Surfing the metasurface: a conversation with Din Ping Tsai

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Professor Din Ping Tsai, City University of Hong Kong (CityU).

Chang: Hello, Professor Tsai. Thank you for joining us. To begin, would you please comment on your early work completed in the course of your PhD studies?

Tsai: In 1985, I went to the United States for my graduate studies. My supervisor mainly worked on the light–matter interaction, such as characterizing semiconductor materials by analyzing the width and position of Raman spectroscopy peaks to determine their crystallization condition and elemental composition. At that time, there were many senior students working on similar research topics in the same group. If I chose to conduct research in a direction similar to theirs, it would take a long time for me to graduate. After discussing this with my advisor, he encouraged me to explore other new research directions.

Following the suggestion from my supervisor and after reading some literature, I started to develop a scanning tunneling microscope (STM) at room temperature and ambient pressure in 1986. At the end of that year, two pioneers of STM from the Swiss IBM Lab were awarded the Nobel Prize in Physics, which further motivated me to study STM science and technology. After discussing with my supervisor, I used an optical fiber probe instead of a metallic tip to investigate the light–matter interaction at the nanoscale. Specifically, the optical fiber probe was chemically etched to obtain an ultrafine tip with a tiny nanometer-scale aperture and used to detect evanescent wave in the near field. I built my own photon scanning tunneling microscope (PSTM) and used piezoelectric ceramics to achieve nanoscale high-resolution probe positioning. I used this PSTM to characterize optical waveguides, which was the content of my PhD dissertation.

Chang: You chose to work in the industry after completing the PhD. Why did you make that choice?

Tsai: At that time, there were few job opportunities in academia, and most PhD graduates could only choose to work in the industry. I attended the American Physical Society annual meeting in Los Angeles in March 1990 and looked for job opportunities at the conference. A semiconductor microelectronics-related company invited me for an interview in April of that year. They were interested in developing optical methods to detect nanoparticles on the protective film called the pellicle of the photomask, which is always used in semiconductor microelectronic processes. Because this was very relevant to my previous research experience, I joined this company as a research staff member immediately after my graduation in June 1990. In September of the same year, I was assigned to go to Japan to test a set of optical inspection systems related to wafer pellicles from Hitachi Company. I learned many things about machine acceptance, patent writing, and team recruitment during this period.

Chang: How did you initiate your research in plasmonics?

Tsai: After working at that company for less than a year, I had an opportunity to work at the Ontario Laser and Lightwave Research Centre at the University of Toronto in Canada, on the construction and application of PSTM. During that period, I had the privilege to collaborate with distinguished scientists, including Professor Martin Moskovits, who first proposed the physical model and applications of surface-enhanced Raman spectroscopy (SERS). To validate his model, I learned how to fabricate fractal structures of silver nanoparticles on glass slides that can generate localized surface plasmon polaritons. Subsequently, I used homemade PSTM to perform near-field optical detection of fractal silver nanoparticle structures. It was the first experimental observation of localized surface plasmon polaritons' enhanced response and polarization dependence. This research was published in *Physical Review Letters* in 1994 and received tremendous attention. The physics community considered this study the first optical characterization measurement of localized surface plasmons at distances much smaller than the optical wavelength, opening up two new research fields: near-field optics and nanophotonics. These two research topics attracted lots of support from funding agencies globally and in the United States. Subsequently, some researchers regarded this work as the interaction between light and electronic systems of metallic nanoparticles. Based on this, Professor Harry Atwater from the California Institute of Technology and some other researchers proposed the new field of plasmonics and invited me to join them as an editor for a special issue on the topic of surface plasmon photonics for the *IEEE Journal of Selected Topics in Quantum Electronics* in 2007.

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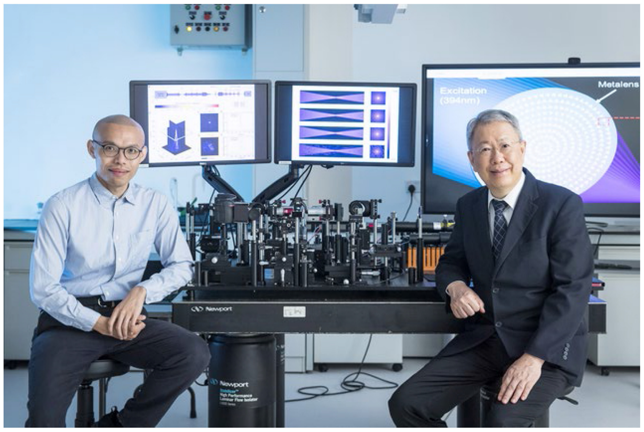


Din Ping Tsai (right) with Mu Ku Chen (left). Image credit: City University of Hong Kong.

Chang: What motivated you to work on metamaterials and metadevices later?

Tsai: In 1994, after returning to work in Taiwan, I continued my research in near-field optics, nanophotonics, and plasmonics. For example, we focused on manipulating nanoscale metal particles, developing plasmonic devices, and developing innovative near-field optical disks. We were able to arrange metal nanoparticles into arbitrary patterns. We also obtained record dots with a diameter of only 23 nanometers on phase-change near-field optical disks. Subsequently, we used femtosecond lasers to directly write and fabricate plasmonic devices for three-dimensional spatial focusing.

In 2007, when I attended an international conference on plasmonic optics in France, I met with Professor Federico Capasso from Harvard University. He asked me if we could fabricate a device at the optical fiber facet to manipulate the optical field. I replied, “Of course.” Subsequently, this research opened up a new frontier and became one of Professor Federico Capasso’s main research directions, which he named metasurfaces. Additionally, Professor Sir John Pendry from the UK and Professor Nikolay Zheludev proposed that three-dimensional metamaterials composed of artificial nanostructures could control the fundamental physical properties of metamaterials by designing meta-atoms. Later, in 2006, we collaborated with Professor Sir John Pendry and demonstrated that hyperbolic dispersive metamaterials, made up of multiple layers of the phase-change material germanium-antimony-tellurium (GeSbTe) and thin metal films, could achieve super-resolution capabilities that break the diffraction limit. Professor Xiang Zhang’s team at the University of California, Berkeley, quickly verified the super-resolution capabilities of this metamaterial in 2007. Subsequently, Professor Zheludev and I collaborated to experimentally demonstrate the first metamaterials that exhibit toroidal dipolar response, by an ultraprecision printing circuit board made in Taiwan. This research work was published in *Science* in 2010. In this way, I kept learning and working on the experiments; my research originally started from PSTM, near-field optics, nanophotonics, and plasmonics, and smoothly moved to metamaterials, metasurfaces, and metadevices.

Chang: Can you briefly introduce the history of meta-optics?

Tsai: The concept of meta-optics has a relatively short history. It originated from the studies of left-handed materials by Professors Sir John Pendry, David Smith, and Victor Veselago. In the following years, the concept of metamaterials became widely known. Researchers artificially designed meta-atoms or metamolecules and stacked them to manipulate electromagnetic waves. The size of meta-atoms/molecules and the working wavelength of metamaterials are correlated and limited by manufacturing capabilities; early metamaterials mainly operated in longer wavelength ranges, such as the infrared or microwave. The rapid advances in nanofabrication technologies made it possible to create meta-atoms or metamolecules that are significantly smaller than the light wavelength. This breakthrough enabled metamaterials to operate at optical wavelengths and led to the emergence of the new frontier field known as meta-optics. Recently, we developed nonlinear metamaterials that can operate at vacuum ultraviolet (VUV) wavelengths (200 to 10 nm).

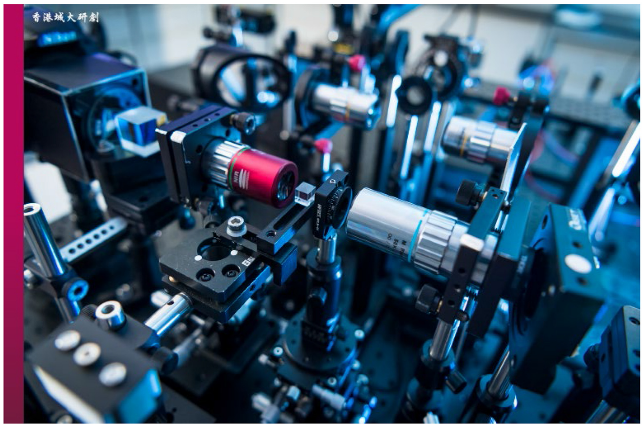
Chang: In the past decade, the research trend shifted from 3D metamaterials to metasurfaces. What was the reason for that shift?

Tsai: Device energy loss is the main concern. Assuming a single layer of metasurface has a loss of 50%, then the losses increase to about 75% for two layers of metasurfaces. Forming a metamaterial requires a large number of metasurface layers and results in excessively high material losses, making the device impractical to use. Compared to 3D metamaterials, metasurface fabrication is relatively simple as it eliminates one dimension of fabrication requirements. Hence, many research teams have adopted metasurfaces to fabricate various meta-optical devices, such as metalenses. This year, there was a review titled “Revolutionary meta-imaging: from superlens to metalens” published in *Photonics Insights* by Professor Tao Li and Academician Shining Zhu’s team at Nanjing University, which highlights the imaging technology and industrial transformation brought about by meta-optics.

Chang: In recent years, your research group has successfully developed broadband achromatic metalenses. Could you please tell us about your work in this area?

Tsai: In early studies, the response of nano-antennas depended on their sizes, and fixed-size nano-antennas exhibited sharp resonances at specific wavelengths. Therefore, early research on broadband achromatic metalenses focused on specific discrete wavelengths. However, in practical applications, metalenses must be able to correct chromatic aberration over a continuous and broad spectral range to obtain high-quality optical images.

To solve this problem, my inspiration from traditional Chinese medicine helped to design broadband achromatic metalenses. In contrast to Western medicine, which treats headaches with a single type of medicine (e.g., aspirin) for individuals of all ages and genders, traditional Chinese medicine individualizes treatment by combining multiple herbs based on the patient’s personal symptoms. It is a unique personal and precision medical treatment. In our research, similarly, we integrated different types of antennas to form an integrated unit. By adjusting various parameters, such as the size, shape, and spacing of the nano-antennas, we can achieve the desired working bandwidth and efficiency. Since a trade-off exists between bandwidth and efficiency, simulation can be used to optimize the coupling effects between antennas to meet specification requirements. Therefore, we proposed the new concept of integrated resonant units (IRUs). Additionally, we developed reflective broadband achromatic high-efficiency metalenses. Compared with a single antenna, a metallic mirror can help to generate counter-directed electric dipoles, which can be coupled to create a magnetic dipole. The interaction between electric and magnetic dipoles produces resonances that cover the 2π-phase, which can also improve efficiency. On the other hand, we used gallium nitride materials to realize highly efficient and broadband achromatic transmissive metalenses. I believe that, by optimizing the design and fabrication according to specific demands, metalenses can be applied in almost all vision-related scenes with extra novel functions.



VUV system with new metalenses. Image credit: City University of Hong Kong.

Chang: Why is gallium nitride chosen as a semiconductor material in the development of metadevices?

Tsai: Silicon, titanium dioxide, and nitride semiconductors are traditional materials used in manufacturing metadevices. We chose gallium nitride semiconductors because the material needs to withstand very high laser power when preparing the broadband achromatic transmissive metalens. Normally, the material has insufficient transparency, or if there are defects or dust on the metalens surface, the generated heat may cause severe damage. The lattices of sapphire and gallium nitride semiconductors match very well, and gallium nitride semiconductors grown on sapphire substrates exhibit superior optical transparency, refractive index, and other physical properties. They perform well under gamma and cosmic rays in space stations and show high damage thresholds and stability in laser-processing applications. Due to the development of the LED industry, the processing technology of gallium nitride is mature, and the low production cost makes it suitable for fabricating metalenses. In addition, nanostructured gallium nitride semiconductors have super-hydrophobicity, which allowed us to develop a binocular lens system based on gallium nitride metalenses that works underwater.

Chang: The current size of metalenses is on the millimetre scale. How to fabricate larger-sized metalenses?

Tsai: At the sacrifice of certain time and economic costs, larger-sized metalenses can be fabricated at the moment. However, with the development of nanoimprinting and metafabrication technologies, the size of metalenses will quickly exceed one inch in the near future.

Chang: You have collaborated with the research team at Nanjing University to apply metalenses to nonlinear optics and quantum information technology. Could you please comment on this work?

Tsai: The collaboration with the team at Nanjing University has achieved fruitful results. After successfully developing broadband achromatic metalenses that can work in the visible wavelength range, we had the idea of using multiple metalenses to achieve high-sensitivity imaging of light fields. To implement this idea, we designed and fabricated a metalens array composed of 60×60 individual metalenses with a size of $20\,\mu$m. Since the size and spacing of the metalenses are known, simple calculations can be used to identify the three-dimensional depth information and edges of the objects. Another collaborative work was the application of a metalens array for a high-dimensional quantum chip, which was published in *Science* in 2020. Traditional high-dimensional quantum optical entanglement uses cascade conversions, causing the loss of originality and fidelity. In collaboration with researchers from Nanjing University, we integrated a 10×10 metalens array with a thin nonlinear BBO crystal to create a high-dimensional quantum optical chip. The size of the 10×10 metalens array is smaller than the diameter of the laser beam and thus can be completely covered by the laser beam. Therefore, 100 down-converted photon pairs can be simultaneously generated, and this light source with entangled photon pairs has high fidelity. This research has received widespread attention from the academic community, and many scholars engaged in fields such as quantum computing, precision detection, and optical communication have sent collaboration invitations.

Chang: Integrated resonant units (IRUs) have solved the chromatic aberration problem in metalenses. Can they also be applied to other metadevices?

Tsai: The concept of IRUs was proposed in the work on broadband achromatic metalenses. A more detailed discussion can be found in the article titled “Integrated-resonant metadevices: a review,” which has been published in *Advanced Photonics*. IRUs can be used in optical multiplexers or metadevices for blue-light filtering, red-light enhancement, etc. In principle, IRUs can also be used for functional optimization in other metadevices. Still, materials need to be chosen for appropriate physical properties such as refractive index and carrier mobility.

Chang: In recent years, many scientific research studies have adopted technologies such as artificial intelligence (AI) and deep learning. What do you think about the prospects of AI in meta-optics?

Tsai: Some of my students applied AI technology in meta-optics, and we published a review article, “Artificial intelligence in meta-optics,” in *Chemical Reviews* in 2022. The content includes the use of AI for meta-optics design and the contribution of meta-optics to the development of AI. This emerging research direction has excellent potential for future development.

Chang: What significant breakthroughs may occur in meta-optics within the next decade?

Tsai: Optics is a subject closely related to human civilization, and meta-optics has the potential to make significant contributions in various areas. For example, in the field of quantum optics pioneered by Professor Jianwei Pan, metadevices are expected to play an important role. The concept of metaverse as proposed by Facebook will also require metadevices. Metadevices can be divided into active devices (e.g., light sources or amplifiers) and passive devices (e.g., components used to deflect or focus light). In addition to potentially bringing disruptive changes to fields such as mobile phones, wearable electronics, imaging and displays, optical detection, and military applications, metadevices may also provide higher-precision detection in the medical field, particularly in areas associated with blood vessels and eyes. It is important to note that a decade is a long time, and technological advancements progress rapidly. Meta-optics has attracted many talented scholars, and the future prospects for its development are promising.

Chang: What metadevices do you expect will be commercialized and widely used first?

Tsai: Many Chinese companies are currently exploring the commercialization of meta-optical components. For example, Huawei has adopted metadevices, including filters and splitters, in the field of optical communication to create compact and lightweight products. Some well-known smartphone lens manufacturers have also attempted to replace multiple-element lenses with single-element lenses based on metasurfaces to reduce the weight and size of smartphone lenses.

Chang: How have you managed to maintain such a high level of productivity and innovation throughout your academic career?

Tsai: I am just an ordinary scholar who continues to study hard. Since my graduate studies in the United States, my life and work have been closely intertwined. Over the years, I have focused primarily on research and devoted much of my time to discussions with students, writing papers, reading literature, reviewing manuscripts, and attending conferences. One distinguishing aspect may be my regular attendance of academic conferences in various countries and regions, including China, America, Asia, and Europe. I have made it a habit to listen to all presentations during each conference, learning about the latest cutting-edge work and considering whether there is something new to explore. For example, after attending a presentation, I quickly developed a new technique for near-field optical disks. I believe that continuous efforts in learning and exploration are key to maintaining innovation and high productivity.

Guoqing Chang graduated with both bachelor's and master's degrees from Tsinghua University's Department of Electronics Engineering, and obtained his PhD in electrical engineering from the Center for Ultrafast Optical Science at the University of Michigan. After staying at the University of Michigan as a postdoctoral research fellow for about a year, he joined the Research Laboratory of Electronics at Massachusetts Institute of Technology as a postdoctoral research associate. In 2012, he moved to the Center for Free-Electron Laser Science (CFEL) at Hamburg (Germany) as the head of the Helmholtz young investigator group "Ultrafast Laser Optics and Coherent Microscopy" under the ultrafast optics and X-rays division. He was granted tenure in 2016. In 2017, he joined Institute of Physics at the Chinese Academy of Sciences as a professor. His current research focuses on high-power ultrafast fiber lasers, ultrafast nonlinear optics, and multiphoton microscopy for biomedical imaging.

Din Ping Tsai is currently chair professor of the Department of Electrical Engineering, City University of Hong Kong. He is an elected fellow of AAAS, APS, COS, EMA, IEEE, JSAP, NAI, OSA, SPIE, PST, and AAIA, respectively. He is also an elected member of the International Academy of Engineering, and academician of the Asia-Pacific Academy of Materials. He is the author and co-author of 363 SCI papers, 70 book chapters and conference papers, and 39 technical reports and articles. He has been granted 69 patents for 45 innovations. He has been invited as an invited speaker for international conferences or symposiums more than 340 times (26 Plenary Talks, 62 Keynote Talks). He has received more than 40 prestigious recognitions and awards, including the "Mozi Award" from SPIE in 2018. He currently serves on the editorial boards of 12 prestigious journals, and as editor of *Light: Advanced Manufacturing* and co-editor-in-chief of *Photonics Insights*.