AUTHOR COMMENTARIES - From Special Topics

Photonic Crystals - October 2008
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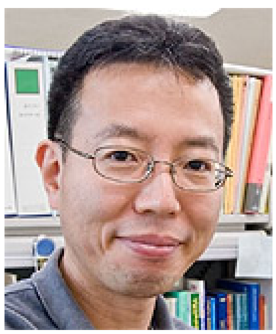

Masaya Notomi

From the Special Topic of Photonic Crystals

According to our Special Topics analysis of Photonic Crystals, the work of Dr. Masaya Notomi ranks at #4 by total cites, based on 49 papers cited a total of 2,332 times. Four of these papers appear on the lists of the most-cited papers in this topic over the past decade and over the past two years. In Essential Science IndicatorsSM *from* Thomson Reuters*, Dr. Notomi's record includes 70 papers cited a total of 2,648 times between January 1, 1998 and October 31, 2008.*

Dr. Notomi is a Distinguished Technical Member of NTT Basic Research Laboratories in Japan, where he leads the Photonic Nanostructure Research Group. He has also been a Guest Associate Professor at the Tokyo Institute of Technology.

In this interview, he talks with ScienceWatch.com *about his highly cited work.*

SW: Would you tell us a bit about your educational background and research experiences?

When I was a graduate student in the department of applied physics at the University of Tokyo, I studied exotic condensed electron states in chemically synthesized one-dimensional inorganic conductors. When I joined NTT Laboratories in 1988, I started a project of low-dimensional electron systems artificially fabricated by nanofabrication lithographic technologies, namely semiconductor quantum wires and dots, particularly for novel optical devices or components.

Over several years of the study, we had demonstrated various interesting optical properties of quantum wires and dots. I was satisfied with the results, but I started to feel that it is not so easy to drastically change the performance of optical devices using those lithographically patterned quantum wires or dots. It requires a large area of 10-nm-order quantum wires/dots with very good homogeneity, which was still not easy even with the state-of-the-art nanofabrication technologies. That was around 1997. Then, I switched my subject to photonic crystals.

SW: What first attracted you to work in photonic crystals?

The concept of photonic crystals, which was introduced in the 1980s, is essentially the photonic analogue of band electrons in solids. A dielectric structure whose refractive index is periodically modulated can exhibit a variety of novel optical properties due to its band nature. Photonic crystals were first realized in radio frequencies, and in the 1990s several groups had already started to fabricate photonic crystals in optical frequencies, which needed nanofabrication technologies.

My first impression was that it seemed rather easier to fabricate them in comparison with quantum wires/dots because the required dimension is one order of magnitude larger, typically 200-400 nm. Though later I found that this simple-minded impression was not very correct, I was somehow attracted to them because they seemed to have potential to drastically change the optical properties more directly than quantum wires/dots, which change the optical properties only via small light-matter interaction. At that time, I had a strong temptation to overcome the weak points of photonics, and I felt that photonic crystals could do much in this context.

"I believe that photonics is superior to electronics in ultrahigh speed information processing with low energy consumption, but photonics has some drawbacks, which are deeply related to fundamental aspects of photons."

SW: Your most-cited original paper in our analysis is the 2000 *Physical Review B* article, "Theory of light propagation in strongly modulated photonic crystals: Refractionlike behavior in the vicinity of the photonic band gap." Would you walk our readers through this paper—its goals, findings, and significance?

Photonic crystals are a very simple concept, and many existing materials and phenomena, such as diffraction grating and x-ray diffraction in crystals, can be, in principle, categorized as photonic crystals or phenomena in them. Some people criticized that photonic crystals were just another interpretation of old things. However, two- or three-dimensional dielectric periodic structures with a large refractive index contrast had not existed or been considered before the photonic crystal research, and I expected that such strongly modulated photonic crystals should lead to totally new optical phenomena.

At that time (1998-1999), various exotic light propagation phenomena were found in photonic crystals. Superprism, which I was coauthoring, is one such example. The propagation angle of light can be steered in a very exotic way in photonic crystals at certain conditions, which found various interesting applications. However, I noticed that such phenomena do not essentially require a large index contrast. In fact, these phenomena are closely related to light propagation in diffraction gratings.

Thus, I next started to look for a distinguishing phenomenon that only occurs in strongly modulated photonic crystals. Soon after, I found that light propagation in strongly modulated photonic crystals can be fundamentally different from diffraction gratings when the frequency is close to the photonic band gap edges. In such situations, photonic crystals behave as if they were homogeneous dielectric materials having artificial refractive index.

The most amazing part of this finding is that this artificial index can be theoretically negative. In those days, refractive index had been believed to be always positive. So, next I tried to figure out what exotic phenomena may arise when the index happens to be negative. It was surprising for me that various interesting phenomena, such as flat lens, open cavity, image transfer, etc., were easily derived by just assuming negative index for conventional geometrical optics. I was especially mesmerized by the flat-lens effect by negative refraction because this lens is so fundamentally different from conventional lens. It does not follow the well-known Newton's formula, and can produce a three-dimensional image. In this particular paper, I demonstrated these phenomena with analytical simple theories and numerical simulations.

It was interesting that negative index was found in metallic metamaterials by Dr. Smith and his colleagues at UCSD at almost the same time. The physics of negative index is fundamentally different, but the timing was exactly matched synchronicitically. Since negative index brought in fundamentally new ways to study conventional optics, many people excitedly joined this field. After our publications, a vast number of publications came up in the field of negative index materials.

SW: A couple of your papers discuss slow light phenomena. What exactly are these and why are they important?

As one of the most important aspects of photonic crystals, photonic crystals can artificially control the light velocity. The light velocity is usually determined by the material’s refractive index, which cannot be varied very much, but it can be drastically altered by the photonic band structure engineering. Prior to our research, it had been demonstrated that exotic material dispersion in ultracold atoms driven by a laser can drastically reduce the light velocity. This achievement was great, but I wanted to realize "slow light in a chip" using a dielectric structure at room temperature.

In 2001, we achieved a photonic crystal waveguide with substantially small loss. Theoretical calculations showed that our waveguide can show significantly slow light states. Soon after, we succeeded in measuring the group velocity of light in our photonic crystal waveguides, and demonstrated that the light velocity is reduced down to c/90. This work was the first demonstration of slow light in dielectric structures, and later on various kinds of dielectric slow light media were reported.

"...slow light has become one of the hottest topics in today's photonics research."

We also published several papers relating to slow light, and recently we achieved c/50000 using an ultrahigh-Q micro-cavity in a photonic crystal (This work was selected as *Scientific American* magazine's Top 50 in 2007). "Slow light in a chip" is important for two reasons. First, it can potentially lead to an optical buffer memory, which is a fundamentally difficult and important component for future photonic circuits. Second, light-matter interaction is strongly enhanced in slow-light media because of long interaction time and spatial compression of light. Thus, it can lead to ultralow-power all-optical devices in a chip. For these reasons, slow light has become one of the hottest topics in today's photonics research.

SW: Is there any aspect of your work that you are particularly excited about?

Yet another important aspect of photonic crystals is their ability in strongly confining light. It is well known that it is intrinsically difficult to confine light in a small space, which severely limits the potential of photonics technologies. A photonic crystal having a band gap is essentially a photonic insulator that does not exist in nature and can block the light propagation and penetration without absorption. This leads to strong confinement of light in a wavelength-scale volume. Currently, many researchers in this field are working towards ultrasmall and ultrahigh-Q cavities in photonic crystals. We reported a wavelength-sized cavity that can store light more than one nanosecond. Such performance is hardly available in systems other than photonic crystals. We are currently studying what we can do with such small and high Q cavities. As I explained, we have applied them to slow light. As another example, we apply them to all-optical switches and memories and have achieved extremely small consumption energy operation.

I have always been looking for breakthroughs in today's photonics technologies. I believe that photonics is superior to electronics in ultrahigh speed information processing with low energy consumption, but photonics has some drawbacks, which are deeply related to fundamental aspects of photons. Electrons can be easily confined, accelerated, decelerated, and stopped by applying voltage. However, photons cannot because of intrinsically small interactions. This makes information processing purely by photons difficult. As I explained, photonic crystals can alter the nature of lightwaves in media. Ultrasmall cavities and slow light states may enable us to overcome these intrinsic weak points of photonics. People are also constantly finding novel optical phenomena in photonic crystals such as negative refraction, which will add new functionality in photonics, as well.

SW: What are your hopes for this field for the future?

My ultimate hope is to control (or design) all the optical properties of materials totally by artificial ways. Photonic crystals are definitely very effective in this respect, but there are other fields relating this issue, such as metamaterials, quantum nanostructures. Although the controllability of intrinsic optical properties in existing materials is rather limited, we may be able to expand the possibility of optics to unthinkably large extent by combining those new fields in optics.

SW: What would you like the "take-away lesson" about your research to be?

In the beginning process of my research on negative refraction, I was motivated by a strong urge to clarify the fundamental newness in photonic crystals. Especially when the research field is in an embryonic stage, many things are mixed up with old things. It is very important to try to figure out what the newness is. In my case, this approach almost automatically led me to find the negative refraction phenomenon.

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Masaya Notomi's current most-cited paper in *Essential Science Indicators*, with 507 cites:

Notomi M, "Theory of light propagation in strongly modulated photonic crystals: Refractionlike behavior in the vicinity of the photonic band gap," *Phys. Rev. B* 62(16): 10696-705, 15 October 2000.
Source: *Essential Science Indicators* from Thomson Reuters.

KEYWORDS: PHOTONIC CRYSTALS, OPTICS, REFRACTIVE INDEX, LIGHT-MATTER INTERACTION, SLOW LIGHT, LIGHT PROPAGATION, BAND GAP, NEGATIVE INDEX.