Bangor Superlens Team (BST)

The group focuses on dielectric superlens research and had developed one of the most powerful white-light nanoscope system in the field, featuring 45 nm resolution under white lighting for super-resolution imaging, sensing, diagnostics and nanofabrication applications in both material and biomedical fields.

The group also carries out research into metamaterial and nanophotonics, developing state-of-the-art anti-laser striking device for wide-angle laser blocking device, laser material processing and cleaning of various industry samples (e.g nuclear materials, optical components, packaging material), developing super-resolution 3D metamaterial printing device based on its unique superlens technology.

1) First generation dielectric superlens: microsphere superlens [1a]

First demonstrated in Nature communication paper [1a] using 5 um Silica bead (2um <diameter < 9 um), with 50 nm resolution under conventional white light illumination. Later, super-resolution (~100 nm) was also demonstrated for larger particles size using 20-80 um sized $BaTiO_3$ particles when they were immersed in a water or PDMS medium [1a2].

The microsphere superlens works in combination with a conventional microscope objective lens, typically 50-100x magnification with Numerical Aperture> 0.6, forming virtual compound lens. The main mechanism includes two: (1) subwavelength focusing by microsphere bead, a phenomena known as 'photonic nanojet (PNJ)' within scientific community. PNJ first publication by Lu and Boris Luk'aynchuk from Singapore when studying laser cleaning problems [1b], PNJ terminology was coined later in 2004 by American scientist [1c] (2) PNJ near-field coupling with nanoscale objects causing super-resolution information transferred to far-field [1d].

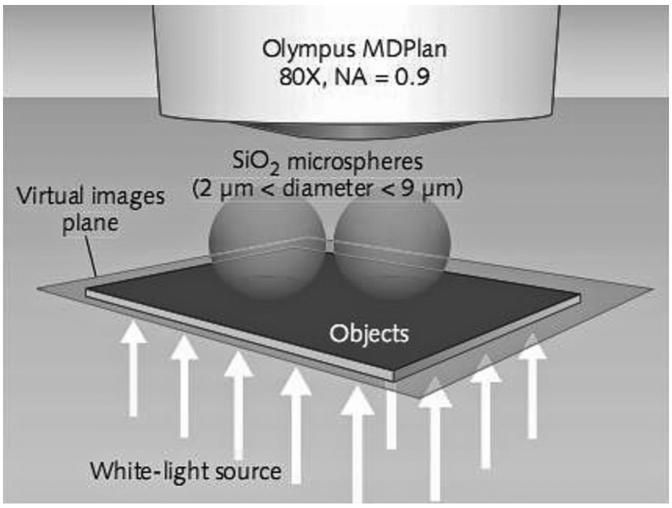

Figure 1: A schematic shows a white-light microsphere nanoscope (a microsphere superlens integrated with a classical widefield optical microscope) with 1/8 imaging resolution. The spheres collect the near-field object information and form virtual

images that are then captured by the conventional lens.

Experimentally, it requires the microsphere lens in close proximity of imaging objects, best resolution achieved in particle-substrate contacting mode.

A useful review on first generation technology can be found in [1d], where it contains many related information. Also a useful magazines article on the first generation technology I written long time ago, can be found in [1e]

2) Development of commercially viable scanning superlens nanoscope system

The microsphere superlens has small sample viewing window, typically a quarter size of the microsphere diameter. For imaging a large sample, the particle lens requires being physically integrated with conventional objective lens, and scanning over the whole imaging area. The group filed a patent on the first generation scanning particle lens system [2a] and published its working prototype in paper [2b].

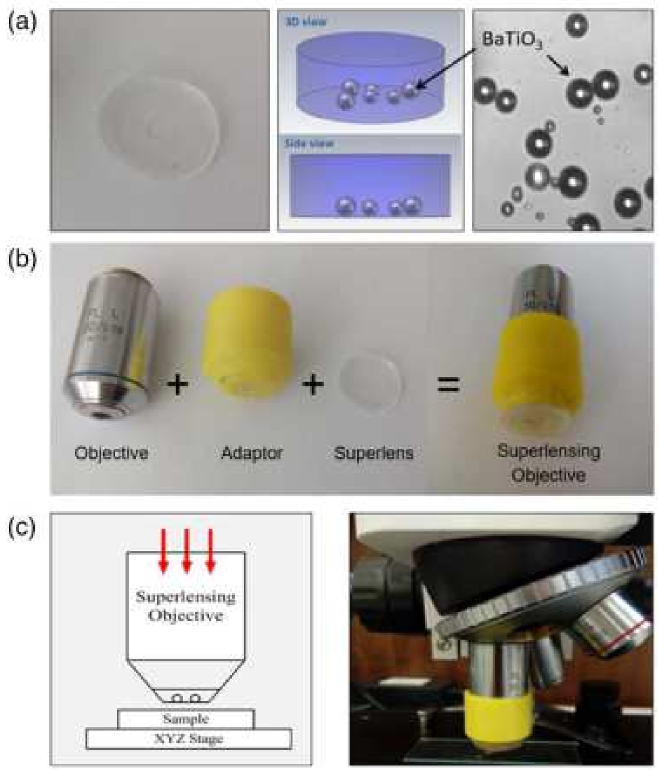

Figure 2 Superlensing objective lens. (a) microsphere superlens was fabricated by encapsulating a monolayer of microsphere lens inside a PDMS material. (b) Super objective was made by integrating a conventional microscope objective lens (e.g., 50×, NA: 0.70, or 100×, NA: 0.95) with microsphere superlens using a 3D printed adaptor (c) Experimental configuration for super-resolution imaging using a developed objective that was fitted onto a standard white light optical microscope

First generation superlens has a varying resolution and magnification, and a unsatisfactory low contrast, when imaging different samples due to its PNJ near-field working principle, this means for each imaging sample the measurement needs to be calibrated which is not acceptable for a commercial system. In order to overcoming these problems, we have developed the second generation dielectric superlens.

3) Second generation dielectric superlens: nanoparticle metamaterial superlens [3a]

Using metamaterial design concept, we used high-index nanoparticles as building block and stack them into desired 3D shape to form new superlens. Here, the densely packed nanoparticle composite medium has shown special optical properties the first generation superlens doesn't have: it generates millions of nanoscale illumination spots (evanescent wave NOT propagating wave) on imaging sample surface and it retrieve very effectively the nanoscale information (.vs. the first generation superlens has single illumination spot containing much weaker evanescent components), the working mechanism here is not PNJ anymore, but high-index nanoparticle super-resolution evanescent illumination and decoupling - a new nanophotonic effect/mechanism first discovered [3a].

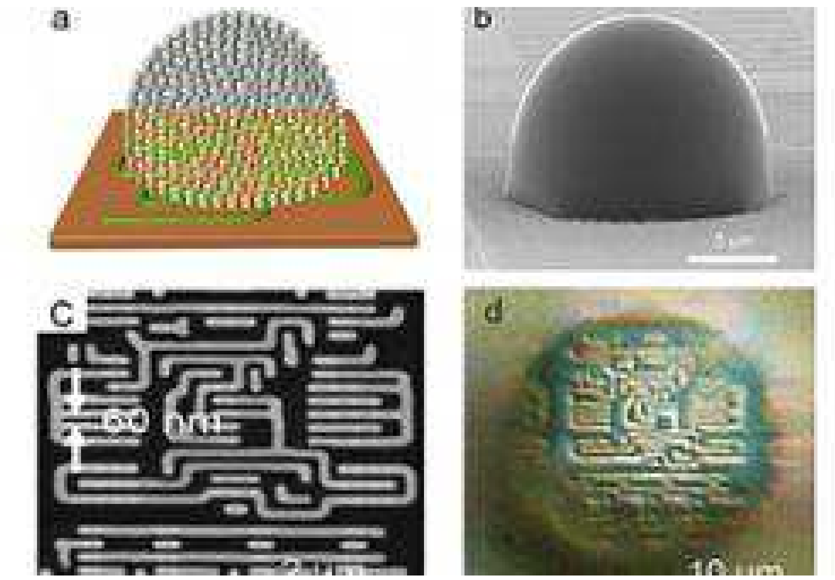

Figure 3 (a) Conceptual drawing of nanoparticle-based metamaterial solid immersion lens (mSIL) (b) Lab made mSIL (c) SEM image of 60 nm sized imaging sample (d) corresponding superlens imaging of the 60 nm samples by the developed mSIL.

The second generation superlens has shown (1) Increased resolution, 45 nm (2) Much stable imaging process (not varying resolution and magnification) and quality, and clarity for different samples, including nanochips and viruses. (3) its theoretical resolution is determined by particle size, not the wavelength (similar to NSOM) so it is possible to achieve a ‘new-perfect’ superlens the optical scientist looking for centuries.

In a recent review article on dielectric superlens, we have included the second generation superlens [3b].

4) Spider silk superlens [4a]

While the dielectric superlenses seem quite high-tech and far away from general public, can one find superlens somewhere that is easily accessible by general public? When playing in back garden with kids as well as on the lovely sand beach, I soon realized maybe the spider silk and fine sands particle could be natural superlens as they are transparent and has size scale a few micrometer to a few tens micrometers, which are the size scale dielectric superlens is. In collaboration with Prof. Fritz Vollrath of Oxford University, we successfully demonstrated that certain types of spider silk does have super-resolution imaging capabilities, of about 100 nm in resolution. This is the first report on 'biological superlens'. Despite these naturally-occurring superlenses are widely available; they cannot provide very high-end resolution like microsphere superlens and nanoparticle metamaterial superlens do, but it does spurred a wave of interests in superlens technology. Currently, the group is investigating using cyanobacteria as live biological superlens.

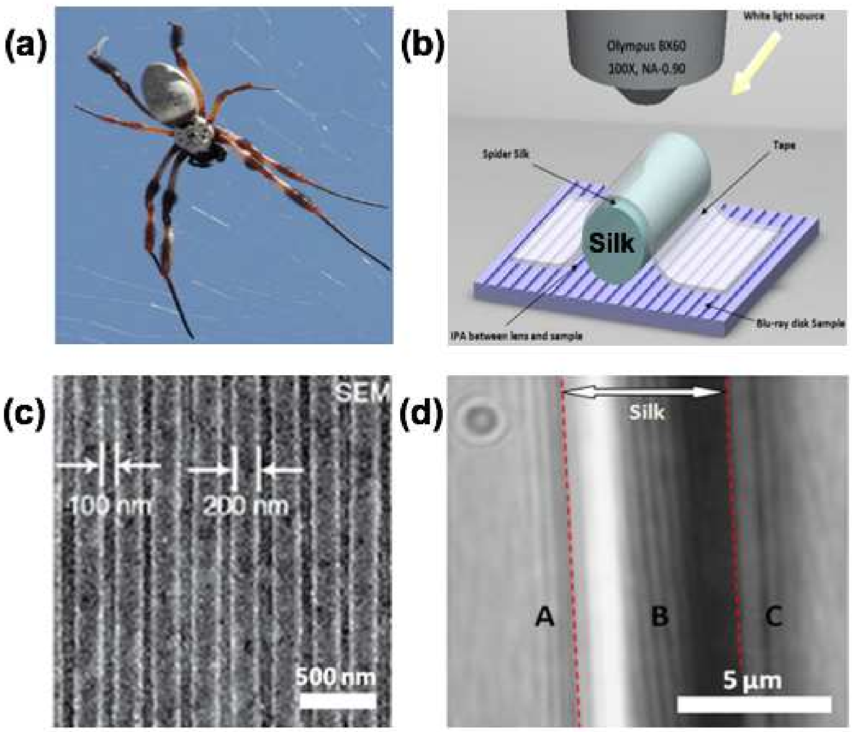

Figure 4(a) Nephila edulis spider in its web. (b) Schematic drawing of reflection mode silk biosuperlens imaging. The spider silk was placed directly on top of the sample surface by using a soft tape, which magnify underlying nano objects 2-3 times (c) SEM image of Blu-ray disk with 200/100 nm groove and lines (d) Clear magnified image (2.1x) of Blu-ray disk under spider silk superlens.

5) PNJ engineering, photonic hook and solar cell research

The group actively looks into ways that can improve PNJ super-resolution beyond its conventional designs, and have reported increased resolution by using pupil masks combined with microsphere [5a]. NRN fellow Dr. Liyang Yue in the group (Now a lecturer at Bangor since 2018) discovered new effect of photonic hook - a curved light that has potential application in nanoparticle guiding and trapping when pupil mask was combined with a cuboid particle [5b].

The groups also develop mulitphysics models for nanophotonic devices simulation including modern solar cell, for example, the group proposed a theoretical design that can effectively boost IR band solar energy absorption [5c], and an anti-reflection layer by using nanospheres [5d]

5) Collaborations:

Collaborations are important for the group. We have collaborated with Oxford, UCL, Cardiff, Swansea, Manchester Universities in the UK, NUS, NTU in Singapore, Fudan, Zhejiang and Qinghua in China, IHP in Germany, UNILIM in France, ENEA in Italy

We are collaborating with Dr. Alan Parker in Cardiff University School of medicine, ScanWel Ltd UK, and local government in Taizhou China to develop biological scanning superlens nanoscope system for biomedical 3D super-resolution imaging application, where super-resolution fluorescent imaging units and second generation dielectric superlens will be integrated. We aim to launch our product in a few years' time, with potential manufacturing partner being sought from China.

The group is also collaborating with Qioptiq, an anchor company in Wales, on the development of wide-angle shift-free anti-laser striking devices, and laser cleaning projects.

The group also collaborates with ValueForm Ltd, a local packaging company on laser processed hydrophobic packaging materials.

Facilities:

Optical Nanoscope

- In-house developed white light nanoscope (45 nm resolution)

Lasers

- Femtosecond laser (Spectra, 800 nm, 100 fs)
- IPG Nanosecond Fiber laser (10w, 100 ns, 1064 nm)
- Trotec Rayjet (30w) CO2 laser
- Speedy 300, 400, 500 CO2 laser

Characterization:

- Wide-field optical microscope (Olympus, BX60, ICM100)
- Near-field Scanning Microscope (NSOM, model: Thermomicroscopes Aurora-2)
- Raman spectroscopy,
- UV-VIS Spectrometer
- Ellipsometry (193 – 3200 nm)
- In-house built 45-nm Scanning Optical Nanoscope
- FTIR, XRD, AFM, SEM
- Class 1000 clean room
- Thin film deposition system (E-beam evaporator, sputter)
- Photolithography (M.A.)

Current members:

Dr Zengbo Wang (PI)

Dr. Liyang Yue (NRN Research fellow since 2015, now lecturer since 2018)

Dr. Rakesh Dhama (postdoc since 2017)

Dr. Bing Yan (PhD student since 2014, Postdoc since 2018)

Mr. James Monks (PhD since 2016)

Mr. Praveen Bhuvya (Master 2018), Ms. Niroopa Rasineni (Master 2018)

References:

- [1a] Zengbo Wang, Wei Guo, Lin Li, Boris Luk'yanchuk, Ashfaq Khan, Zhu Liu, Zaichun Chen, and Minghui Hong, "Optical virtual imaging at 50 nm lateral resolution with a white-light nanoscope", ***Nat. Commun.*** 2, 218 (2011)

- [1a2] S.Lee, L. Li, Z.B. Wang, W. Guo, Y. Yan, T. Wang, "Immersed transparent microsphere magnifying sub-diffraction-limited objects", ***Appl. Opt.*** 30, 7265-7270 (2013)

- [1b] Y. F. Lu, L. Zhang, W. D. Song, Y. W. Zheng and B. S. Luk'yanchuk,JETP Lett., 72, 457–459 (2000).
- [1c] Z. G. Chen, A. Taflove and V. Backman,Opt. Express, 12, 1214–1220, (2004)
- [1d] Z.B.Wang, "Microsphere super-resolution imaging", ***Nanoscience***, 3, 193-210, DOI: 10.1039/9781782623717-00193 (2016).

- [1e] Zengbo Wang and Lin Li, "MICROSCOPY: White-light microscopy could exceed 50 nm resolution", ***Laser Focus World*** 07, 61-64 (2011) - invited feature article

- [2a] Z. Wang, *Improvements in and Relating to Lenses* , PCT/GB2014/052578 AND GB1603139.5, 2014.
- [2b] B. Yan, Z.B. Wang, A.L. Parker, Y. Lai, P.J. Thomas, L. Yue, J.N.Monks, "Superlensing microscope objective lens", ***Appl. Opt.***, 56, 3142-3147 (2017).

- [3a] W. Fan, B. Yan, Z. B.Wang, L. Wu, Three-dimensional all-dielectric metamaterial solid immersion lens for subwavelength imaging at visible frequencies, ***Sci. Adv.*** 2, e1600901 (2016).

- [3b] B.S. Luk'yanchuk, R.Paniagua-Dominguez, I. Minin, O. Mini, Z.B. Wang, "Refractive index less than two: photonic nanojets yesterday, today and tomorrow [invited]", ***Opt. Mater. Express*** 7, 1820-1847 (2017).

- [4a] J.N.Monks, B.Yan, N. Hawkins, F. Vollrath, Z.B.Wang, Spider silk: Mother Nature's Bio-superlens, ***Nano Lett***., 16(9), 5842–5845, DOI: 10.1021/acs.nanolett.6b02641 (2016)

- [5a] B.Yan, L. Yue, Z.B. Wang, "Engineering near-field focusing of a microsphere lens with pupil masks", ***Opt. Commun***, 370, 140-144 (2016).
- [5b] L. Yue, O.V. Minin, Z.B. Wang, J. Monks, A.S. Shalin, I.V. Minin, "Photonic hook: a new curved light beam", ***Opt. Lett.*** 43(4), 771-774 (2018).
- [5c] L.Yue, B. Yan, M. Attridge, Z.B.Wang, "Light absorption in perovskite solar cell: Fundamentals and plasmonic enhancement of infrared band absorption", ***Sol. Energy,*** 124 143–152 (2016).
- [5d] Q. Luo, X. Deng, C. Zhang, M.Yu, X. Zhou, Z.B.Wang, X. Chen, S. Huang, "Enhancing photovoltaic performance of perovskite solar cells with silica nanosphere antireflection coatings", ***Sol. Energy*** 169, 128-135 (2018).