told *Nature Photonics*. “The key features will be very low losses and CMOS compatibility.”

Despite all the high-level research into plasmonics for integrated optics and optoelectronic devices such as nanoantennas, waveguides, detectors and modulators, it seems that the application closest to fruition and commercialization in the near term may actually turn out to be a strikingly simple and visual one. The answer is pigment-free decorative labels and security marks that exploit the structural colour associated with plasmonic resonances.

Anders Kristensen from the Technical University of Denmark gave a talk entitled Nanoplasmonics for Structural Colours

on Consumer Products, during which he explained that the automotive industry in particular is interested in new types of visual surfaces, which could be very robust, visually striking and easy to manufacture. Working with Levy and the Israeli firm Nanonics Imaging, the team has developed thin plastic foils that feature metallic nanostructures to provide colourful, scratch-resistant labels. In Germany, the company Louisenthal is developing similar structural colour films for use in ambient light conditions with the prerequisite that the fabrication approach must be scalable to large areas and suitable for cheap mass production. In both cases, arrays of silver or aluminium nanostructures on the scale of a few hundred nanometres in size are embedded into a plastic film.

Joel Yang from IMRE in Singapore described how plasmonics based on metal nanostructures can overcome some of the limitations of conventional colour printing

such as limited resolution, the fading of dyes and misalignment errors when printing with multiple colours. In contrast, he says that a plasmonic-based approach allows you to “print colour at the diffraction limit of light” and reach a resolution as high as 100,000 dpi. He’s now looking at the possibility of colour mixing using different sizes of several nanostructures within a single pixel and says that he has switched from using silver to aluminium as it is much cheaper and CMOS compatible. “We’ve been talking to companies about applying marks to plastic bank notes or gold coins in order to improve their appearance.”

Perhaps, if these printing applications take off, plasmonics will continue to have a colourful future after all. □

*Oliver Graydon is at Nature Photonics, The Macmillan Building, 4 Crinan Street, London N1 9XW, UK.
e-mail: o.graydon@nature.com*

PHYSICS

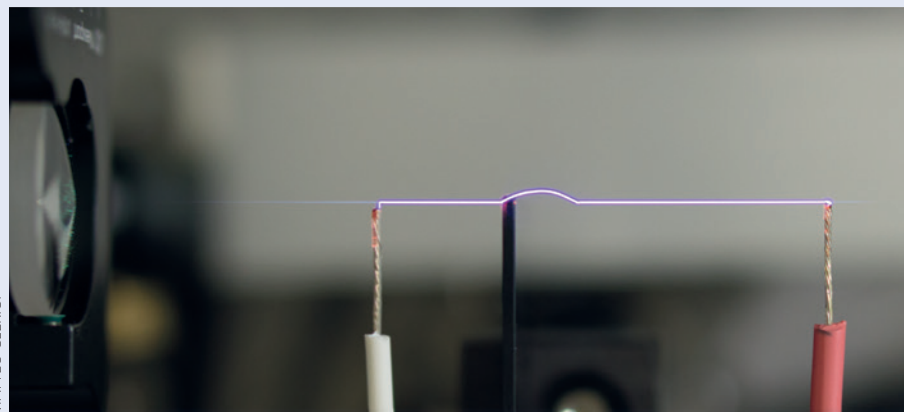
Laser-guided sparks

Electrical discharges are widely used in applications such as electric welding, micromachining and fuel ignition in combustion engines, to name just a few examples. Despite their ubiquity, the ability to control and shape the exact path of a discharge along a specific trajectory remains a significant challenge. Now, Matteo Clerici and colleagues from Canada, the UK, China, France and the USA have shown that specially shaped laser beams can perform this feat (*Sci. Adv.* **1**, e1400111; 2015).

Three kinds of beam shapes — a standard Gaussian beam, a Bessel beam and an Airy beam — were investigated in the study. All beams were produced by an amplified Ti:sapphire laser system and sent between two wire electrodes. The beams were 10 mm in size (full width at half-maximum), featured an input energy of 15 mJ and were pulsed with a pulse duration of 50 fs.

The concept of the scheme is to use the laser pulses to ionize the air between the electrodes and create a preferred path for a discharge, which is created by applying a high voltage (nearly 15 kV over a 5 cm gap) between the electrodes.

The Bessel and Airy beams were able to create well-defined discharge paths (pictured), whereas in the case of the Gaussian beam the trajectory of electric



MATTEO CLERICI

discharges is heavily disordered and effectively unpredictable.

The differences in behaviour are thought to be due to the different electric field strength of the beams. The central high-intensity peaks of the sub-diffractive Bessel beam and Airy beam were $\sim 7 \mu\text{m}$ and $\sim 20 \mu\text{m}$, respectively, considerably smaller than the diameter of the Gaussian optical filament ($\sim 50 \mu\text{m}$). The international team further investigated the electric breakdown for the three cases and observed that the breakdown field was 3.5 and 10 times lower for the cases of the Airy and Bessel beams, respectively.

Surprisingly, the team found that laser-guided discharge could take place

even when the laser beam encountered an obstacle between the electrodes (pictured). In the cases of a Bessel-type and an Airy-type propagation, the beam restored itself after the obstacle and the electric discharge occurred along an almost unaffected trajectory.

According to Matteo Clerici, one of the authors of the study, the next challenge is to find the limits of this technique. Two questions that he says need answering are: “How much can we bend a discharge and how high is the current we can transport in a controlled way?”

NORIAKI HORIUCHI