Chief Investigator: Min Gu

CI short biography

Min Gu, an Australian Laureate Fellow of the Australian Research Council and a University Distinguished Professor in optoelectronics, is a Node Director of the CUDOS and the Director of the Centre of Micro-Photonics (CMP) at Swinburne University of Technology. His research interests include nanophotonics and biophotonics with internationally renowned expertise in photonic crystals, optical data storage, optical endoscopy, and multi-dimensional optical data storage. Prof. Gu is a Fellow of both the Australian Academy of Technological Sciences and Engineering (ATSE) and the Australian Academy of Science (AAS). He is also a Fellow of the Australian Institute of Physics (FAIP), the Optical Society of America (FOSA), the International Society for Optical Engineering (SPIE), the Institute of Physics (IOP) and a Senior Member of International Institute of Electric and Electronic Engineers (IEEE). He is a topical editor of Applied Optics: Optical Technology and Biomedical Optics of the Optical Society of America, a topical editor of Optics and Photonics Letters (Singapore). He has been appointed as a member of the Fellows and Honorary Members Committee of the Optical Society of America. He also served on the editorial boards of 14 international journals.

Awards, honours, major international visits

In 2010 Prof. Min Gu was awarded the highly prestigious Australian Laureate Fellowship to tackle some of the most urgent and complex research issues facing Australia and the world. He was also awarded a 2010 Einstein Professorship from the Chinese Academy of Science.

Professor Min Gu conducted the following international scientific visits in 2010

- Tsinghua University Graduate Institute at Shenzhen, China, April 8,2010.
- Zhejing University, April, 2010
- Stanford University, USA, May 18, 2010
- Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Science, China, June 25, 2010.
- Tsinghua University, China, July 29, 2010.
- National Busan University, Korea, September 13-20, 2010.
- Fudan University, Oct 16, 2010
- National Hualian University. Taiwan, Oct 25-28, 2010
- Institut d'Optique – Graduate School, Palaiseau, France, Oct 30, 2010

The following persons in CUDOS-Swinburne node have received Awards, conducted international scientific visits and given invited talks

- Dr. Michael James Ventura received the Swinburne University of Technology Vice-Chancellor's Early Career Research Award for research excellence in 2010.
- Mr. Mark Tuner and Mr. Md Muntasir Hossain won the 2010 CMP Student of the Year and Student Innovation prize respectively.
- Mr. Mark Tuner was awarded the OSA student prize for best student presentation at the AIP/ACOFT conference held in Melbourne, December 2010.
- Dr. Baohua Jia was awarded the Victoria Fellowship from the Victoria Government.
- Dr. Baohua Jia received travel award from Australian Academy of Technological Sciences and Engineering (ATSE) to conduct scientific visit to China.
- Dr. Michael James Ventura visited the group of Prof. Tony Wilson at the University of Oxford in November 2010.
- Dr. Baohua Jia visited Prof. Nikolay Zheludev at University of Southampton in UK for a month supported by the Australian Academy of Science under the Scientific Visit to Europe scheme. She presented two lectures in University of Southampton.
- Dr. Baohua Jia visited Prof. Tony Wilson in Oxford University on October 27.

Visitors to CMP during 2010:

Dr. Yaoyu Cao (Chinese Academy of Science, China), Prof. Alessandro Martucci, Dr. Alessandro Antonello (Padova, Italy), Prof. Yanrong Song (Beijing University of Technology, China) Prof. Tony Wilson and Dr. Patrick Salter (Oxford University, UK).

Key areas of research contribution within the Centre

- Three-dimensional (3D) dielectric and metallic photonic crystal fabrication, functionalisation and characterisation.
- Spontaneous emission control of infrared quantum dots inside 3D photonics crystal.
- Photonic crystal based devices such as superprisms and microcavities.

Researchers and students

The CUDOS group at Swinburne University of Technology, headed by Professor Min Gu is located at the Centre for Micro-Photonics. It includes; six researchers Dr. Baohua Jia, Dr. Yaoyu Cao, Dr. Dario Buso, Dr. Michael James Ventura, visiting academic Dr. Alessandro Antonello from the University of Padova Italy and visiting professor Prof. Yanrong Song from Beijing University of Technology, China; six PhD students Ms. Elisa Nicoletti, Mr. Md Muntasir Hossain, Mr. Ben Cumming, Mr. Mark Turner, Mr. Zongsong Gan, Mr. Han Lin and one master student Mr. John He; two administrative staff members Ms. Johanna Lamborn and Dr. Dru Morrish; and one technical staff member Mr. Mark Kivinen.

Research achievements during 2010:

3D photonic crystal fabrication in ChGs (by Ms. Elisa Nicoletti), adaptive aberration compensation in high refractive index materials (By Mr. Ben Cumming), 3D lifetime mapping and radiation dynamics

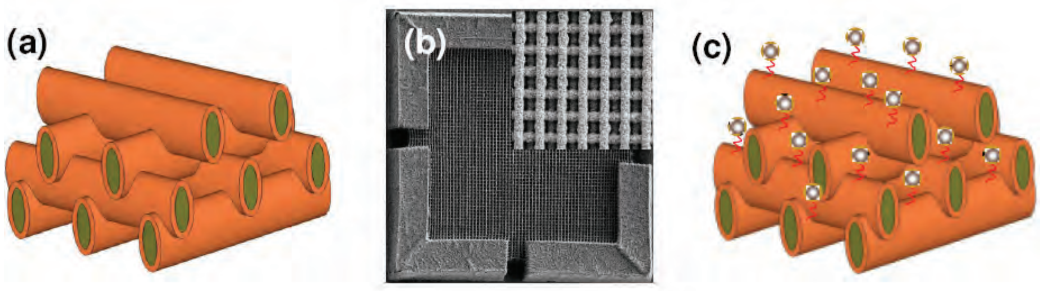

Fig 1: (a) Schematic of HPC. (b) SEM image of HPC. (c) Schematic of core/shell QDs activated HPC.

in 3D photonic crystals (by Mr. Zongsong Gan) and nonlinear nanocomposites synthesis and photonic crystal fabrication (by Dr. Baohua Jia) are reported in detail in the Flagship project: 3D Bandgap Confinement. The followings are the highlights of other achievements in 2010.

Activating hybrid photonic crystals by core-shell quantum dots

Dr. Baohua Jia has been working on the incorporation of near-infrared core-shell quantum dots as nano-emitters into the newly developed three-dimensional plasmon merged photonic crystals (Fig. 1). The hybrid photonic crystals were constructed by stacking hybrid rods made of dielectric-cores and metallic-nanoshells. It has been found when the metallic-nanoshell is much thicker than the metal skin depth, the hybrid photonic crystals present complete photonic bandgaps, which are useful for investigating the spontaneous emission from quantum dots. When it is smaller than the skin depth, the hybrid photonic crystals present strong localized plasmon resonances providing a unique platform for investigating plasmon enhanced light emitting.

Aberration compensation for 3D nanofabrication

Work is continuing towards the compensation of the strong spherical aberration present when direct laser writing through high refractive index mismatches with the installation of a new femtosecond amplifier system (Coherent Libra HE) operating with an average power of 3.5 W and a repetition rate of 10 kHz. The laser will be used with adaptive optics to enhance and extend the previously demonstrated photonic stopgap improvements in 3D lithium niobate photonic crystals to more complex structures in arsenic trisulphide thin films. This material allows stronger index contrasts without the introduction of cracks and complex voxel shapes seen in the birefringent lithium niobate crystal, but requires a laser repetition rate large enough to quickly create smooth structures and small enough to avoid thermal build-up that can cause excessive local annealing of the thin films.

Plasmonic structures for nano-photonic applications

Plasmonic nano-structures are attractive for waveguiding due to their ultra-high energy confinement and reasonable propagation length which have potential applications in integrated nano-photonics. Here, we report on a plasmonic waveguide with mode confinement beyond the diffraction limit and with moderate propagation length. Metallic nano-shells can possess resonant plasmon modes within the metallic surfaces. Cylindrical metallic nano-shells can support both localised and propagating plasmons. The propagating plasmon modes can effectively guide light with subwavelength mode confinement. We characterise their waveguiding features with the optical properties of the bulk material and also on the physical sizes of the nano-structures. Figure 2a shows the energy density of a cylindrical plasmon waveguide with core refractive index of 2.5 at the telecommunication wavelength of 1.55 µm. The core material is assumed to be coated with 50 nm silver coating. The mode energy is strictly confined within the core dielectric region surrounded by the metal. Fig. 2b shows the calculated (finite element method) propagation length and effective mode area of the plasmon waveguide with varying core refractive index. The mode area is normalised to the diffraction limited area at the operating wavelength. We are also currently working on to develop two photon polymerised devices with thin metallic coatings to experimentally demonstrate the guiding features of these plasmon modes.

Chiral photonic crystals

Chiral photonic crystals (PCs), such as the spiral PC possess strong discrimination between circularly polarised light, causing effects such as circular dichroism. However, designs such as those based on spirals have only uniaxial chirality and lacks cubic symmetry, limiting these chiral phenomena to a single direction. We have designed and fabricated a novel class of chiral PCs based on the Gyroid Ia3d minimal surface (Fig. 3a). These three-dimensional (3D) network designs are geometrically chiral, have cubic symmetry, are fully interconnected and are mechanically stable. We have fabricated the chiral network PCs using direct laser writing in the commercial polymer photoresist IP-L (Nanoscribe Gmbh), see Fig. 3b and c.

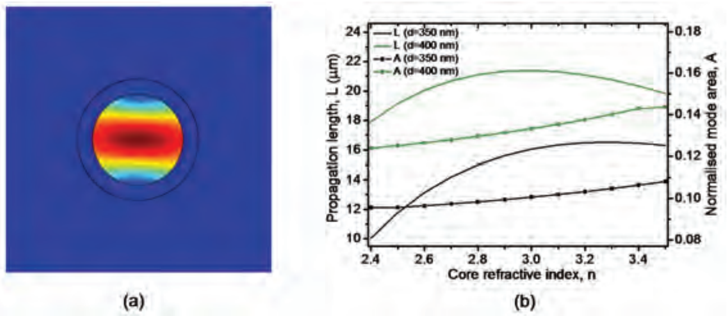

Fig 2: (a) Energy density of the plasmon mode within the waveguide with diameter d=350 nm. (c) Propagation length and effective mode area of the plasmon mode for variation of the core refractive index n.

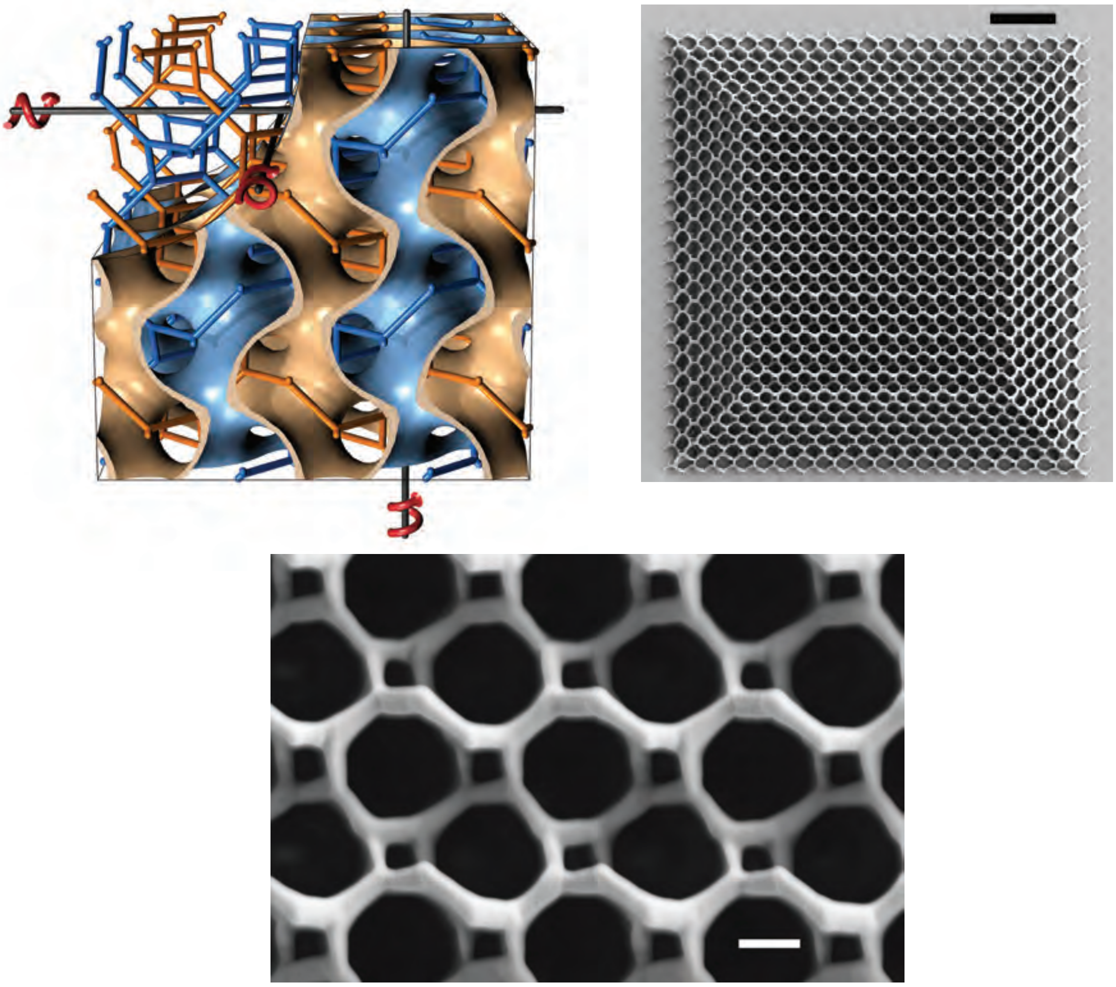

Fig 3: (a) The Gyroid minimal surface with Ia3d group symmetry and the two chiral cubic networks with left handed (blue) and right handed (brown) chirality.
(b) A chiral PC fabricated using direct laser writing based on a single chiral network of the Gyroid surface. The overall structure has been designed in a pyramid-like shape to help maintain the structural integrity.
(c) A close up view of the right-handed network, showing excellent replication of the network design.

Chalcogenide glasses nanofabrication

Chalcgenide glasses (ChGs), in particular As_2S_3, are known to be susceptible to photo-structural changes when exposed to light .Using a femtosecond laser beam it is possible to induce structural modification in a highly localised area of the glass through a two-photon induced nonlinear process at a wavelength of 800 nm. However similar phenomena can also be induced through thermal effects. Using a high repetition rate (Rr) laser, heat can be accumulated over a number of pulses, which generates local heating within the glass. A thermal diffusion model has been applied to study the influence of the repetition rate on the direct laser writing (DLW) fabrication in ChG thin film. The calculations show that 1.6 MHz gives the optimum condition of fabrication, combining the advantage of the thermal effect while avoiding an excess accumulation of heat close to the focal spot.In order to confirm the theoretical predictions we fabricated two-dimensional lines at different laser powers and different scanning speed. Figure 4a shows the experimental plot of the lateral rod dimension versus the laser power For the first time lines with resolution of $\approx \lambda/12$ were fabricated in As_2S_3, glass. Fig. 4b shows a SEM image of a line fabricated at a power of 450 μW and at a scanning speed of 150 μm/sec. The later rod dimension is only 68 ± 14 nm. All the fabricated rods are smooth and homogeneous, maintaining strong mechanical properties as well. This achievement is an important step towards the realization of all-optical devices.

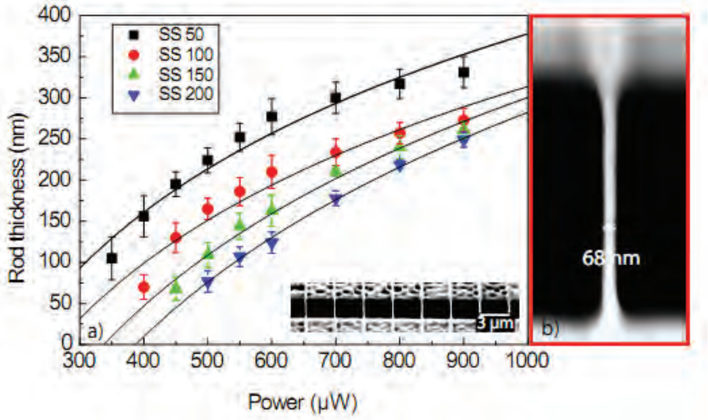

Fig 4: (a) Experimental plot of the lateral rod dimension versus the laser power for 4 different scanning speeds (50 μm/sec, 100 μm/sec, 150 μm/sec and 200 μm/sec. In the inset a SEM image of the 2D lines fabricated at constant power but at different scanning speed. (b) SEM image of a line fabricated using a laser beam power of 450 μW and a SP of 150 μm/sec.

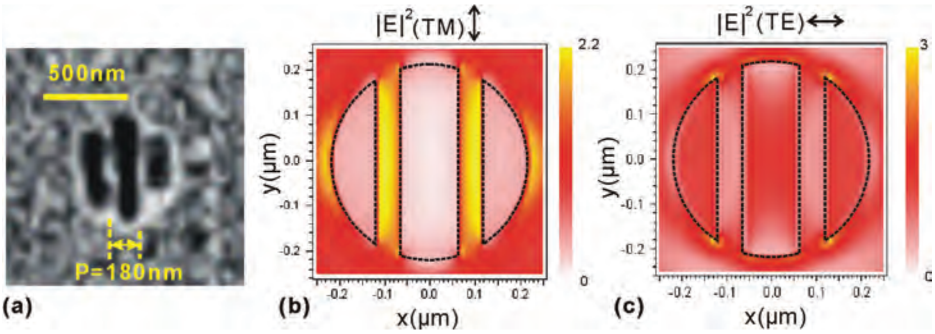

Fig 5: (a) SEM image of a fabricated nanograting structure; Simulated E field intensity distribution at 650 nm wavelength, (a) TM mode; (b) TE mode.

Chalcogenide glasses nanogratings

Chalcogenide glasses are high refractive-index materials with large transparent window spans from 650 nm up to infrared. Compared with silica glasses, ChGs are optically highly nonlinear (with χ^3 values approximately two orders of magnitude higher than that of silica). Nanogratings with a period of 180 nm have been achieved using multipulse laser irradiation at a power close to the break up threshold of the material. However, the optical properties of ChG nanogratings have yet to investigate. In this study, the optical transmission of linearly polarized light at 650 nm in the ChG nanograting structures is investigated numerically using the RSoft program package based on the 3D FDTD method. It is shown that the coupling efficiency of light into the nanogratings strongly depends on the polarisation direction of the incident beam. As shown in Fig. 5, strong coupling can be achieved when the polarisation is parallel to the orientation of the nanogratings (TM mode). The energy density, which is normalised by the incident intensity, has a peak of 2.2. In contrast, the light intensity in the nanograting is nearly zero and the peak intensity (which is 3) is at the corner of the nanograting when the polarisation is perpendicular to the nanograting (TE mode). In conclusion, the light coupling to the nanogratings exhibits a strong selectivity to the light polarisation.

Super-resolution fabrication

We have developed a fabrication technique of super-resolution based on direct laser writing. The fabrication utilizes two focused laser beams of two colors of 488 nm and 375 nm, respectively. The 488 nm laser was used to initiate photopolymerisation, while the 375 nm laser was used to terminate the photopolymerisation. As shown in Figure 6a, in the case of the fabrication of a polymer line, the segments exposed with two laser beams simultaneously were unpolymerised, which attributed to the formation of a dashed line. The super-resolution effect appears when the focal spot of 375 nm laser was engineered to a doughnut shape. The spatial overlapping of the focal spots of 375 nm laser and 488 nm laser enabled the photopolymerisation trapped in the centre region, activating inhibitors to terminate the photopolymerisation in the outer ring. As a consequence, the fabrication resolution could be greatly improved. Figure 6b reveals the line fabricated in the presence of doughnut-shaped 375 nm laser is much narrower than that obtained without 375 nm laser. By optimising the power of 375 nm laser, the smallest feature size was realised 130 nm, compared with the feature size of 420 nm of the line fabricated without 375 nm laser. We are currently investigating the mechanism of the inhibited photopolymerisation applied for super-resolution fabrication and working on decreasing the feature size of polymer structure further.

Optimization of enhanced absorption in woodpile metallic photonic crystals

Metallic photonic crystals (MPCs) possess complete and ultra-wide band gaps in compare to dielectric photonic crystals (PCs) which can be of significance for specific nanophotonic applications. However, MPCs also contain resonant absorption near the photonic band edges. For realistic applications the optical losses within the MPCs need to be minimised. We have demonstrated a theoretical analysis which helps to explain the resonant dissipative behaviour of 3D woodpile MPCs. Investigating the dispersive properties of the woodpile MPCs theoretically we found that the absorption resonance within the MPCs can be easily optimised by inducing appropriate structural modifications.

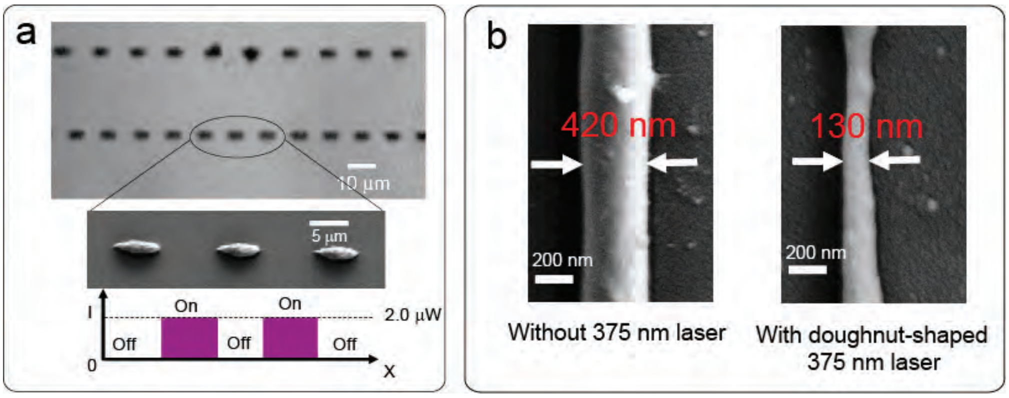

Fig 6: (a) A optical microscope image and SEM image of the dashed line fabricated by applying two focused laser beams of two colors of 375 nm and 488 nm. The two focal spots are spatial overlapping. (b) The SEM images of polymer lines fabricated without 375 nm laser (left) and with doughnut-shaped 375 nm laser (right), respectively.

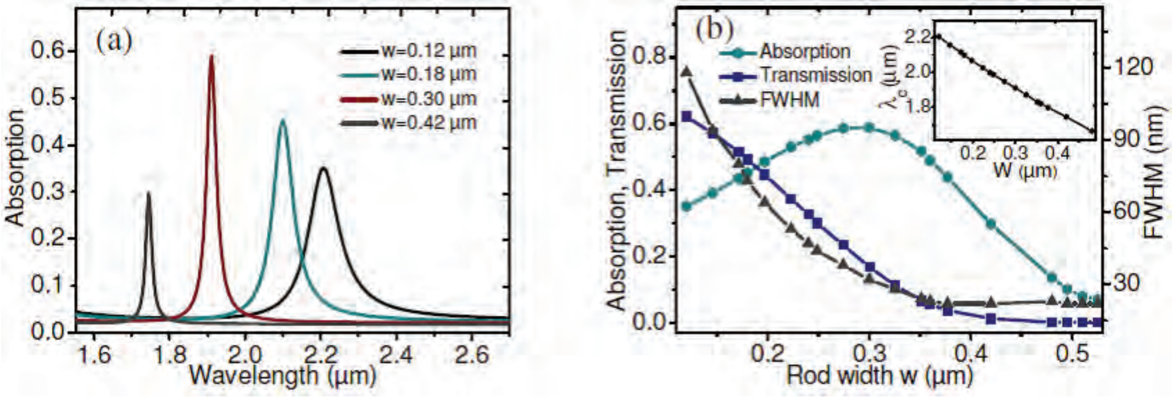

Fig 7: (a) Calculated absolute absorption spectra for different values of *w* of the metallic rods in MPCs. (b) Calculated absorption peaks, transmission peaks and the FWHM of the absorption as a function of w. Inset: The linear relation of the absorption peak position and w.

Figure 2a shows the calculated absorption spectra of a four layer silver woodpile metallic photonic crystal for different values of rod width *w*. The metallic rod height *h* was set to 0.6 µm and the lattice constant was kept fixed at 1 µm. Fig. 2b shows the peak values of transmission, absorption and the full width at half maximum (FWHM) of the absorption peak. These results show that the absorption magnitude and the band width of the MPCs can be efficiently tuned by altering structural parameters. [3]

Inverse Doppler effect in negative index photonic crystals

Working with collaborators in China (Professor Songling Zhuang's team, Shanghai University of Science and Technology), the Swinburne team (Min Gu, Baohua Jia and Xiangping Li) has successfully demonstrated the inverse Doppler effect in a 2D photonic crystal prism with negative index. The counterintuitive inverse Doppler effect was theoretically predicated in 1968 by Veselago in the so-called left-handed material (LHM) or the negative-index material (NIM). However, because of the tremendous challenges of frequency shift measurements inside the NIM, most investigations of the inverse Doppler effect have been limited to either theoretical predications or numerical simulations. Non-relativistic inverse Doppler shifts have never been observed at optical frequencies in an NIM. The Swinburne team with collaborators in China have demonstrated for the first time the inverse Doppler shift at the optical frequency (λ=10.6 µm) by refracting a laser beam in a photonic crystal prism, which has the NIM property. This work has been accepted to publish on Nature Photonics.