# R&D Spirits

## *Ultrasmall Photonic Integrated Circuits Using Photonic Crystal*

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The unique optical properties of photonic crystal, a material born of nanotechnology, are attracting considerable attention. The Photonic Nanostructure Research Group at NTT Basic Research Laboratories is researching ways of applying those properties to new forms of optical information processing. Can information-processing devices based on photonic crystal open up new possibilities for communication networks? We put this question to Group Leader Masaya Notomi, who also told us about his future vision for photonic devices and networks and the cutting-edge research now taking place in this area.

### Successful fabrication of optical switches after seven years of effort

*—Dr. Notomi, could you briefly describe your present research?*

Our group is currently researching photonic crystal, which is an artificial structure having a periodically modulated refractive index (**Fig. 1**). In this research, we fabricate a two-dimensional photonic crystal on a silicon-on-insulator substrate using advanced ultrafine processing technology developed by NTT. Our plan is to use this structure as a basis for developing new optical materials. Photonic crystal has unique optical properties. For example, it has a wide photonic band gap in the wavelength region of optical communications that can function as an optical insulator. The use of this property for creating previously unachievable devices has, in fact, been researched for about ten years on a theoretical basis, but it wasn't until 2000 that advances in ultrafine processing technology overcame previous implementation difficulties and made it possible to actually fabricate photonic crystal. Our group has worked on the fabrication of several devices since we began full-scale research on photonic crystal in 1998.

*—In what way do you think this research will lead to advances in information communications?*

Well, I think it will mean a real breakthrough in optical communications. Although light is extremely good at transmitting information at high bit rates, information processing has not been one of its strong points. That's why electronic circuits have traditionally been used in nodes that require information processing. Since I have been researching photonics my entire working career, it seems to me that this has been an obstacle to higher speeds and lower power requirements in communication networks. Actually, the use of light for information processing is not impossible with present technology, but there are worries that doing so would require excessively large equipment consuming lots of power and high costs, resulting in a rather impractical system. On the other hand, if optical information processing can be achieved on a chip using photonic crystal, the stage is set for the construction of a low-power low-cost all-optical network providing ultrahigh transmission speeds. Such a chip would also reduce equipment size drastically enabling that equipment to be installed just about anywhere. At the extreme end, we can envision photonic-crystal chips being incorporated inside personal computers for use by individual users.

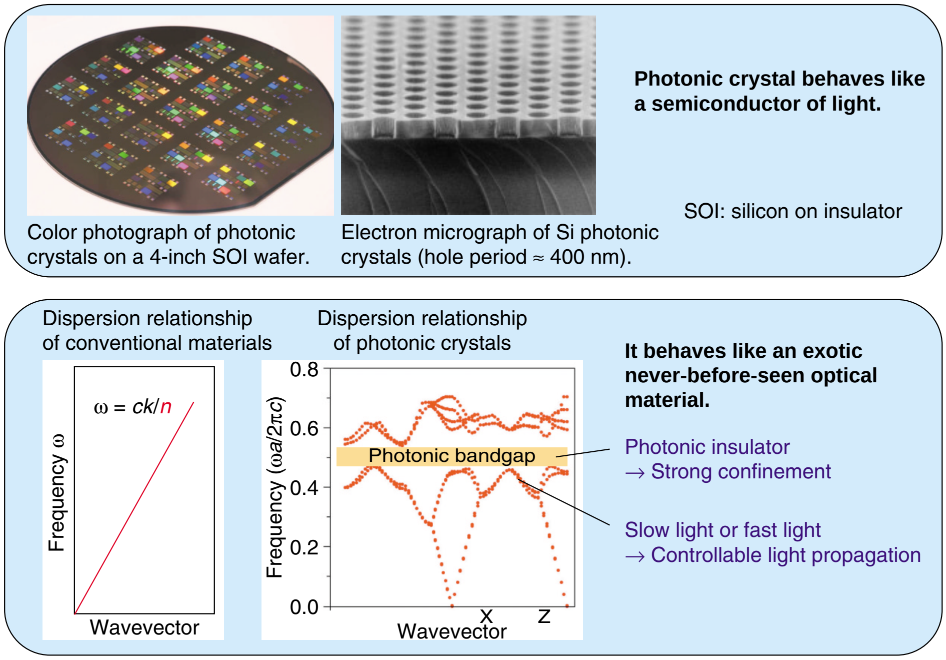


Fig. 1. Photonic crystals as new artificial optical materials.

Of course, this is still at the conceptual stage, but we are carrying out our research with such possibilities in mind.

*—What technology comes into play when attempting to achieve devices based on photonic crystal?*

First of all, in electrical engineering, functions can be achieved using the electrical properties of various types of material. This is not the case in the field of optics, where refractive index is the only physical property that can be used and it cannot be varied very much. In other words, there are no equivalents to electrical insulators and semiconductors in optics. This has been a limiting factor in optical technology. A photonic crystal, however, plays the role of a crystal lattice for light. This means that if a periodic structure can be fabricated with a period of from 200 to 400 nm, which is applicable to optical wavelengths, a photonic band gap can be achieved that allows no light to propagate, or in other words, that completely confines light. The photonic band gap is enabling designers to control light in ways that were impossible in the past. This, in conjunction with advances in ultrafine processing technology, is bringing devices like photonic ICs and photonic LSIs out of the theoretical domain and into the real world (**Fig. 2**).

*—How is this research progressing at present?*

We have already fabricated photonic-crystal waveguides and resonators as well as optical switches that combine those devices. Of these, the waveguide is the simplest of all. With our waveguide, we can slow down the propagation of light to 1/100 its speed in vacuum. We expect this feature to enhance light-matter interaction, namely to enable sufficient use of even extremely faint light for switching and controlling, and we even envision its application to optical buffer memory. We have also achieved a high level of quality with our resonators, and in 2005, we successfully fabricated an optical switch by combining one resonator and two waveguides. This was our first genuine device. In addition to these achievements, we have started work on the fabrication of a spot-size converter for connecting a photonic-crystal chip with optical fiber. As you can see, our research is finally beginning to produce some tangible results, but in terms of our ultimate objectives, we sometimes feel that we are still at the starting gate.

*—What form do you think your research will take three and five years from now?*

Our ultimate objective is large-scale integration, or photonic LSIs. Reaching this goal, however, will need about ten more years based on current forecasts,

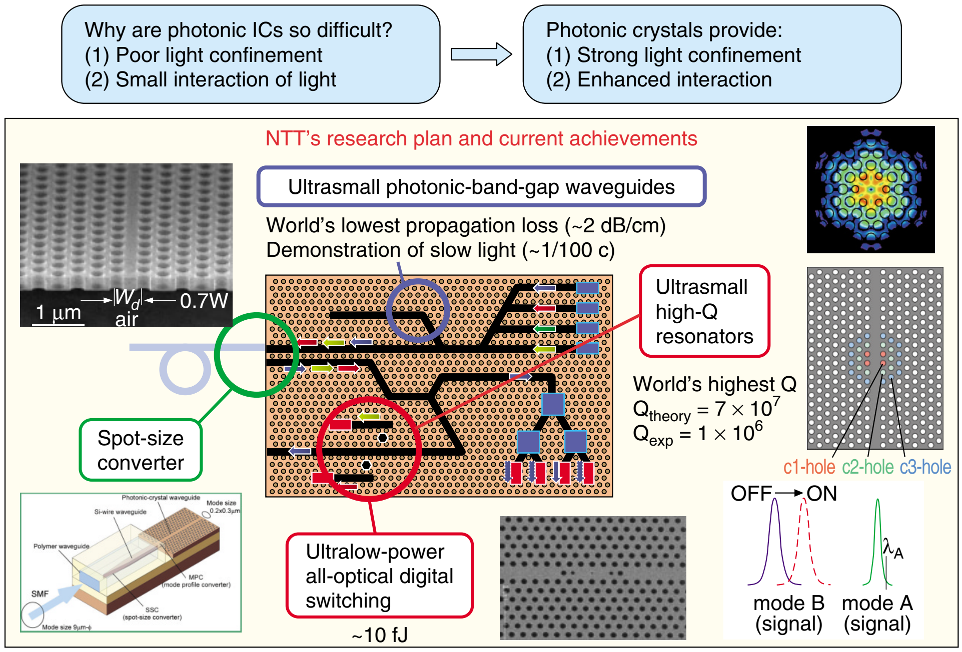


Fig. 2. Photonic integrated circuits on photonic-crystal platform.

so we see our medium-term goals as focusing on processes. To be more specific, our goal for the next three years is to interconnect several devices and perform logic processes that have traditionally been difficult to achieve with light. And since we have yet to construct an all-optical information-processing chip, we would like to do that as well. Within five years, we would like to be able to deploy some of these devices in some form of prototype for optical-communication systems.

## Taking the lead at the device process level amid expanding research in Japan, the United States, and Europe

*—Could you tell us about research trends in photonic crystal at both the international and domestic levels?*

Research into photonic crystal has become quite active during the past few years. The first international conference specializing in photonic crystal was held in 1999 with about 100 researchers attending. Since then, the number of photonic-crystal researchers has been increasing in Japan, the United States, and Europe. Attendance at the 2005 conference was 400–500, which is higher than at the top conferences on semiconductor lasers.

In terms of research trends, the theory behind photonic crystal was originally proposed by American researchers, who are still strong in theory. There are excellent theorists at MIT and Stanford University issuing a steady stream of new theories. Europe takes a more physical approach, while Japan is more involved in practical research. NTT and a number of universities in Japan are performing research with an eye to photonic ICs, and the devices fabricated by NTT are on a world-class level. In particular, we have achieved world record values for waveguide loss and resonator Q-value, which are the most important figures of the performance of photonic-crystal devices. In the field of photonic crystal, research related to device fabrication requires appropriate lithography equipment and process technology, which is one of NTT's strong points. Nevertheless, we must strive to keep ourselves up to date in this area so as not to lose this lead.

*—Are you involved in any joint research with other research institutions?*

Not at present, but we have previously been involved in joint research on several occasions. For example, we performed joint research on photonic-crystal resonators with the Korea Advanced Institute of Science and Technology (KAIST). This institute has produced the most results in photonic-crystal research in Korea, and their research on light-emitting devices has been making significant progress. At that time, we were both researching resonators, but there was really no competition because our research target was not light-emitting devices. The mutual need for resonators was also an important factor in pursuing this joint research. Collaboration, as opposed to direct competition, can therefore provide huge benefits for each partner. Given the right situation, I would definitely want to engage in joint research again.

*—On the other hand, are you now competing with anyone in any areas?*

There are indeed other institutions conducting research on photonic-crystal devices using the same materials as we are using. We are basically neck and neck with other institutions in terms of waveguide loss, for example. Competition can therefore be painful at times, but it can also spur us on to achieve even better results. It is also natural for competitors to be conscious of each other's successes, and meeting with competing researchers at conferences and elsewhere can actually lead to enjoyable conversations. The field of photonic-crystal research is dominated by young researchers, so discussions tend to be frank and to the point. The theme itself was born of interdisciplinary studies, and we all feel that we are helping to develop the field of photonic-crystal research. While knowing that other researchers in this field are both rivals and colleagues, I always look forward to meeting with them at academic societies.

*—What other international activities have you been involved with?*

I have had the pleasure of serving on committees associated with various international conferences such as IEEE LEOS, Optical Fiber Communication (OFC) of the Optical Society of America (OSA), Integrated Photonic Research (IPR), CLEO Pacific Rim, and SPIE (International Society for Optical Engineering). I would often be asked to serve on such committees when there were plans to set up a section on photonic crystal within general academic societies related to optics. I have also served on the editorial boards of academic journals dealing especially with photonic crystal research. Recently, I have frequently been a guest speaker at international conferences, perhaps five or six times a year, which has been making me quite busy during the conference season. But I feel that speaking like this at such forums provides a much needed public relations effect for photonic-crystal research.

## Opening the door to the world of optics through the properties of nanostructures

*— Dr. Notomi, how was your technical "backbone" formed?*

To begin with, I was a member of the superconductivity research laboratory at my university, but among the many students there, I was the only one researching the charge-density wave state instead of superconductivity, which is another low-temperature physics theme. In any case, it was a field entirely unrelated to light. This was a time of "superconductivity fever" in the world of research, and while I was advised by my instructors not to diverge from superconductivity themes, I did not feel the need to follow others and I simply formed my own path. Then, on entering NTT, I was again expected to research superconductivity, but as that was something that I had chosen not to pursue in university, I again held fast and did not change my mind. In the end, I expressed the desire to research new physical properties using nanostructures, and I was consequently assigned to NTT Optoelectronics Laboratories. This assignment surprised me at first as I was thinking more along the lines of electronic devices, but researching artificial nanostructures turned out to be just what I wanted and I adjusted to my new environment quickly.

*—What research themes have you tackled to date?*

The first theme that I worked on at NTT was semiconductor quantum wires and dots. The idea here was to fabricate one-dimensional or even zero-dimensional semiconductor structures using fine processing technology. Since our goal was to confine electrons—at dimensions even smaller than the wavelength of light—in artificial structures, our problem was to achieve feature dimensions on the order of 10 nm. This turned out to be a huge challenge, but I came to write books and papers on the subject and even obtained a degree in relation to it. But to be quite honest, I eventually realized that continuing that research theme in its present form was going to be an extremely difficult undertaking.

Then, around that time, a professor from Linköping University in Sweden came to NTT as a guest researcher. He suggested that I perform measurements on our samples at Linköping University because he thought that I might be able to obtain interesting data. Thinking that this was a good opportunity that I should not pass up, I took up his offer and ended up spending a year there from 1996 to 1997 as a visiting researcher. During that time, while measuring samples and writing papers, I thought about a variety of things. In fact, I had lots of time to think, which was very fortunate. I also had a chance to observe world research trends, and it was at that time that I first took notice of research on photonic crystal. Compared with quantum wires, the feature dimensions of photonic crystal (200–400 nm) are one order of magnitude larger. These were dimensions that I thought I could work with. Then, upon further study, I found that there were many things that had yet to be theoretically explained about photonic crystal since it was a new field, and my interest in photonic crystal deepened all the more. But what attracted me the most was that I was in a position to work on the most difficult problem in photonics—the confinement of light. With my future direction found, I started research on photonic crystal soon after returning to Japan.

At first, I proceeded alone, but as I began to talk to more and more of the people around me, the number of researchers working with me began to increase. Then, in 1999, when whole groups at NTT Optoelectronics Laboratories were moved to the present NTT Basic Research Laboratories, photonic crystal became the central research theme of my group. After that, I also became involved in management duties in parallel with my own research.

*—What do you aim for in your research activities?*

While there are various theories and technologies on my mind, what I have come to aim for on the whole is how to collaborate with many researchers to achieve results that could not be achieved by a single person. This style dominates my research today and makes my work feel even more worthwhile. Of course, arriving at this point in my research career took some time, but the environment that I need has gradually taken form. In just these last two years, I feel that research itself is starting to progress rapidly, and I think that things are going to become very interesting from here on.

## Advancing photonic-crystal research with an eye to new possibilities

*—Where do you think your research is headed from here on?*

For one thing, we want to move toward photonic integrated circuits as I mentioned earlier. In parallel with this effort, I also wish to research related themes, especially the physical properties of photonic crystal not found in conventional materials and the other fascinating physical phenomena that it exhibits besides the photonic band gap.

For example, while the refractive index of materials in the natural world is always positive, light can undergo negative refraction in photonic crystal (**Fig. 3**). That is to say, light passing through an interface like glass will normally become diffused, but on passing through a photonic-crystal interface, it can undergo the opposite effect and become focused. This means that a flat panel can act as a lens! In this case, imaging is also peculiar. A normal lens makes faraway things appear closer and nearby things farther, but photonic-crystal imaging does just the opposite—it makes faraway things farther and nearby things nearer. In the past, this negative refraction of light was discussed in theory from a mathematical perspective,

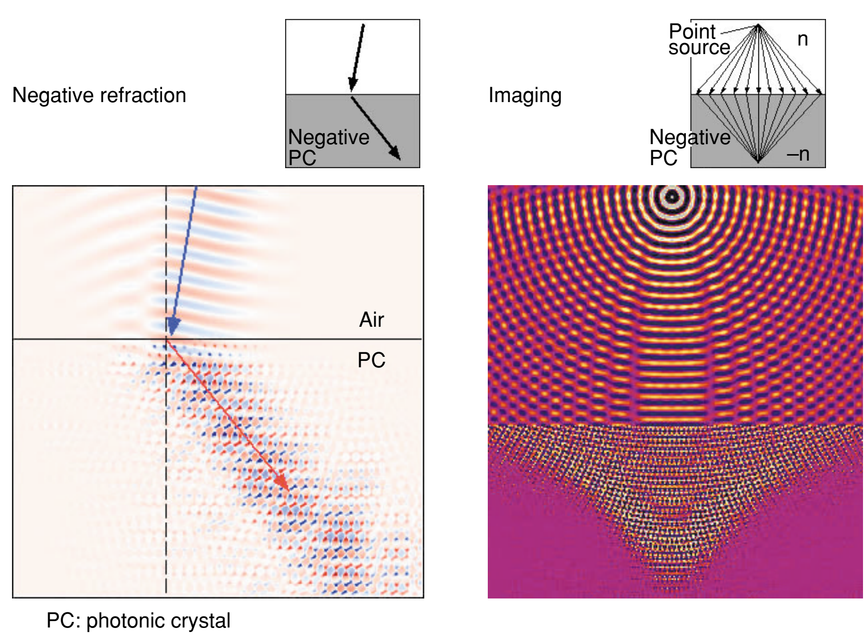


Fig. 3. Negative refraction in photonic crystals.

but as no demonstrations were forthcoming, it wasn't actually given much attention. This changed in 2000 when I wrote a paper describing the discovery and demonstrations of negative refraction using photonic crystal [1]. The paper generated keen interest in negative refraction as a new principle that held many possibilities. I myself find the possibility of three-dimensional photography based on negative refraction very interesting. Technically speaking, this might be more difficult than photonic ICs, and there is a study being performed on whether it would be appropriate as an NTT research theme. At any rate, I would love to pursue this research if and when appropriate.

*—What is your ultimate goal as a researcher?*

I wish to propose new theories, make things based on those theories, and demonstrate their operation with the hope that they will come to be accepted and used by the outside world. I would also like to work on cultivating photonic-crystal research—which is now enjoying a sudden rise in interest—into a major field worthy of its own full-fledged textbooks.

*—How do you yourself find working at NTT Laboratories?*

I would be hard pressed to find anything better. On entering the company, I first thought in a somewhat simplistic manner that the wonderful facilities provided by NTT Laboratories would make it a good place to undertake basic research. But it didn't take me long to realize that the wonderful people who worked there were of even greater importance. Here, there are specialists in a wide variety of fields. If there's something that I don't understand, no doubt there will be someone who is quite familiar with the subject and can help me out. NTT Laboratories is like a fountain of knowledge. It is also a place where organizational boundaries are relatively easy to cross to exchange information and know-how. For example, I have been able to conduct joint projects with researchers in NTT Photonics Laboratories and Network Innovation Laboratories. Another attractive point is that NTT Laboratories provides systematic connections between basic research, platform research, and application research and even with commercialization on the business side of things. Although I had a choice to stay on at university and continue with basic research, I now feel that I was very fortunate to have entered NTT. I am working in a superb research environment rare even by world standards, and I would like to produce results that make the best of what NTT Laboratories has to offer.

*—Dr. Notomi, could you leave us with a message for young researchers?*

Well, I must first say that young researchers appear to be a bit conservative these days. This is perhaps particularly true in the field of optics. The reason for this may be a feeling that the future direction of this field has already been decided and that there is no use in trying to develop new themes. In research and development, however, it is hard to obtain good results without challenging yourself and taking on a certain amount of risk. When I was starting out on photonic-crystal research, it was often referred to as a dead-end theme. But a strong feeling of conviction that I was on the right path and a step-by-step approach eventually led to great things. I would therefore emphasize to young researchers that it is very important to undertake a research theme that you are convinced has merits and to continue with it without getting pessimistic in the face of setbacks. Be positive in your research and do not jump to conclusions about its possibilities. Challenge yourself to achieve great things!

## Reference

[1] M. Notomi, "Theory of Light Propagation in Strongly-modulated Photonic Crystals: Refraction-like Behavior in the Vicinity of the Photonic Band Gap," Phys. Rev. B62, 10696, 2000.

**Interviewee profile**

■ Career highlights

Masaya Notomi received the B.E., M.E., and Dr. Eng. degrees in applied physics from the University of Tokyo, Tokyo in 1986, 1988, and 1997, respectively. In 1988, he joined NTT Optoelectronics Laboratories, Atsugi. Since then, his research interest has been to control the optical properties of materials and devices by using artificial nanostructures, and he has engaged in research on semiconductor quantum wires/dots and photonic crystal structures. He is currently a Distinguished Technical Member of NTT Basic Research Laboratories, Atsugi and the leader of the photonic nanostructure research group. From 1996-1997, he was with Linköping University, Sweden as a visiting researcher. Since 2002, he has been a guest associate professor of Tokyo Institute of Technology. He is a member of the Japan Society of Applied Physics and the American Physical Society.