In the limelight

Twenty five years since the birth of the field of photonic crystals, Eli Yablonovitch talks to *Nature Materials* about his pioneering contributions to the field and his vision for nanophotonics.

In 1987 you started working on the idea of a photonic crystal. What made you consider such a problem?

At that time, some papers had appeared suggesting it was possible to suppress spontaneous emission (SE). I think the first paper was by Dan Kleppner, an atomic physicist from MIT, who suggested putting an atom between two metal plates[1]. However, that covers only 50% of the SE, that is, it suppresses one polarization but not the other. Then a series of papers appeared where instead of using a metallic reflector, use was made of one-dimensional (1D) Bragg gratings. I looked at that and said: "That can't possibly be right" because you cannot suppress SE in that way — it will simply go sideways, propagating parallel to the planes, and therefore there would be little benefit by using a 1D Bragg reflector. I asked myself how to convert a 1D reflector into a 3D Bragg reflector, and started drawing lines on a page. They were just cross-hatched lines. Staring at them, the lines 'turned' into a checkerboard. I visualized a checkerboard in two dimensions. I then realized that a checkerboard extended in the third dimension is a face-centred cubic crystal — and that's what started it.

What was the initial reaction by the photonics community?

I got no reaction, and I was very surprised because I thought it was a pretty exciting idea. It seemed like the photonics community just ignored it for quite a long time and did not necessarily regard it as of any great significance. I would estimate that in the first five years after I published that paper[2] there were only five citations and two were mine. So, the idea was misunderstood and not really grasped at the initial stages.

What were the specific challenges that had to be overcome before the idea gained wider acceptance?

A realization of the potential importance of the idea began to emerge when I published some experimental results, and then the theorists could have something to calculate. That was three years after the original idea. At first I thought it would be easy to create a photonic bandgap and that I would discover it right away. As I went along I found that coming up with the right structure was much harder than I expected. And because we were using an 'Edisonian' (cut and try) approach, we were literally drilling holes in ceramic-filled plastic, done with a numerically controlled machine tool, hoping for a microwave bandgap. A breakthrough emerged when Professor Kai-Ming Ho from Iowa State University analysed the diamond structure. To the present day we don't know of any better electromagnetic structure for creating photonic bandgaps.

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In what way did photonic crystals break away from earlier works on periodic photonic structures?

The early work really dates back to Lord Rayleigh. Lord Rayleigh was a brilliant man and he figured out that if you have a 1D periodic structure you get a bandgap. It seems that for 100 years people knew about the 1D forbidden bandgap but for some reason nobody considered the 2D or 3D versions — in particular, how to attain a full photonic bandgap in all three dimensions, a non-trivial result. Sajeev John also had the same idea. So even though we were neglected by the photonics community, at least we were noticing one another. I was very encouraged that I was not alone. I remember I thought that this would develop into an important field. So I made an appointment to visit John — he was at that time an Assistant Professor at Princeton. I visited him and while we were having lunch I said "Look, if we both call it 'photonic crystal', probably the name will stick"; and so, we agreed between ourselves that this would be the name — it was a decision the two of us made together.

During these 25 years, what have been the fundamental or technological implications of research in photonic crystals?

There are a series of different applications. First, silicon photonics integrated circuits, in which the coupler is in effect a 2D grating coupler (2D photonic crystal) taking the optical signal from a fibre and sending it into a silicon circuit. This is commercialized by Luxtera. The next application is photonic crystal fibres. Here, one use is in quasi-continuum generation, with many more in nonlinear optics. Such fibres have been commercialized by a Danish company, NKT Photonics. The third application is actually not a true 3D photonic crystal, it's more like a Bragg reflector but it's used for cancer surgery. The company commercializing it is OmniGuide. It is used to guide laser light for cancer surgery when people have cancer inside their throat. I would say that this particular application is saving many people's lives, every day. The fourth is to enhance the emission from light-emitting diodes. It is solving the problem of extracting the light from light-emitting diodes, which is a very big problem in trying to achieve high efficiency. Here, our aim is not so much to control SE but to extract it. A company that specializes in this is Luminus Devices, which is using these for projection displays. The fifth application is to assist accelerators. There are high-frequency modes in microwave cavities that are used in electron accelerators. These undesired modes disturb the electron trajectories; so the aim here is to use a metallic photonic crystal to suppress the higher-frequency modes. Finally, we have now discovered many different types of photonic crystals in nature — which had photonic crystals long before we came across the idea. The most famous example is the peacock, which has brilliantly coloured feathers, and these are 2D photonic crystals. But throughout the animal world, whenever you have a blue or white colour, it's usually coming from a natural photonic crystal.

Were there any early ideas that did not work?
That's an interesting question. It is now possible to make a high-Q resonator without using a 2D or 3D photonic crystal. For many years, we believed that the only way to make a high-Q resonator was with a 2D or 3D photonic crystal, and now we have designs of high-Q resonators that are 1D. I think that's an example of an idea that has evolved over time. To make a high-Q resonator is not as hard as we thought, and does not necessarily require 2D or 3D periodicity. Another example is that in one of my early papers[2] I said that a simple face-centred cubic crystal was enough to create a full photonic bandgap, but it was proven that it only had a pseudo-gap[3–5]. This idea was later superseded, when it was shown that only a special type of face-centred cubic crystal is appropriate, the diamond structure.

Where do you see the field going in the next 25 years? What challenges lie ahead?
I'm always looking for bigger applications. Silicon photonics is poised to become a gigantic technology and part of every silicon chip. This will emerge over the coming years. It has taken a long time to get to this stage but every silicon company is now examining the use of silicon photonics, which employs a 2D grating coupler-photonic crystal. Another area where photonics have a large impact is solar cells. Today, they have a random surface texture for trapping light, but over the next 25 years as solar cells become thinner, the random texture is going to become a periodic (photonic crystal) structure.

In your view, what are the grand challenges for photonics today?
Photonic crystals were dedicated initially to suppressing SE but the world is much more interested in enhancing it, and there we see that optical antennas can play a role. With antenna enhancement, we will have SE that is faster than stimulated emission, and this will become of great importance for short-distance optical communications. In a sense, the opposite of a photonic crystal is an optical antenna. Instead of suppressing SE, the optical antenna can accelerate it by many orders of magnitude. If we can speed it up by a factor of 200, light-emitting diodes will be faster than the fastest laser. That's a big projection — people will find it hard to believe that SE can be faster than stimulated emission.

Photons are great for transmitting information, but how about digital or logical operations? Could photons outperform electrons for such applications?
That has been a hope for at least 30 years, but it doesn't seem like that's the technological direction. For photonics it seems that the direction is towards communications rather than digital logic functions. In fact, you cannot have digital functions without communications. The reason is that if you have a logic function, it is worthless unless you can transmit it somewhere. Photons can be used to communicate digital information — that's really the more challenging function. We have many ways to do logic but we do not have very many ways to communicate. We shouldn't feel that there is something missing if we cannot use photonics for logic. Instead we're using photonics inside logic chips for the most important function of all, that is, for communicating data.

Other fields, such as metamaterials, have been influenced by and, to a certain extent, born out of research on photonic crystals. Are you keeping an eye on developments in those related fields?
Certainly. Metamaterials are the low-wavevector limit of a photonic crystal, and by using metallic structures there is much more richness available. We can get an effective permeability, effective permittivity and very unusual properties. And this has certainly been very important. But the other thing that has come from the study of such materials is the recognition of the power of metals in controlling electromagnetics. When radio waves were initially discovered they were controlled — not surprisingly — by metals, but for some reason it has taken 100 years to transfer those ideas into optics. I think we are now going beyond metamaterials, we are going to metal optics where we are making metallic nanostructures. The most famous is the optical antenna itself, by which we can get enhanced rather than inhibited SE. I think that we will say we have accomplished something very important in metal optics when we have accelerated SE to a faster modulation speed than stimulated emission. When that happens, we can say that we will have reached an important milestone in the field.

You have also been working on solar cells and low-energy switches. Tell us about your research in these areas and whether nanophotonics has a role to play there too.
We have a project, based in Berkeley but including other key universities, to make electronic digital processing more efficient. We are looking at replacing the transistor with another type of a switch that operates at a much lower voltage. At the same time, we also need to reduce the energy cost of short-distance optical communications. So, we have a number of interesting structures — which involve nanophotonics and optical antennas. Today's transistors seem to require approximately 1 V to operate, and we need to reduce this to a few millivolts. Thus, we need a new low-voltage switch to replace the transistor. This is within the realms of materials science and electronics. Optics will contribute towards some of the on-chip communication.

You have also been very active in commercializing scientific research. Does this now occupy most of your working time?
My philosophy about commercializing ideas is to hire the very best people possible and give them a lot of independence. They do a great job — each company is doing something revolutionary in its field. It's not me, it's the people in the company who are doing these revolutionary things. My most recent company, AltaDevices, has broken the world record for solar-cell efficiency — not by a small amount; they've taken the world record from where it was, at 25.1% efficiency, to where it is now at 28.8% efficiency. This emerged from the discovery that in addition to absorbing light, a solar cell only achieves the highest efficiency if it is also emits a small amount of light. This was not recognized before. Among the other companies that I've co-founded are: Ethertronics, a pioneer in the field of antennas for cell phones, and Luxtera, a pioneer in silicon photonics.

What are your future plans?
My plans are to continue doing research, as long as I continue to be blessed with good health. There are still so many unsolved problems: What is the new low-voltage switch that will replace the transistor? That's a big problem. How will we raise the solar-cell efficiency from where it is now to much higher efficiencies, by splitting the colours of the solar spectrum? Spectral splitting of the solar spectrum can raise the efficiency of solar cells from where it is now, almost 30%, all the way up to 50%. That's a big challenge. My third main goal is to make a SE source faster than a stimulated emission source. So, I think I have a lot of work left in basic research.

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