Nanoplasmonics

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The Nanoplasmonics team aims to investigate loss mitigation through plasmonic nanostructures with gain media, miniaturisation through advanced super-resolution all optical lithography techniques, and enhanced nonlinearity using materials whose optical response is a function of light intensity. We also aim to develop the fabrication tools to enable the realisation of Functional Metamaterials.

Our vision is to develop three- and two-dimensional nanoplasmonic structures with gain, high nonlinearity and polarisation sensitivity. In particular we aim to:

- Develop super resolution optical techniques allowing for nano fabrication,
- Gain physical insight into the localised field interactions in non-homogeneous nanostructures,
- Enhance the nonlinear response of optical materials,
- Provide polarisation manipulation, and
- Include gain and exploit nonlinearity.

Progress

The 2011 milestones for Nanoplasmonics were:

1. Fabricate nanoplasmonic structures in two- and three-dimensions with resolution of 50 nm.
2. Study electro-magnetic interactions in hybrid plasmonic nanostructures.
3. Fabricate a metallic nanostructure through electro-deposition.
4. Infiltrate nano-diamonds into nanoplasmonic structures.

Highlights

λ/12 feature size achieved with super-resolution photoinduction-inhibited nanofabrication (SPIN)

In collaboration with CSIRO we demonstrated patterning with resolution approaching 50 nm using the newly developed super-resolution photoinduction-inhibited nanofabrication (SPIN) technique [1]. This technology enables the rapid prototyping of two- and three-dimensional structures with resolution well below the diffraction limit. It offers an all-optical alternative to optical beam lithography, which has a diffraction-limited resolution equivalent of λ/2.

By photo-generating inhibitor radicals in a highly photosensitive photoresist, we realised [1] a feature size of λ/12 (40 nm) for dots fabricated on cover slips in single-photon SPIN.

Adaptation of the SPIN approach to 3D requires simultaneous photoinitiation and photoinhibition. By developing a suitable two-photon photoresist, we made the first demonstration of the SPIN technique using the two-photon absorption process, with state of the art in the fabrication of dots and suspending lines. A femtosecond pulsed laser beam at a wavelength of 800 nm initiated the polymerisation and a CW laser beam at a wavelength of 375 nm activated the inhibitor.

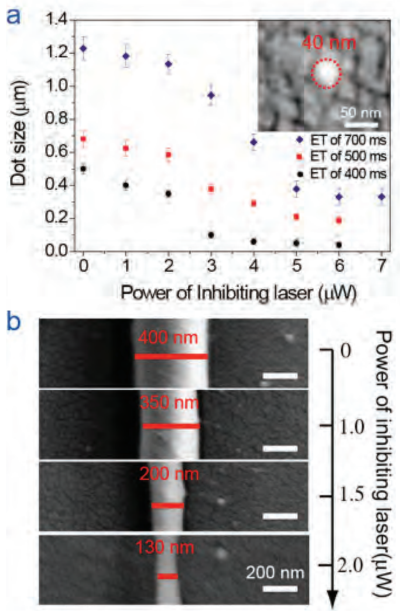

Fig. 1 (a) Dot sizes are plotted as a function of the power of the inhibition laser and SEM image of the dot fabricated with the exposure of the initiating laser and the inhibiting laser beams at the power levels of 200 nW and 6 μW, respectively, at the exposure time of 400 ms. (b) SEM images of lines fabricated with different power levels of the inhibiting laser, at a fixed scanning speed of 3 μm/s, and under the irradiation of initiating laser beam of 200 nW.

Generation and interference of non-diffracting Airy plasmons.

The emerging field of plasmon optics - the manipulation and engineering of plasmon beams – is motivated by applications in bio-sensing, particle manipulation and photonic circuitry. We generated self-accelerating Airy surface plasmons with non-diffractive propagation over a parabolic trajectory. Due to their unusual self-bending and self-healing properties, Airy plasmons open new opportunities for selective on-chip manipulation of nanoparticles, optical sensing, and plasmonic circuitry.

We produced the Airy wave using a diffraction grating with the phase and amplitude modulation required to couple light from free space to surface plasmon-polaritons. The grating was fabricated on 150 nm gold film deposited on a glass substrate and illuminated by a laser beam. The distribution of the field near the metal interface was mapped by a Scanning Near-Field Optical Microscope. We observed Airy plasmon beams to exhibit self-acceleration (bending) during the propagation and self-healing after passing through surface defects.

These results were published in Physical Review Letters [2] being highlighted on the cover of the issue, and featured in Viewpoint in Physics [3]. The results were also included into the article published in a special end of year issue Optics in 2011 of Optics and Photonics News [4].

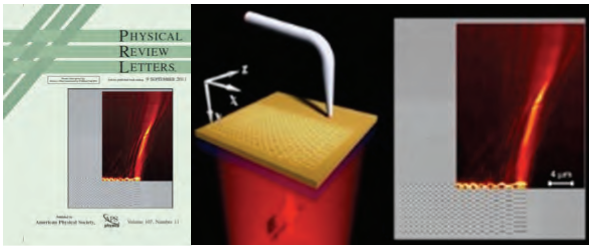

Fig. 2. The impact of this research was recognised by Physical Review Letters who ran the article as there cover story for volume 107, number 11.

Generation of λ/12 nanowires in chalcogenide glasses

During the year we made nanowires in nonlinear chalcogenide films. This ground-breaking work [5] opens possibilities for active nanoplasmonic interconnects for the next generation of all optical circuits in CUDOS. We fabricated nanowires of dimension of λ/12 (<70 nm) in arsenic trisulfide (As_2S_3) films with all-optical direct laser writing (DLW) by careful optimisation of the laser pulse train rate. This had a significant impact on the structural modifications of the chalcogenide films at the focal spot, which in turn affects the nanofabrication inside the glass.

The successful generation of nanowires allows the footprint of the future photonic chips to be reduced significantly. The fabrication method used is laser direct writing, a flexible method that can be adopted for up-scale fabrication. The nanowires are made of a nonlinear chalcogenide glass, which is key to the fabrication of all-optical signal processing devices. The strength of the nonlinear response is significantly enhanced because of the nanoscale confinement, enabling reductions in the size of the photonic devices.

We received wide spread media coverage locally in The Age [6] and COSMOS magazine [7] and internationally though web based newsfeeds culminating in over 200 individual articles.

Three-dimensional linear and nonlinear chiral lattices

Chiral networks display circular dichroism and optical activity, effects impossible to achieve in any two-dimensional structure. Direct laser writing (DLW) can generate 3D chiral lattices in a single step. We fabricated a series of biomimetic chiral microstructures inspired by a recent finding in butterfly wing-scales [1] showing cubic symmetry as well as chirality, with strong circular dichroism due to the chirality of the three-dimensional (3D) network.

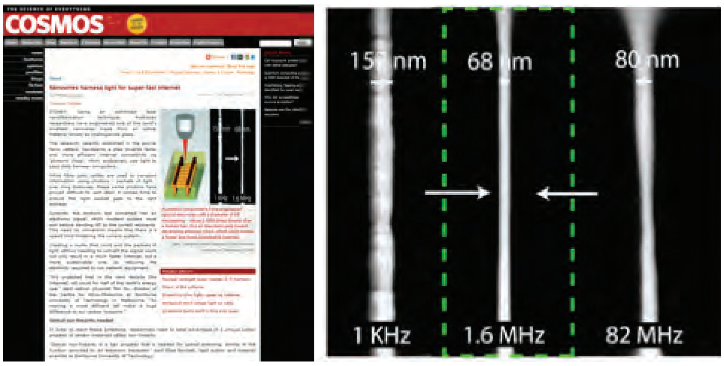

Fig. 3 (a) COSMOS magazine story covering the realisation of nanowire in nonlinear materials [7]. (b) SEM image of nanowires fabricated under different laser repletion rates showing an optimal resolution of 68 nm at a repletion rate of 1.6 MHz.

Nanoplasmonics Continued

We introduced a novel galvo-dithering method to transform the normally elongated fabrication spot to a more spherical one. This leads to a huge improvement in the fabricated microstructure as seen in Fig. 4a-c, with small (1.2 µm unit cell sizes) complex 3D microstructures with a photonic bandgap in the telecom wavelength band of 1.55 µm (see Fig. 4d).

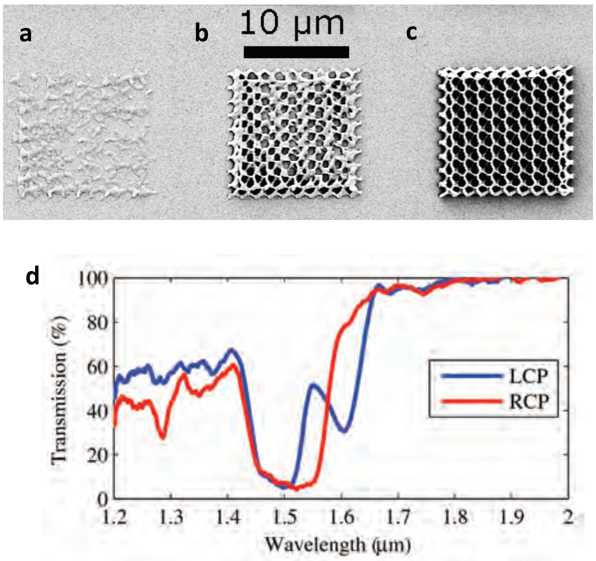

Fig. 4. Fabrication of 3 polymer chiral Gyroid srs-networks of unit cell size 1.2 µm. a) No galvo-dithering is used - the structure is mechanically weak. b) A small dithering is used, with small improvement in structural integrity. c) The correct amount of dithering is used greatly improving structural integrity and optical quality. d) Experimentally measured transmission spectra of the improved Gyroid srs-network, for left (blue) and right (red) circularly polarised light.

These 3D chiral microstructures can also be realised via direct laser writing in highly nonlinear materials such as chalcogenide. The technique suffers from optical aberration which introduces unwanted distortion, resulting in mechanically unstable, non-uniform structures (Fig. 5). Aberration compensation can be used to counteract the spherical aberration, permitting fabrication with near diffraction limited performance throughout a large depth of material. We collaborated with Innsbruck Medical University and the University of Oxford to demonstrate aberration-free fabrication in lithium niobate using this technique. We used a liquid crystal spatial light modulator [8] to correct for spherical aberrations introduced from a refractive-index mismatch associated with the high refractive-index of $LiNbO_3$.

Following this work, we investigated dynamic aberration compensation in thick arsenic trisulfide (As_2S_3) films. Unlike $LiNbO_3$ crystals, the As_2S_3 films act like a negative photoresist that can be etched out after irradiation, leaving a hollow structure suitable for metallic coating. The first aberration-free chiral network structures in this nonlinear material were fabricated in late 2011. The structures displayed strong circular dichroism and showed dramatic improvement in mechanical strength and optical properties once aberration compensation was applied.

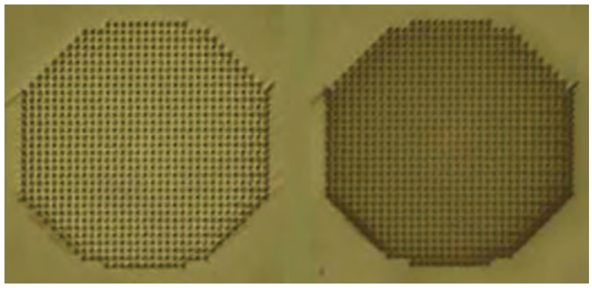

Fig. 5. Chiral networks fabricated in As_2S_3 without (a) and with (b) compensation of the refractive-index mismatch aberration.

Generation of an axial super-resolved quasi-spherical focal spot using an amplitude-modulated radially-polarised beam

One of the main challenges in 3D optical microscopy is to overcome the axial elongation of the point spread function (PSF). Several methods based on linearly polarised incidence have been proposed. A shaded-ring filter to modulate the amplitude distribution is preferred, but it is lossy (~20% in power efficiency) and laterally asymmetric.

We demonstrated an axial super-resolved quasi-spherical focal spot with 65% power efficiency using an amplitude-modulation filter combined with a tightly focused (NA=1.4) radially polarised beam. This resulted in a 34% improvement in aspect ratio and 18.5% enhancement in axial resolution [9] compared with results without amplitude-modulation (Fig. 6).

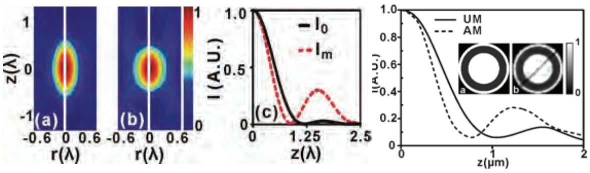

Fig. 6 (a), (b) Calculated electric field density distributions in the focus for unmodulated (I0) and amplitude-modulated (Im) radially polarised beams using the vectorial Debye theory. (c) Cross sections of the focal spots in the axial direction as marked in (a) and (b) with the white lines. r and z are coordinates normalised by the wavelength of the incident beam (d) Measured axial responses for unmodulated (UM) and amplitude-modulated (AM) radially polarised beams. Inset a: Designed amplitude modulation pattern. Inset b: Measured intensity distribution of the generated amplitude modulation measured by a wavefront sensor.

Near field surface plasmon characterisation

We are developing near field scanning optical microscope techniques for observing surface plasmons. In collaboration with Dr James Downes at Macquarie we fabricated planar gold waveguides on planar and opal substrates for characterisation of surface plasmons using the Otto prism-coupled geometry. We observed surface plasmon resonance with gold coated polystyrene opals, which behave as 2D diffraction gratings. Images of the opals taken by white light profilometry and atomic force microscopy show individual microspheres (size approx.. 670 nm) in Fig. 7.

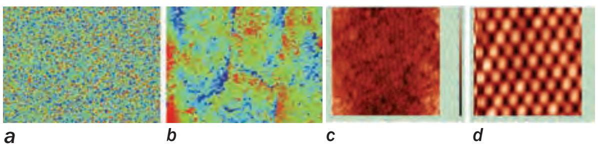

Fig. 7. White light interferometer image of silica (a) and polystyrene opals. Atomic force micrograph of silica (c) and polystyrene (d) opals

Future Directions

The following milestones have been identified for 2012:

Building on the successful demonstration of nano structuring of polymers on surfaces, we will extend this cutting edge research to two- and three-dimensional patterning, focusing on demonstration of nanoplasmonic functionality.

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Project Leader

Michael James Ventura received his PhD in the field of passive and active three-dimensional photonic crystals in 2008 at Swinburne University of Technology. His research interests include micro-photonic and nanoplasmonic device with applications to signal processing and imaging. Pioneering the development of void direct laser writing as well as novel micro and nano photonic devices at infrared wavelengths, Michael is now a postdoctoral fellow at the Centre for Micro-Photonic at Swinburne University. In 2010 Michael received a Vice Chancellor's Early Career Research Award for his contributions to the field of photon manipulation using periodic media.

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