AUTHOR COMMENTARIES - From Special Topics

Photonic Crystals - October 2008
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Willem Vos

From the Special Topic of Photonic Crystals

According to our Special Topics analysis of photonic crystals research over the past decade, the work of Prof. Dr. Willem Vos ranks at #11 by total cites, with 24 papers cited a total of 1,585 times. He is a coauthor of the top-ranked paper on the list of 20 most-cited papers over the past 10 years. Three of his papers have been recognized as Highly Cited Papers in their field by Essential Science Indicators*SM from* Thomson Reuters*. The* Web of Science® *lists 48 original papers authored or co-authored by Prof. Dr. Vos cited a total of 2,511 times from 1998-2008.*

Currently, Prof. Dr. Vos is Group Leader in the Center for Nanophotonics at the FOM-Institute for Atomic and Molecular Physics AMOLF in Amsterdam, and Professor on the chair "Complex Photonic Systems" (COPS) at the Department of Science and Technology and the MESA+ Institute for Nanotechnology at the University of Twente, the Netherlands.

In the interview below,* ScienceWatch.com *correspondent Gary Taubes talks with Prof. Dr. Vos about his photonic crystals research.

SW: What factors or circumstances led you to your highly cited 1998 *Science* paper, "Preparation of photonic crystals made in air spheres in titania," (Wijnhoven JEGJ and Vos WL, 281[5378]: 802-4, 7 August 1998)?

After I started to work on photonic crystals in 1993, when it was a very young field, I first made them from colloidal nanoparticles. A photonic crystal is like a crystal of atoms—silicon, for instance—but magnified 10,000 times. The nice thing about colloidal crystals is they have just the right length scales for these photonic crystals. You can make really big crystals, fairly easily; you don't need any complicated fabrication infrastructure.

The downside, though, is that photonic crystals require a high refractive index contrast. What that means is this: a photonic crystal is a structure made of two different materials and they are interspersed in a regular fashion with typical length scales comparable to the wavelength of light. An important property of these two materials is that they should have as different as possible a refractive index—that tells you how fast the speed of light is in a material.

By using materials with different refractive indices, you achieve strong scattering, and light will be strongly perturbed in that material, which is exactly what you want. So these colloidal crystals had an insufficient refractive index contrast. The contrast was too small for what we wanted to do. I was thinking of how we could increase the difference.

"With these crystals, you can really drastically change how light is behaving."

SW: So how did you go about increasing the refractive index contrast?

Well, we had also made a kind of photonic crystal called an opal. This is like a stack of spheres, in which the nanoparticles are the spheres, stacked like canon balls, or oranges in the supermarket. And there's space between these spheres. The problem with this opal, though, is that it still had an insufficient refractive index contrast.

Then I was inspired by some work in which researchers had filled the space between spheres with another material. I thought that you could use this technique to infiltrate the space between the spheres with a material that has a high refractive index. That was the first step. The second step was the realization that we could then remove the original spheres from the opal. What you have achieved is called an inverse opal that consists of hollow spheres or air spheres, which is what we call them, now sitting in this high-index material. Now you have a photonic crystal with a very high index contrast.

SW: Is this structure called an opal because it has the same structure as the opal you would buy in a jewelry store?

Yes. What you buy at a jewelry store is pretty similar to what we make. It has nice colors, which are interference colors from this ordered structure.

SW: Why did you choose titanium dioxide for the material?

We chose it because we knew it has a high refractive index and it's also transparent for many wavelengths of light. You have to make a compromise here: if you chose a high-index material, the price you pay is that you have to use materials that tend not to be transparent. I wanted a material that was transparent in the visible spectrum, and titanium dioxide has about the highest-index out there. It was also fairly easy to make. For your information, titanium dioxide is also the stuff that makes paper and toothpaste white.

SW: Were you surprised at the results?

In a way, no, and in a way, yes. No, because I was indeed hoping for these results. Yes, because we first tried this with silica, which is silicon dioxide (the stuff in glass), and that didn't work at all. We tried that first because we thought it might be easier to do, and we were already working with silica. It didn't work. Then we said, "OK, if this isn't working, let's try the other one—titanium dioxide—and hope for the best." And it worked right from the start.

SW: What, in your view, is the significance of this paper for the field? Why do you think it's garnered such a remarkable number of citations?

Okay, this is, of course, guessing, but here goes. My guess is that we described how to make photonic crystals like these inverse air spheres, and then we also did optical experiments on them. We made a crystal much better than all the previous ones and showed that it was easy to make. You didn't need any involved clean-room methods or chemistry. You could basically make it in your own kitchen.

What's interesting, though, is that at the same time we published our paper, a similar paper was published by a group of chemists. But they didn't do the optical experiments that we did. We showed in our paper what such a sample looks like, and optical spectra. You could really see that it works. You could see this colorful luster. That's one of the reasons it's been so popular and that was an advantage we had over the other paper. They didn't realize the optics connotations of these crystals; they only showed electron microscope pictures.

SW: What are the technological applications for inverse sphere photonic crystals?

With these crystals, you can really drastically change how light is behaving. So the obvious applications are optics. After we published our *Science* paper, we showed you could put light sources inside these inverse opal crystals. We demonstrated that the crystals can make these light sources more efficient, or you can choose conditions that get them to emit less light. That's good if you want to collect light. You want it so that it does not reradiate away as light. Also, the type of crystals we described can probably be spray painted on surfaces. You can make coatings from them.

I should also add that the group of chemists who published their paper at the same time as we did wanted to make catalysts from these air spheres. That's an application that we hadn't considered. So you can probably combine chemistry with optics to make materials that react in specified ways under the influence of light.

SW: How has the field of photonic crystals and your own research evolved in the last decade since you published the *Science* paper?

I think our 1998 paper was influential in creating the big interest in this field. We made it easy to make interesting photonic crystals, and many people started doing it. So the inverse opals created an explosion of research that probably lasted until 2003.

"… science is useful in the long term, but it's also fun in the short term."

By that point, people had developed so many different inverse opals for so many different purposes that they shifted to doing the kinds of optical experiments necessary to study and measure the various phenomena predicted. Now there is much more of a push toward functional photonic crystals that will be useful different in applications.

SW: Can you give us an example?

One example would be similar to what I already mentioned. You put a light source inside your crystal and make the emission stronger or more directional. So you improve the efficiency of your light source. Another one would be switching photonic crystals with a short laser pulse to make a very fast optical switch.

SW: What have you been working on for the past few years?

We've been focusing more and more on how to make cavities inside photonic crystals. The cavities are important for making these crystals functional. The reason why photonic crystals were invented in 1987 was that you could really trap light in these three-dimensional cages.

We've also been working a lot lately on quantum dots, which are an important kind of light source that you can then put inside photonic crystals. And we are working a lot on using photonic crystals and cavities as optical switches.

SW: Which of your professional achievements brings you the most satisfaction?

I suppose that's the work in which we were first to control the emission of light sources by using these photonic crystals. We published that in *Nature* in 2004 (Lodahl P, *et al*., "Controlling the dynamics of spontaneous emission from quantum dots by photonic crystals," 430[7000]: 654-7, 5 August 2004) and that was the culmination of a lot of work, including the original work on these inverse opals. You can think of the *Science* paper as the infrastructure that we needed to do the 2004 experiment.

SW: Why did it take six years to go from the infrastructure to the culmination of the work?

In hindsight, you can always think that some period of time was too long. But when you're doing it, you're just finding out all the things you don't know at that very moment. For instance, one thing that we bumped into is that we first chose the wrong kind of light source to do the experiment. The first kind of light source we used basically died within the crystal. Then we chose a different light source (quantum dots), one that was much more stable, and we were able to demonstrate both this enhancement effect and inhibited emission.

SW: What would you like to convey to the general public about your work?

Well, quite often people ask scientists, "OK, that's nice what you've done, but what is it good for? Why should I be interested?" Since, realistically speaking, applications might typically be 10 or 20 years in the future, it does not impress Joe Sixpack. But you can also compare doing research to a Formula One car race. You can ask, "What's the use of a Formula One race," and the answer is not much and it wastes a lot of gas. Maybe they'll develop some new technology that they test in these races, but it's unlikely to be something I'll have at home, or at least not for another 10 years. The point is that it's still fun and exhilarating, both to the drivers and the spectators.

You can look at any field of science as a competition between different groups all over the world. In science we also want to win; we want to be first to make a new discovery. Our air sphere crystal paper in *Science* was the first of its kind—if it hadn't been, *Science* would not have published it. And that was fun for the participants and could be exhilarating for the onlookers. Science is also very cruel in that sense. It's like sports. You only remember the gold medal winners from the Olympics. No one remembers who won the silver medal. The other thing is that there's always a new race. So each one can have a different winner. So science is useful in the long term, but it's also fun in the short term. Finally, one often tends to forget that doing top-level science is essential to train young researchers, who are the people that make tomorrow's inventions.

SW: What do you see happening with photonic crystal research in the next few years?

Realizing that even my one-year prediction is likely to be completely wrong, I'll say that one thing I hope will happen—I don't know if it will—is that photonic crystals will branch out into other fields of sciences. For instance, you can imagine that they might start being used in biophysics and that there could be a whole field of biophotonics changing the properties of biological systems in a novel way. Furthermore, we will surely see surprises in our efforts to make more efficient light sources, lasers, and LEDs. And I think that tiny and sensitive photonic sensors could be a big hit in fields such as chemistry, biology, and perhaps other life sciences.

Another thing that I would love to see within 10 years is that photonic crystals will be used as elements in optical circuits. These are circuits where photons are running around instead of electrons. That will be very difficult to pull off, because photonic crystals as we now know them have too many imperfections. But we have just come up with technological tricks to use the light scattering from these imperfections to our advantage.

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Willem Vos's current most-cited paper in *Essential Science Indicators*, with 854 cites:

Wijnhoven JEGJ, Vos WL, "Preparation of photonic crystals made of air spheres in titania," *Science* 281(5378): 802-4, 7 August 1998. Source: *Essential Science Indicators* from Thomson Reuters.

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