Innovation in metamaterials and beyond: an interview with Prof. Xiang Zhang

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Prof. Xiang Zhang, University of Hong Kong

Ren-Min Ma: Prof. Zhang, you have made a series of groundbreaking discoveries in metamaterials. How did you get started in this field?
Xiang Zhang: The research in metamaterials started about two decades ago. We are very lucky to have worked in this field from the very beginning, especially with John Pendry and David Smith. The field originated from John Pendry's theoretical proposal, which suggested that artificial materials might be constructed to exhibit electromagnetic properties not attainable in naturally occurring materials.

At that time, John Pendry and his colleagues proposed to use metamaterials to achieve magnetic response in electromagnetic waves. However, research in this topic was limited at microwave frequencies. As is well known, conventional materials can also have magnetic response at microwave frequencies, but at THz and optical frequencies, very rarely can they have magnetic response. So, we decided to construct an artificial material with magnetic response at higher frequencies. The experiment succeeded. In 2004, we realized terahertz magnetic response from artificial materials. This experiment was of high importance. The scalability of magnetic metamaterials to THz range and potentially into optical frequencies promises many applications, including negative refraction at optical frequencies, which we realized later on. This work resulted from the cooperation with John Pendry, who conducted the theory part. Soon after, European scientists pushed magnetic response of metamaterials to mid-infrared and even shorter wavelengths. In this way, a series of experiments promoted the development of metamaterials.

Meanwhile, we were working on subdiffraction-limited optical imaging with a metamaterial superlens. With metamaterials, it became possible to surpass the diffraction-limited imaging resolution pointed out by German physicist Ernst Abbe in 1873. In a conventional imaging system, the evanescent waves that carry subwavelength information about the object decay exponentially and are lost before reaching the image plane. The metamaterial superlens can compensate for the evanescent loss outside the superlens and thus restore an image below the diffraction limit. In 2005, we first demonstrated a silver thin film based superlens to realize near field subdiffraction-limited resolution, and later on, in 2007 a cylindrical metamaterial with a hyperbolic dispersion to realize far field subdiffraction-limited resolution. These experiments led to various novel imaging systems that can break the optical diffraction limit.

Ren-Min Ma: Besides efforts works to break the optical diffraction limit in imaging systems, you also realized plasmonic nanolasers with deep subwavelength feature size. Could you talk about that?
Xiang Zhang: Breaking the diffraction limit opens great opportunities in practical applications. For instance, nanoscale lasers can be realized. As is well known, the feature size of photonic devices is much larger than that of the electronic devices, because the wavelength of photons in photonic devices is much larger when compared with electronic devices. So, the bottleneck in integrating photonics with electronics on a chip is how to make photonic devices as small as electronic devices.

For lasers, the feature size cannot be smaller than optical diffraction limit, which is roughly hundreds of nanometers in optical frequencies. Metamaterials and plasmonics are the very solution to make a laser with a feature size of tens of nanometers or even smaller. At the interfaces of metals and dielectrics, surface plasmon polaritons originating from collective electron oscillations can be formed, which can be with an effective wavelength of tens of nanometers, or even a few nanometers. When we put a semiconductor nanowire on top of a metal surface, a plasmonic nanocavity can be formed and the gain from semiconductor nanowire can fully compensate cavity losses, leading to a nanoscale plasmonic laser.

Back then, the nanowires were synthesized by Prof. Lun Dai and Ren-Min Ma at Peking University. Those nanowires had a high refractive index. In the cavity design, we inserted a very thin layer of low refractive index material between the nanowires and plasmonic metal substrate to extract more electromagnetic field to the nanowires from the metal substrate. It's essentially a photonic–plasmonic hybrid mode with best properties of both worlds, low loss, and strong field confinement. The realization of plasmonic nanolasers is an important milestone in laser physics.

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Ren-Min Ma: You also have developed plasmonic nanolithography technique. Can you comment on that?
Xiang Zhang: Yes, about 20 years ago, we started to seek a new technique that can potentially replace current lithographic machining. Due to the same diffraction limit we discussed, it becomes increasingly expensive and complicated for the optical lithography to continually increase its resolution. But with a plasmonic lens, we can break the diffraction limit and focus light down to tens of nanometers and even smaller. Over the course of 10 years, we developed a new plasmonic nanolithography technique, and developed a prototype plasmonic nanolithography machine, with dedicated physical principles and engineering design. My former students are continuously working in this field. I think it will be very promising and find practical applications as it is much lower cost.

Ren-Min Ma: In 2017, you discovered intrinsic ferromagnetism in two-dimensional materials. Could you please comment on that, too?
Xiang Zhang: Yes, it is indeed a remarkable discovery. About half a century ago, N. D. Mermin and H. Wagner developed the so-called Mermin–Wagner theorem, which says that the long-range magnetic order will be strongly suppressed by thermal fluctuations in two dimensional systems. But we experimentally found the intrinsic ferromagnetism in the 2D vdW crystal $Cr_2Ge_2Te_6$, and confirmed it by the renormalized spin-wave theory calculations. The key is that 2D vdW crystal $Cr_2Ge_2Te_6$ has a small intrinsic magnetocrystalline anisotropy to resist the thermal fluctuations. It is nearly an ideal two-dimensional Heisenberg ferromagnet, which can be used to study fundamental spin behaviours. From a technological perspective, it may lead to new applications such as ultracompact spintronics.

Ren-Min Ma: You have done so much wonderful research. Could you comment on how you choose a research topic?
Xiang Zhang: It is very important to think thoroughly, keep open minded, and think outside the box. Let me first take 3D printing as an example. In the early 1990s, 3D printing technology emerged in Japan and then spread to US. But at that time, it was only a prototype with low yield limited by slow printing speed. And therefore, few researchers were attracted.

For a long time, I had been thinking about how to make 3D printing much faster. It was very slow because it printed in a point-by-point manner. You first print many points to form a line, and then many lines to form a layer, and lastly many layers to form a 3D object.

So, in the early stage, 3D printing was only used to print some rapid prototypes, like mechanical components with very complex geometric structure, in big companies like Ford. How to accelerate the printing speed for mass production? In the mid-1990s, we finally invented the layer-by-layer 3D printing technology. We print layer by layer instead of point by point, which leads to a much faster speed.

How did we get this idea? Actually, I was inspired by the slide projector. When we use a slide projector, we project pictures slide by slide. If we change the slides fast enough, it can display a video, like a movie projector. I thought if we use this technology in 3D printing, we can print a 3D object layer by layer instead of point by point, and it can be much faster. We then bought a slide projector, reassembled it into a 3D printer, which was the first 3D printer in the world that printed in a layer-by-layer manner.

So, it is important to find bottleneck problems, and then think creatively to solve those problems.

Here I have another example: one morning, I watched some very interesting TV news about researchers at Harvard University who grew an ear of the back of a mouse. The host pondered whether human organs can also be grown in that way, which actually emerged as an important research field later on. Soon after watching the news, we wrote a proposal about growing human organs on 3D-printed organic materials. We submitted the proposal to the NSF, but it was rejected. The reviewers commented that the idea seemed bizarre and impossible to realize. Some reviewers commented that we doing physical science and engineering might never have had a chance to see a cell. While had not seen a cell, we still decided to conduct the experiment and published a few articles in this topic. In 1999, we had the first Bio manufacturing workshop at Tsinghua University, where I explained the advantages of our technology. This field became prosperous later on. However, by that time, I had started metamaterials research and left that field.

Ren-Min Ma: Thank you for sharing that. Metamaterials and plasmonics are still very active research fields. Can you share your opinion on their future research directions?
Xiang Zhang: Metamaterials and plasmonics are two related fields. Both of them use structured materials, especially metallic materials, to manipulate electromagnetic fields. I think we will continue to seek electromagnetic properties not attainable in naturally occurring materials. Fundamental breakthroughs in this field will lead to new techniques for practical applications. Combining metamaterials and plasmonics with quantum science will be very interesting too. For instance, one can construct an artificial light field to simulate quantum processes or novel quantum phases. Also, artificial light fields can be used to simulate atomic systems to verify processes that can be hardly realized using current methods.

Ren-Min Ma: Your group has a very dense academic atmosphere with intense debate and enthusiastic discussion. Can you share the way you developed your group?
Xiang Zhang: Thank you, I think many groups have this kind of atmosphere. I think first we should encourage students to pursue academic excellence instead of just publishing papers. It is very important to be interest-driven. The interest is nurtured from problem solving. In an experiment, 95% of the time is spent on problem solving, the other 5% is just data collecting. We should also stimulate everybody's interest in scientific originality, and encourage competition and discussion. Don't be afraid of asking questions, even you feel your questions are very naive. Ask questions like a child. Curiosity is very important. Have crazy ideas! Get to the bottom of something. These are essential characters for an outstanding researcher.

For Chinese students, I think many of them have very solid background in their major, but they usually do not argue with their advisors. It might be due to their training experience in elementary and middle schools. It also results from our eastern cultural tradition.

I pay particular attention to encouraging my students to argue with me. There is no absolute authority inherent in advisors. We make mistakes, too. As you know, when students graduate from our group, they should have argued me down once or twice. That means they are near or better than me in some aspects. That's very important.

It's crucial to encourage students to argue scientific questions with their classmates, with their teachers or advisers. Of course, this should be under an atmosphere of equality. There is no hierarchy in science. Right is right and wrong is wrong.

In our group, I am like a chef cooking a soup. The soup is an atmosphere, a culture. When students join our group, wherever they come from, they bring in their own cultures, characters, interests, and expertise. I put all of them together, like adding carrots and cabbages in the soup. All of them contribute to the culture, enrich the culture, and learn from the culture. When they leave the group, the culture they contributed is still there. 10 years or even 20 years later, the newly joined students can still be nurtured and benefit from it.

I am just the chef cooking the soup. All of the students contribute and learn. They become part of the soup. When they leave the group, they carry the culture with them.

Ren-Min Ma: You have tens of students that are now faculty members. And you are a role model for them. Can you share more of your experience in educating students?
Xiang Zhang: Whether students, postdocs, or visiting scholars are joining our group, I emphasize that everyone should be equal in science. The atmosphere of equality in science is essential. I also emphasize the pursuit of science and truth. It is important to have the spirit of questioning. As I said, we advisors make mistakes too. Our students should dare to have their own opinions and to argue. With that in mind, they can start to discuss and explore freely.

In addition, we have to give students freedom. For example, I had a student who is now a professor at MIT. He was not a particularly outstanding student when he first joined the group. There was no achievement for the first 4 years, but I thought this student had a lot of brilliant ideas and extraordinary patience. So, my patience had to keep up with his. Later on, in his 5th and 6th year, he had a blowout and completed lots of top work. I remember that in the sixth year I wanted him to graduate, but he was unwilling to do that. He'd become fascinated by doing scientific research, so he postponed his graduation and completed several better research projects. This is an example a person who is really interested in science.

Just like carrots and cabbages, students are also different, and they need to be handled differently. It takes strategy and patience to nurture these students. They need encouragement as well as strict requirements. We should encourage students to come up with new ideas.

I remember that when I was a student, I often asked five questions in each class. Of course, 95% of them were stupid questions, and sometimes people joked about it. But you have to raise your question in this spirit and dare to challenge academic authority. At that time, a teacher of mine was one of the top professors in the world. I often debated with him, but he didn't like other people arguing with him very much, so he was very angry and took me from my seat to the podium, and we had a debate on the podium. I was wrong most of the time, and then he had to laugh at me. There was a young professor in this class who sat in the back, learning how to teach in the future. Ten years later, when I came back to teach at Berkeley as a new professor, that young professor had become a middle-aged professor. When he welcomed me as a newcomer, what he said surprised me. He said that I asked a lot of stupid questions in that class back then, but among them, there was a brilliant question which had become a major direction of his own research. I feel very moved. Therefore, sometimes asking questions is the path to new directions and we should have the courage to ask questions.

As we discussed just now, when I saw researchers cut off a mouse's ears and transplant them into its back, I wondered if I could use 3D printing to do this. In the early 1990s, this thought was quite ahead of its time. It is now called Biofabrication, and there is even a magazine called Biofabrication. So, there are many innovations that emerge by asking questions.

Ren-Min Ma: As you mentioned, Chinese students might not have a strong spirit of questioning. Why do you have that? Why could you boldly argue with professors when you were a young student?
Xiang Zhang: I think I am very lucky. I was strongly encouraged to ask questions by some of my teachers and advisors when I was a college student at Nanjing University about 40 years ago. One of them was Prof. Zhiguang Feng in the Department of Physics. He was vice chancellor and had just come back from the US. He liked to wear a red jacket, very bizarre at that time. He encouraged students to ask questions, to challenge him in his classes. I was also encouraged to ask questions by my advisors, Prof. Duan Feng and Prof. Naiben Min. So, I feel I am very lucky, and I sincerely hope that the younger generations of professors can also encourage students to ask questions, to challenge them. As I said, it's very important to ask questions, to have an atmosphere of equality in discussion.

Ren-Min Ma: You have a legendary career. You got your college education in China and your PhD in the US. You achieved great success as a professor, and became academician of engineering a while ago. You are now the President and Vice-Chancellor of the University of Hong Kong. Can you share your experience in achieving that?
Xiang Zhang: Again, I feel I am very lucky. Many of my classmates chose to do business or other things, leaving us the opportunity to do science.

I think, especially people like us do research of science and engineering primarily from enthusiasm for truth and knowledge. As I mentioned, one must not be afraid of challenging academic authority. In many cases, the teacher may also make mistakes during discussion. As a teacher, it's important to let your students know you're wrong, and this will help to encourage their ambitions. The student feels that if the teacher also makes mistakes, then it is possible to find the teacher's problems and faults. Gradually, the student would have the same spirits as the teacher. Upon graduating, the student's cognitive competence would be actually about the same as the teacher's. It is like when a young monk from Shaolin Temple is about to leave: he will have a contest with the old monk. If he could defeat the old monk, it means that his ability is similar to the old monk. This is why I believe this ability must be trained.

Second, I think perseverance is very important. In fact, as I said earlier, I am not the smartest person, but maybe I am a person with more diligence and persistence. Such characteristic is very important, and it is also needed whether it is for learning or doing other things. Since 95% of the time spent in science is either for failing or for solving problems, perseverance and persistence are very important.

Ren-Min Ma: When I instruct students by myself, I often tell them to persevere, but maybe at a relatively young age, it is difficult for them to realize the great value that perseverance can create. They have maybe full of questions about the future, or may be inclined to choose other ways when they encounter setbacks. Especially for these young students, can you give some advice on how to maintain the perseverance you just mentioned?
Xiang Zhang: Yes, this is actually a question of cultivating talents, and I've also spent a lot of time thinking about it. In fact, there are many merits in our eastern culture, but also with many utilitarian ideas. Both parents and students want to constantly plan the future, but if you plan too much, the real genius will not result from such plans. Therefore, young people should be given broad space to explore freely.

But we live in a realistic society, and everyone is planning about what should be done after graduation. This is normal. But regarding cultivating scientific talents, especially big talents, we need to encourage them to have imaginative ideas and be patient. That is to say, don't constantly think about some particularly practical problems. Don't be restrained by practical problems such as how high the salary you can get after graduation.

I just mentioned that one of my students did not publish a single article in the previous 4 years, not even a successful experiment, but in the end, he performed very well. Another experiment we had done for 6 years, and it has solved a major scientific problem, that is, whether phonons can propagate in a vacuum. Previously, scientists believed this was impossible. Phonons are vibrations of atoms; then how do you vibrate when you don't have atoms? How do phonons propagate?

I was asked a question by a professor during my doctoral qualification exam, and this man, who is now the President of Virginia Tech University, named Timothy Sands, asked me a question. He asked, "If I'm talking to you in this room, and you can hear me, why?"

I answered, "Because your vocal cords vibrate when you speak, and the air transmits this vibration to my ear, then my eardrum is vibrating, so I can hear your voice." He continually asked, "If we exhaust all the air out of this room, can you hear my voice then?" I answered, "Of course not."

I answered this question 30 years ago, but 25 years later we proved it was wrong. Sound can actually travel in a vacuum, which is incredible. We had been doing this experiment for 6 years, and three doctors contributed to it one after another, and finally the third person fulfilled it. So, if you want to do something big, patience is necessary.

So, I think, for young professors, you must encourage your students to have original thoughts. Even it means cutting down one or two indifferent papers, you must do something great. Then the next question comes out. Students may say that we have challenged great things but failed to publish papers, and we can't find a good job, or can't go to Harvard or MIT for the further study, so what should we do then? In fact, there are many paths in life. In the future, no matter what you do, be a politician or be a banker, even if you take a job that is not physics-related at all, as long as you have had such an experience, you will think a step beyond the others, which is very useful for your future career.

So, from a practical point of view, doing this is also very useful for long-term intellectual development. You can have a perspective that others can't have, and solve problems that others can't solve.

Ren-Min Ma: Thank Prof. Zhang for your sharing. Every time I talk with you, I feel that I benefit a lot.
Xiang Zhang: There are two words I have been talking about recently. Our country and universities often talk about cultivating talents, but you have to differentiate the concept of "talented person" from that of "qualified person." A "talented person" is someone who is talented, creative, and has the potential to change the world. A "qualified person" is the one who can do a good job and work conscientiously. The two are very different.

Well, a society as big as China is definitely going to cultivate some talented people who are going to create something brand new that we can't even imagine today.

Ren-Min Ma: I think this may be what you most want to do now, Prof. Zhang. Can you share with us your current focus and what you most want to achieve?
Xiang Zhang: What I am most pleased with is that while making a little achievement in science, I have cultivated a group of students who have served in many schools, such as MIT, Yale, Berkeley, etc. They are leading the development of many academic fields, especially in the field of photonics, which is quite gratifying to me.

My current focus is mainly administrative work, such as trying to create a good scientific research and teaching system to cultivate talents. This is of course not the same as doing pure science, but I hope to be able to apply some of the previous successful experience to my current work. I think about how to create an atmosphere with both eastern and western cultures, and a simultaneously free and innovative environment in Hong Kong. Our professors can also challenge me. We are now doing a lot of reforms in the salary system and academic culture. The purpose is to enable everyone to give full play to their abilities and to do top-notch research. Of course, this includes liberal arts, philosophy, finance, and all other aspects: How can academic excellence be realized at HKU?

I think that's what a lot of other principals are considering too. Let me continue the metaphor of the chef. There are many different elements at hand, and what I have to do is figure out how to combine them to produce a synergistic effect, a synergy whereby the outcome of 1+1 is greater than 2. Cultivating such a culture and innovative atmosphere will enable our thousands of scientific researchers at HKU to do the best research and the top science and technology work.

Ren-Min Ma: Thank you, Prof. Zhang. Last year you won the "SPIE Mozi Award" – congratulations! Please share some of your feelings about winning this award?
Xiang Zhang: Well, thank you. First of all, I thank SPIE for the recognition of our work, which is the result of the hard work of many of our students and postdocs. It is a reward for our entire team, and it is also an honour for all of us.

I still do research, but cannot spend as much time as before. What makes me really happy is that many of the lab alumni have become leading researchers in their fields. They are faculty members in top universities in China, US, and Europe. Even the third or fourth generation students are now becoming recognized researchers. So, I am very happy for having the chance to do research, for having discovered some interesting phenomena, for having supervised these outstanding students.

Ren-Min Ma: Thank you, Prof. Zhang. Lastly, I would like to take the chance to thank you for mentoring and advising us.
Xiang Zhang: It's my great pleasure. I would like to thank all of you too. I often watch your websites and learn about your recent progress. I am very happy to see you all are opening new fields. The spirit of innovation and challenge are our tradition, and are most important for doing excellent science.

Ren-Min Ma received his PhD degree in physics from Peking University in 2009. He was a postdoc researcher at UC Berkeley from 2009 to 2014. His research interests include laser physics, nanophotonics, light-matter interaction, non-Hermitian, and topological photonics.

Xiang Zhang is the President and Vice-Chancellor of the University of Hong Kong. Prior to joining HKU, he was the inaugural Ernest S. Kuh Endowed Chair Professor at the University of California, Berkeley, and the Director of the US National Science Foundation Nano-scale Science and Engineering Center (SINAM). He has also served as the Director of Materials Science Division at Lawrence Berkeley National Laboratory (LBNL). He is an elected member of the US National Academy of Engineering (NAE) and of Academia Sinica, a foreign member of the Chinese Academy of Sciences, and a fellow of the American Physical Society (APS), the Optical Society of America (OSA), the American Association for the Advancement of Science (AAAS), and the International Society for Optics and Photonics (SPIE). Professor Zhang's research focuses on materials physics, metamaterials and nanophotonics. He has published over 390 journal papers including over 90 publications in the *Science* and *Nature* portfolios. In 2008, his research was selected by Time Magazine as one of the "Top Ten Scientific Discoveries of the Year" and "50 Best Inventions of the Year"; Discover Magazine's "Top 100 Science Stories," in 2007; and R&D Magazine's top 25 Most Innovative Products of 2006. His research has been frequently featured in international media, including the BBC, CNN, ABC, *The New York Times*, and *The Wall Street Journal*. In 2019, his research team's work on the "Casimir effect" was selected as one of the Top 10 Breakthroughs for 2019 by *Physics World*.