From a practical point of view, an important question is how much investment is needed to incorporate quantum-enhanced techniques into today's telecommunications systems. The cost of constructing devices capable of operating at the quantum limit must be balanced by the benefits of increased transfer rates. It would be premature to predict how quickly the development of this technology will progress. What is certain, however, is that sooner or later optical communication will approach the performance limits defined by quantum mechanics. We are already getting prepared for the ensuing challenge, while at the same time gaining fascinating insights into the physical foundations of modern information technologies. ❒

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VIEW FROM... FRONTIERS OF PLASMONICS

The new facets of plasmonics

Quantum plasmonics, Fano resonances, surface plasmon–polariton Airy beams and plasmon-enhanced Raman spectroscopy are some of the new aspects of plasmonics that are now being explored.

Noriaki Horiuchi

Using nanostructures to control surface plasmon–polaritons (SPPs) opens up important new avenues for interdisciplinary research in the field of plasmonics. Plasmon resonance biosensors and tip-enhanced Raman spectroscopy — well-known examples of such interdisciplinary work — demonstrate one of the main advantages of SPPs: their ability to achieve electric field localization within an area smaller than the wavelength of the probe beam. However, SPPs are also endowed with a range of other properties that are yet to be fully explored in photonics research. Such new and intriguing properties were the primary focus of the Second International Conference on Frontiers of Plasmonics (FOP2), which was held on 8–12 April 2012 at Sichuan University, Chengdu, China.

Quantum plasmonics, although long a subject of interest to researchers in the field of plasmonics, has proved difficult to observe owing to surface–ligand interactions and inhomogeneity in ensemble measurements, which blur the plasmon resonance spectrum. Jennifer Dionne from Stanford University in the USA reported experimental results on the quantum plasmon resonances of ligand-free silver nanoparticles. The key success demonstrated by Dionne and co-workers was the simultaneous measurement of aberration-corrected transmission-electron microscope (TEM) imaging and monochromated scanning TEM electron energy-loss spectroscopy. She presented a direct correlation between a particle's geometry and its plasmon resonance, in which decreasing the nanoparticle diameter


NORIAKI HORIUCHI

More than 150 attendees from 17 countries gathered at the 2nd International Conference on Frontiers of Plasmonics.

from 20 nm to 2 nm caused the plasmon resonance to blue-shift from 3.3 eV to 3.8 eV. However, for a particle with a diameter smaller than 10 nm, the results presented a substantial deviation from the numerical simulation, which is based on conventional SPP theory. "This deviation is due to a change in particle permittivity. The analytical quantum-mechanical model well-describes the plasmon resonant shift," Dionne explained to *Nature Photonics*.

Javier Aizpurua from the Spanish Council for Science Research presented a number of theoretical examples in which quantum plasmonics could result in a conductive contact between the two arms of a gap antenna. "The classical description, which is an abrupt change of the electron density at the surface, is no longer valid for calculating optical response of a gap antenna with subnanometre arm-separation distance. A quantum description, which involves modelling how the electrons spill out at the surface of the metal, seems more accurate," explained Aizpurua. The problem with the full quantum-mechanical description is that performing the necessary calculations for every electron involved in the optical response of a standard plasmonics system is beyond the capabilities of today's computers, he added. Aizpurua therefore proposed a new technique for calculating the quantum effect based on parametric inputs derived from simpler classical calculations, the validity of which he also examined.

Another exciting subject discussed at the conference was Fano resonances, which result from interference between excitation modes. The line shape of a nanoplasmonic resonance can be tuned by appropriate design of the nanostructures used to control the SPPs. One particularly interesting aspect of Fano resonances is their potential for line-shape narrowing, which could enable new kinds of highly sensitive optical nanobiosensors. Peter Nordlander from Rice University in the USA highlighted a number of recent applications that employ Fano resonances. Stefan Maier from Imperial College London in the UK described his group's theory of Fano interference, which provides a parameter-free description of the resonance by adapting Fano's original formalism to cover the case of a plasmonic nanocavity. According to Maier, their theory enables cavities to be designed with a desired modulation depth at the Fano resonance and provides an understanding of how such resonances arise in complex cluster systems.

Tao Li from Nanjing University in China discussed the potential of SPPs to act like light waves. He presented his research on the development of a new non-perfectly matched in-plane diffraction technique and the experimental demonstration of an SPP Airy beam, whose intriguing characteristics include being non-diffractive, non-dispersive, self-bending and self-healing. The device used in this work was a silver nanocave array fabricated on an SiO_2 substrate. The in-plane propagating SPP wave was generated from the grating coupling of a HeNe laser. The position of the nanocave was gradually changed from 420 nm to 780 nm in the propagating direction while remaining periodic in the vertical direction. A leakage radiation microscope was then used to observe the electric field distribution of the propagating SPP Airy beam. "The important thing for the generation of SPP Airy beam is the graded array of nanocaves," explained Li. "This allows the incident beam to diffract in a direction determined by the local lattice parameters. This phase evolution in turn manifests as a gradual change in the diffraction direction." Li has already explored the potential applications of SPP waves. According to him, the phase modulation method used for the SPP Airy beam can, in principle, be used to generate any form of SPP beam at will. Li and co-workers were able to demonstrate broadband SPP focusing and a plasmonic device that implements wavelength-multiplexing division. "We expect our method to fulfil the requirements of many plasmonic function elements for in-plane integration," explained Li.

The topic of surface-enhanced Raman scattering (SERS) was as popular as ever. Around one-sixth of the presentations at the conference were relevant to SERS. Zhong-Qun Tian from Xiamen University in China described the dependence of the SERS enhancement factor on the particular facet of the metal sample. The electromagnetic field supported by a localized SPP is very sensitive to the specific dielectric complex function of the metallic materials. Tian found that the dielectric functions of different metal facets, although only slightly different, are clearly observable in plasmon-enhanced Raman spectroscopy (PERS). "The enhancement factor of PERS along Au [001] is 30–50 times larger than the other two zones, [1$\bar{1}$0] and [01$\bar{1}$]," Tian explained. This facet-dependent PERS features could potentially be used to study chemisorptions and heterogeneous catalysis on these facets. Tian and co-workers anticipate a growing emphasis on the direct detection and identification of analytes through vibrational fingerprinting.

The areas discussed at the conference — quantum plasmonics, Fano resonances, SPP Airy beams and the facet-dependent features of PERS — help to explain some of the novel optical features of plasmonics at subwavelength scales. The next Frontiers of Plasmonics will be held in Xiamen, China, in 2014. ❐

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