Three decades riding the photonic crystal fiber wave: an interview with Prof. Philip Russell

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Prof. Philip Russell, Emeritus Director of the Max Planck Institute for the Science of Light in Erlangen, Germany. Prof. Russell sat for an *Advanced Photonics* interview with Prof. Long Zhang. View the video at 10.1117/1.AP.6.6.060501

Zhang: Hello, Professor Philip Russell, nice to meet you in Shanghai! The first question I would like to discuss with you today is: you led a research team that produced the world's first photonic crystal fiber (PCF) in 1995. Can you briefly introduce to the general audience what PCF is and what its functions are?
Russell: Sure! The most common form of PCF is a strand of glass, slightly thicker than a human hair, and it contains a 2D lattice of hollow microchannels running along its length. This lattice of very thin hollow channels mimics a crystalline array of atoms such as you see in a semiconductor crystal, but at scale is some 100,000 times bigger. But even so, these channels are so small that a million of them would fit along your arm if you laid them side by side, they are really very small. If you design this lattice of channels correctly, it has the amazing ability to perfectly reflect light, even though it's made from transparent materials, typically air and glass. This is because it supports a photonic band gap, which means that under certain conditions, light is unable to enter the 2D lattice of hollow channels, because it makes a perfect mirror. You can make a hollow waveguide by surrounding a larger hollow channel with this photonic bandgap lattice. Light is unable to escape into the photonic crystal cladding, and remains in the hollow core.

Zhang: It's said that you were inspired by the design of this type of fiber while attending the CLEO conference. I am curious about what kind of discussion inspired you.
Russell: Yes, it's a bit of a long story so I'll take a few minutes to explain. When I did my PhD at the University of Oxford in the second half of the 1970s, I became very interested in the theory of electromagnetic band structure and optical Bloch waves, as a result of working on the theory of volume holography. After my PhD I was very fortunate in 1982 to join a group at the Hamburg University of Technology, as an Alexander von Humboldt fellow. This group was headed by Reinhard Ulrich, he's not so well-known anymore, but at that time he was very famous for his work on guided-wave optics. While he was at the Max Planck Institute for Solid-State Physics in Stuttgart, he started an experimental project with PhD student Remigius Zengerle in 1974, investigating optical band structure in what are now known as photonic crystals. So he was probably the only scientist in the world who was thinking back then along the same lines as me about optical band structure. So, having carried out experimental and theoretical work on optical Bloch waves from 1978 to 1983, I was in a very good position to understand the implications of Eli Yablonovitch's suggestion, at the end of the 1980s, that it might be possible to create a photonic band gap.

There was lots of excitement back then about this idea of a photonic band gap. Of course, I wanted to have a piece of the action. I didn't want to be standing in the sidelines, I wanted to get involved. I happened to be working in fiber optics at the same time, so it was very natural, actually not difficult, to imagine putting these two fields together. At the beginning, though, I was faced with a lot of skepticism from experts on fiber optics, they had all sorts of comments: "Photonic band gaps, they won't form because the index difference between glass and vacuum is too small." Or "Making such a complex and perfectly ordered microstructure, that's near-impossible using fiber drawing." Then journalists would ask a question like, "You have a fiber with hollow channels and you're using it in telecommunications and it's going under the sea, what happens if the fiber breaks and the sea water goes into the hollow channels?"

As a result of all this, I actually made a joke of the idea and I would say I wanted to make holey fiber, and I'd point out that "holey" had an "e" in the word because if it doesn't have an "e," it means something entirely different (Fig. 1).

Zhang: Many people think that the single-mode fiber developed by Charles Kao, and the photonic crystal fiber developed by you, may be two of the most important inventions in the field of fiber optics. So, the question is: how did the photonic crystal fiber, you think, change the field?
Russell: I'm not sure I'd agree to a comparison with Charles Kao, I mean his invention has really revolutionized all aspects of our lives.

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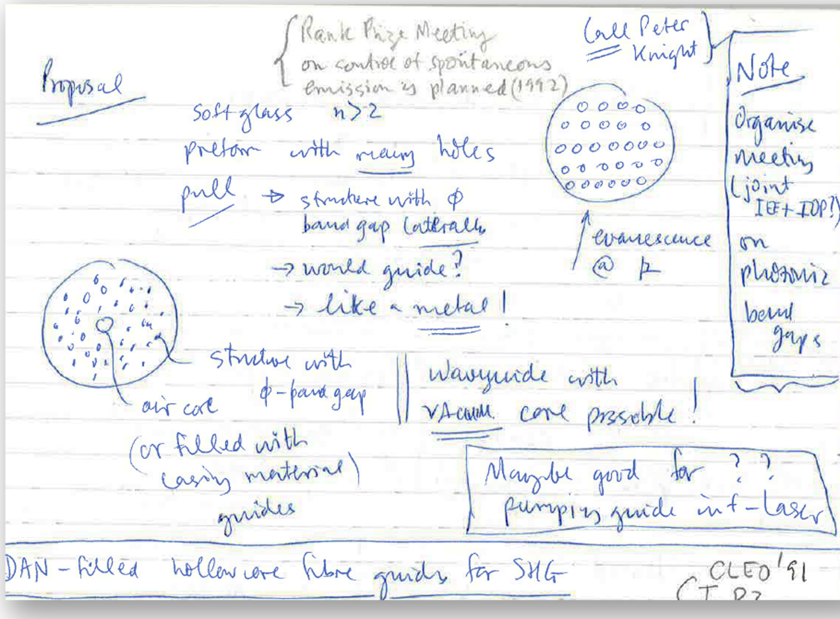

Fig 1 Notes made at the Conference on Lasers & Electro-Optics (CLEO), Baltimore, USA (May 14, 1991).

The modern high bandwidth internet exists entirely because of his brilliant idea.

But PCF has also contributed some interesting breakthroughs. It has radically extended the range of things that you can do with optical fibers. The main reason for this is the larger refractive index difference between glass and air, compared to the very small refractive index difference in conventional fibers. This offers a much bigger "lever" allowing you to change the properties of optical fibers over a much wider range than you could before (Fig. 2).

So, not only did this make a photonic band gap guidance mechanism possible, but it also revolutionized nonlinear optics in gases because you could make a hollow core and keep light tightly focused over very long distances in basically empty space, which you could never do before, due to diffraction and the Rayleigh resolution limit. If you focus a laser beam using a lens you get a certain depth of focus in a certain spot size; they're proportional to each other. You can't keep the light tightly focused over hundreds of meters. Hollow core fiber made this possible for the first time and that is really revolutionary. If you put gas in the hollow core and vary the pressure, you can change what we call chromatic dispersion, which causes different colors to travel at different speeds. This ability to tune the chromatic dispersion has turned out to be an incredible tool for doing all kinds of new experiments in nonlinear optics.

Zhang: In fact, after the successful development of PCFs, they had an unlimited impact on ultrafast optics. In 1999, Bell Laboratories used PCFs to generate a frequency comb across one octave in a titanium sapphire femtosecond laser, which made substantial contributions to John L. Hall and Theodor W. Hänsch's 2005 Nobel Prize in Physics. As the founder of PCF, could you say a little bit more about the significant impact of PCFs in ultrafast lasers and nonlinear optics?

Russell: Certainly, supercontinuum generation as we call it, this was the first major breakthrough application of photonic crystal fiber. The story is that there was a team at Bell Laboratories who, after

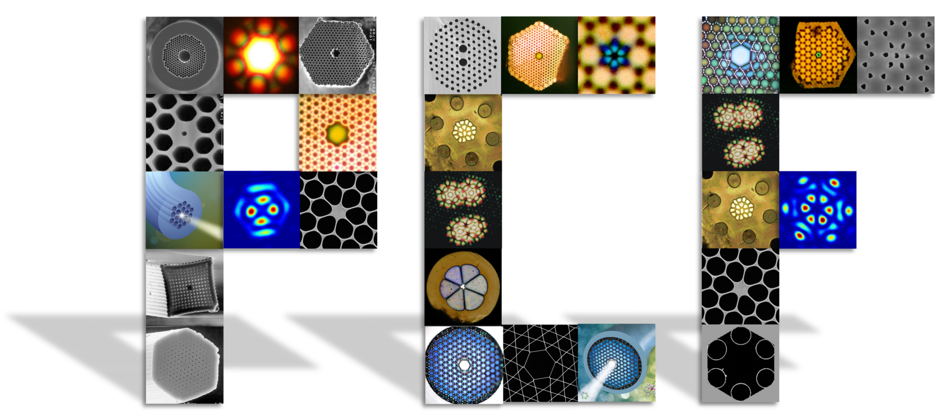

Fig. 2 Different types of PCFs and some beautiful optical modes propagating in them.

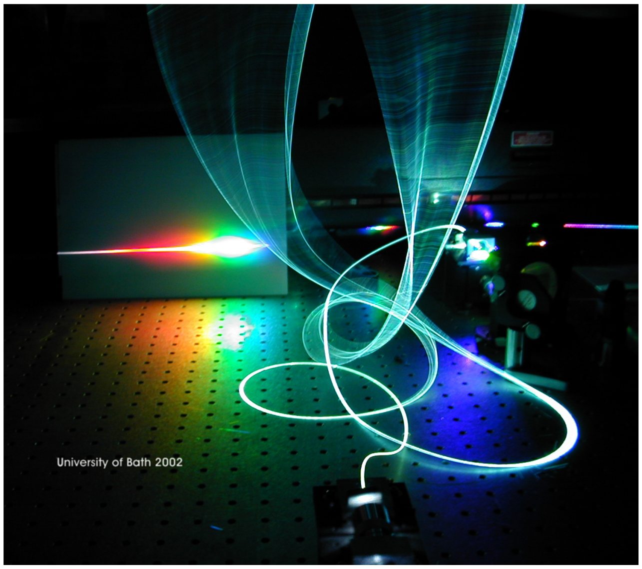

Fig. 3 Supercontinuum generation in PCF.

noticing our post-deadline paper at the Optical Fiber Communications Conference in 1996, said why we don't try and make a fiber like these guys are working on. So, they went back to the lab and set about reproducing our work. They produced what to be truthful wasn't a very nice-looking fiber, but it had a very small glass core which allowed the chromatic dispersion to be made anomalous (blue light travels faster than red light) at 800 nm. They had access to an 800-nm ultrafast mode-locked laser in the laboratory of Alex Gaeta at Cornell, and so were the first to observe ultra-broadband supercontinuum generation. In a fiber like that, anomalous dispersion is caused by a very small core surrounded by hollow channels, which overcomes the normal dispersion of the glass and shifts the zero-dispersion point to shorter wavelength. The result was an octave-spanning femtosecond frequency comb, that was used by Hall and Hänsch to build a simple optical clock with astonishingly high temporal precision and helped them win the 2005 Nobel Prize (Fig. 3).

Continuing on the topic of nonlinear optics, gas-filled hollow core fiber is even more revolutionary in terms of the physics and the science. In 2003, my group at the University of Bath reported stimulated Raman scattering in hydrogen at a threshold power that was 100 times lower than ever seen before. Mike Downer of the University of Texas in Austin wrote a perspective for *Science* at that time in which he stated that "A new era in the nonlinear optics of gases is about to begin."

After moving to Erlangen in Germany, we started exploring in more detail nonlinear optics in gas-filled hollow core PCF, showing for example that you could compress pulses down to single cycle durations using only a few micro joules of energy—about a thousand times lower than in any previous experiments. All you needed was just a short length of hollow core PCF and a system for adjusting the gas pressure. The opportunity to use mode-locked lasers running at very high repetition rates and generate trains of single cycle pulses at mega-hertz rates has made all kinds of experiments much easier and faster to carry out. We also discovered that you could generate wavelength-tunable deep and ultraviolet light by varying the pressure appropriately. This has become a very important new source of ultraviolet light in recent years.

Zhang: I noticed that after successfully preparing PCF, you and your team applied for technology patents in different countries and regions such as the UK, the US, Europe, China, Japan, and Republic of Korea as soon as possible. How did you realize at that time that there were huge business opportunities for PCF beyond scientific research applications?

Russell: Yes, while at the University of Bath in the late 1990s, I became increasingly convinced that there must be some commercial opportunities in these ideas, so we started filing patents. Then just by chance in the early 2000s, some venture capitalists from Canada turned up at the university, wanting to visit various groups and discuss opportunities for funding startup companies.

So, that was about 1999 or 2000. I spent about half an hour introducing PCF and then one of them, a technology guy (they always have a technology guy), said he would sign a check for 60 million dollars on the spot! He almost pulled out his checkbook and we were really shocked by this. I mean of course we didn't accept it, that's a lot of money to take. But after further negotiations, we ended up taking 9 million dollars and launched the company Blaze Photonics Ltd. The company worked on a few different ideas, but eventually settled on developing hollow core fiber for long-haul telecoms.

Unfortunately, after the financial collapse in the early 2000s Blaze Photonics ran out of money, so we weren't able to push the idea further. As it turned out, we were 20 years too early.

Zhang: So, what is the latest research in the field of PCF that surprises you? What areas of breakthrough progress do you hope for in the next 5 to 10 years?

Russell: Yes, there are a lot of things I can talk about. But as I just mentioned, the goal of Blaze Photonics was ultralow loss hollow core fiber for long-haul telecoms. Recently a team at the University of Southampton (which is actually where my group made the very working PCF in 1995), led by Francesco Poletti, has recently succeeded, 20 years after Blaze Photonics ran out of money, in producing a hollow core PCF with a loss at 1550 nm which is lower than the best conventional solid-core fibers. After propagating along 40 km length of this fiber, only half of the power is lost. It's almost as transparent as free space.

I actually always thought that extremely low loss might be possible since the light is traveling basically in empty space, it hardly interacts with the glass at all. Nevertheless, this is a very, very exciting result. Apart from astonishingly low loss, we'd always realized that guiding in a hollow core fiber made it possible to work at shorter wavelengths, you could use near-infrared light for telecommunications because Rayleigh scattering is very much weaker than the conventional fibre with its solid glass core.

To bring the story up-to-date, Microsoft has recently invested in hollow core fiber for ultra-broadband communications between the huge data-centers that we have these days. Incidentally, light travels one and a half times faster in the hollow core fibers. That turns out to have some advantages too. There are lots of other things I could discuss, I could go on for a long time with all the other results that we're come up with.

Zhang: You are a cofounder of the Max Planck Institute for the Science of Light (MPL), which has now grown into a world-class optical research center and continuously produces surprising academic achievements. What opportunities did you encounter in founding such a research institute, and what was the original intention behind the establishment of the institute?

Russell: The idea for creating a new Max Planck Institute that focused more strongly on optical technologies was the brainchild of my co-director, Gerd Leuchs, who's the current president of Optica, and the late Herbert Walther, who was actually his PhD supervisor.

Fig. 4 Russell Division, Max Planck Institute for the Science of Light (April 2015).

So, the two of them cooked up the idea of a new Max Planck Institute. And initially they raised five years' worth of funding to set up a Max Planck research group. This was a pilot group to see if it was feasible to create a full Max Planck Institute, that was in 2003, and I joined this group in 2005 from the University of Bath.

We had the task then of proving that we could establish strong research programs in anticipation of the formation of a full Max Planck Institute. Finally, we succeeded and in January 2009, the Max Planck Institute for the Science of Light was established. The Max Planck system is very nice if you're a director, because you have generous funding and complete freedom to work on whatever interest you. That was very attractive for me, since raising funding in the UK was getting increasingly difficult. So, that's the story of my involvement in the MPL (Fig. 4).

Zhang: During your nearly 50 years of scientific research, you have cultivated a large number of outstanding young talents. Could you share your experiences in guiding and cultivating the next generation of scientists in the field of optics?
Russell: First of all, I'd like to make clear that the achievements of my groups were only possible because of all the talented, mostly young, people I've worked with over the years. I've always been very keen to encourage students and young scientists to think for themselves, and always be skeptical of what you read in a journal paper. Don't believe anything until you've checked it yourself, until you've thought it through. This is very important, because there are actually lots of mistakes in the literature, also in my own papers!

I also like to encourage students to spend a proportion of their time in what I like to call "conscious dreaming," where you just sort of shut your eyes and just let thoughts come by and float in. By letting your imagination wander freely you can capture new ideas. Though of course there's a lot to learn in photonics and physics, the learning never stops, certainly not in my case. Also, don't just read papers, but actually go deep into understanding what the papers are about. That means actually doing all the theory and so on. And also, never forget that research goes in cycles, you can have periods of depressingly low productivity, when you say, "Oh, is anything ever going to happen?" Then followed by, you know, a peak of exciting new results and maybe even breakthroughs if you're lucky enough.

The other thing I think is that open discussions with fellow students and postdocs are absolutely vital to success, because this produces a fertile environment for new ideas to be caught, captured, and maybe pursued. That's not always present in every group, but I've always made sure to invite everyone to participate in discussions so that there are no kind of secrets or whatever, nothing is going on in the background that can cause difficulties between people. It's very important, I think, if you're managing a group, to make sure that doesn't happen.

Zhang: What advice would you give to young students and technicians who aspire to pursue the field of fiber optics and nonlinear optics?
Russell: Nice question. Work hard, take time to dream, like I said. Aim to understand the physics of your work at the deepest possible level, don't be superficial. Discuss openly with your colleagues and choose your research group very carefully. And don't be afraid to suggest apparently stupid ideas; they may actually be very important. Always make sure to ask lots of questions at seminars and talks.

Zhang: Yes, to take time to dream. In your opinion, what role can photonics research play in current hot topics such as climate change, life and health sciences, and renewable energy?
Russell: Photonics has become a massive field, penetrating every aspect of our lives. PCF itself has proven useful, for example, in realizing very high-power fiber lasers for industrial machining, and in creating ultraviolet light sources for medicine and sensing. Photonics as a whole has of course revolutionized so many things. Solar panels, which have revolutionized electricity generation, and the now ubiquitous LED lights, which have revolutionized lighting, emerged from photonics research. Almost every aspect of life has some photonics in it.

Fig. 5 Russell Centre for Advanced Lightwave Science, SIOM, Hangzhou, China (May 2024).

Zhang: We know that following retirement you have joined former members of your MPL group in establishing a new research centre in Hangzhou – the Russell Centre for Advanced Lightwave Science (RCALS, https://www.r-cals.com). Can you say something about your plans, and also about your vision for the new centre?

Russell: Yes, I see my role in RCALS, as we call it, as helping steer the research into new curiosity-driven directions. That's basically what I do, establishing a culture of free and open discussion. I think that's, as I mentioned, really important. During this initial phase, of course, a lot of effort is going into setting up all the equipment and the laboratories and recruiting top quality students and staff (Fig. 5).

I'm hoping within maybe 2 or 3 years, we'll have established a successful and growing research program, exploring a number of exciting new topics around the opportunities offered by PCF. These could include new laser sources, new kinds of light guide, optical sensors, advances in the fundamental understanding of nonlinear optical processes, for example. I'm also hoping we'll be able to attract more international students and postdocs to Hangzhou. They could come for a few years as part of their career path. We already have an excellent core team of professors and we're recruiting more. So, I believe we're already on a good path.

Zhang: Thank you for your precious time to accept the interview.

Russell: Thank you for the invitation.

Long Zhang is vice director, doctoral supervisor, and professor at Shanghai Institute of Optics and Fine Mechanics (SIOM), Chinese Academy of Sciences. As leader of the infrared materials team, he graduated from SIOM with a PhD degree in 2000 and worked as a postdoc at Muenster University in Germany from 2001 to 2005. He invented high-performance large-size infrared glass and fibers with independent intellectual property rights, which is internationally leading in comprehensive performance, and has continued to obtain important applications in aviation and aerospace. He has studied the control of artificial microstructures on light fields, and explored the basic photophysics of microcavity control, achieving high-performance micro-nano single-mode laser output.