Science Watch 日本版
－日本の研究者による注目論文&インタビュー－

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著者インタビュー(フォトニック結晶)

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もっとも引用された論文: Trapping and emission of photons by a single defect in a photonic bandgap structure (Nature, 2000)

Professor Noda hails from Kyoto University, where he heads up the Quantum Optoelectronics Laboratory and is a leader in the program on "Photonics and Electronics Science and Engineering."

In the interview below,* ScienceWatch.com *talks with Professor Noda about his work in photonic crystals.

SW: 1. Please tell us a little about your research and educational background.

I received B.S., M.S., and Ph.D. degrees from Kyoto University, Kyoto, Japan, in 1982, 1984, and 1991, respectively, all in electronics. From 1984 to 1988, I was with the Mitsubishi Electric Corporation, where I studied semiconductor lasers called distributed feedback (DFB) lasers with one dimensional (1D) periodic refractive index distribution, and also crystal growth technology (molecular beam epitaxy).

In 1988, I joined Kyoto University as an assistant professor and became a full professor in 2000. I am currently serving also as a leader of Kyoto University Global Center of Excellence (GCOE) program on "Photonics and Electronics Science and Engineering." After joining Kyoto University in 1988, I extended my research areas to more general photonics and optoelectronics including ultrafast nonlinear optical phenomena and optoelectronic materials and devices. In particular, in the early 1990s, I started research on photonic crystals with 2D and 3D periodic refractive distribution by extending my previous work on DFB lasers with 1D periodic refractive index distribution.

I have been fortunate to receive several awards, including the OSA Joseph Fraunhofer Award/Robert M. Burley Prize (2006), an honorary degree from Gent University, Gent, Belgium (2006), IEEE Distinguished Lecturer awards (2005), IEEE Fellow awards (2007), the Japan Society of Applied Physics Achievement Award on Quantum Electronics (2005), and the IBM Science Award (2000).

> *"Compact light sources with a range of beam patterns are important for progress in several areas, including optical tweezers, micro-fluidics, ultrahigh-density optical memories, and related photonics."*

SW: 2. What prompted you to study photonic crystals?

Photonic crystals are a kind of nanostructures for light with a periodic refractive index distribution described above. A photonic bandgap, which blocks photons in certain wavelengths, is formed as an analogy of solid-state crystals. By controlling the photonic crystal structures, novel manipulations of photons in all aspects of optical phenomena including photon emission, propagation, amplification, storage, and interaction with other materials are expected to be realized. The existence of the photonic bandgap itself in a periodic refractive index distribution was discovered about 120 years ago. The importance of 3D periodicity was then pointed out in 1987 for light emission control. However, the realization of 3D photonic crystals had been very difficult in optical regime because the optical wavelength size nanotechnology is required. Thus, the developed crystals at the initial stage of the photonic crystal research had been limited to the "microwave" regime, even though the word "photonic" was used. In other words, the photonic crystals had been a kind of "a pie in the sky." Therefore, the most important and urgent issue was to realize photonic crystals at optical regime.

This fact strongly prompted me to study photonic crystals, especially to realize true "photonic" crystals. My experience on the study of the DFB laser with 1D periodic refractive index distribution also pushed me in that direction. In 1999, after various trials and errors, we succeeded in developing 3D crystals with a complete bandgap by stacking GaAs stripes with the period of 700nm with the accuracy of <50nm based on our own nanotechnology. The crystals showed unprecedented optical rejection of –40dB and were proved to possess complete bandgap at 1.55µm region. The result was published in *Science* in 2000, and was highlighted as the realization of the world's foremost crystals.

After this success, we have extended and deepened the works on photonic crystals in all aspects and found various interesting phenomena and new concepts, which include spontaneous emission control (*Science* 305: 227-229, 2004; *Science* 308: 1296-1298, 2005), photonic nanostructure devices (*Nature* 407: 608-610, 2000; *Science* 300: 1537, 2003), high-Q photonic nanocavities (*Nature* 425: 944-947, 2003; *Nature Materials* 4: 207-210, 2005; and *Nature Photonics* 1: 449-458, 2007), and novel photonic crystal lasers (*APL* 75: 316-318, 1999; *Science* 293: 1123-1125, 2001; *Nature* 441: 946, 2006; and *Science* 319: 445-447, 2008). Some of them are described more in detail here in later answers.

SW: 3. A key paper in your publications is the 2000 *Nature* paper, "Trapping and emission of photons by a single defect in a photonic bandgap structure," (407 [6804]: 608-10, 5 October 2000)." Would you sum up the major points of this paper for our readers?

This paper concerns 2D photonic crystals. In this case, one of the most important issues was how to confine light for the vertical direction. We found that quasi-3D confinement of light becomes possible by using a slab structure with appropriate thickness, refractive index contrast, and designed lattice structures from the knowledge obtained through work on 3D photonic crystals. We then demonstrated a very unique phenomenon of "trapping and emission" of photons by a point-defect nanocavity formed at the vicinity of a line-defect waveguide. This phenomenon indicates that photons can be introduced and/or extracted through a tiny nanocavity. This is the achievement discussed in this paper.

This work was highlighted as "Defects boost optical communication" (Physics Web). In addition, we further introduced a new concept of "In-plane Heterostructure" in 2D photonic crystals and succeeded in developing photonic nanostructure devices (*Science* 300: 1537, 2003) with a function of multiple wavelength channel add/drop function. I believe that these works became an important step for the realization of a full photonic-crystal network with waveguides, nanocavities, etc., and is one of the holy grails in nano-optics.

SW: 4. Your most-cited paper in our analysis is the 2003 *Nature* paper, "High-Q photonic nanocavity in a two-dimensional photonic crystal," (425 [6961]: 944-7, 30 October 2003). Would you talk a little bit about this paper and its significance for the field?

In the photonic crystal nanocavity described in the answer to question #3, the cavity Q was limited to around several hundreds. If the Q factor of nanocavities can be increased significantly while keeping their very small modal volume V, it should have a significant impact in broad areas of physics and engineering, including coherent electron-photon interactions, ultra-low threshold nanolasers, photonic chips, nonlinear optics, and quantum information processing. This is because Q/V determines the strength of various cavity interactions; an ultra-small cavity enables large-scale integration and single-mode operation for a broad range of wavelengths. However, a high-Q nanocavity of optical wavelength size had been difficult to build, since radiation loss increases in inverse proportion to cavity size.

In the 2003 *Nature* paper, we reported an important concept that "light should be confined gently to be confined strongly." More precisely, the form of the cavity electric field distribution should vary slowly, ideally as described by a Gaussian function, in order to suppress out-of-slab photon leakage. Based on this concept, we demonstrated a nanocavity with Q=45,000 and V=7.0x10-14cm3, or Q/V=6.4x1017cm-3, a factor 10 to 100 times larger than in previous studies. Currently, the Q of nanocavities has been increased up to 2,500,000 by extending this concept (also see our paper, *Nature Materials* 4: 207-210, 2005; *Nature Photonics* 1: 449-458, 2007; and *Optics Express* 15: 17206-17213, 2007). Fortunately, these works have had significant impact to the aforementioned various fields, and many researchers are currently using our cavities.

SW: 5. One of your more recent papers is the 2006 *Nature* paper, "Lasers producing tailored beams," (441: 946, June 22, 2006). Would you discuss the findings of this work?

In the answer to question #4, I have explained that photonic crystals are very useful for confining photons in an ultra-small volume of wavelength size. The photonic crystals can also manipulate photons nicely in a broad area. The 2006 *Nature* paper describes such a broad-area control of photons. More concretely, this paper reports on an unprecedented type of lasers that can produce a tailored beam on demand while keeping stable single longitudinal and lateral mode.

Compact light sources with a range of beam patterns are important for progress in several areas, including optical tweezers, micro-fluidics, ultrahigh-density optical memories, and related photonics. For example, lasers with single- or multiple-doughnut beams are important for the manipulation of both transparent and non-transparent materials. Lasers possessing a single-doughnut beam having radial polarization are important for light sources with super-resolution, which can be focused to a size much less than the wavelength. In addition, lasers with a circular single-lobed beam have useful applications in many existing optical systems.

"By controlling the photonic crystal structures, novel manipulations of photons in all aspects of optical phenomena including photon emission, propagation, amplification, storage, and interaction with other materials are expected

to be realized."

The 2006 *Nature* paper describes that such very unique and important lasers can be actually produced: A range of beam patterns—including doughnut, twin-doughnut, quadruplet-doughnut, shifted-doughnut, and circular single-lobed beams—were successfully produced while maintaining stable single-mode oscillation. The principle of the lasers is based on "band edge effects in 2D photonic crystals, where a 2D broad area cavity mode is constructed" and "design of unit cell structures and lattice phases." These findings suggest a new direction for semiconductor lasers, and could allow the realization of compact lasers capable of producing diverse beam patterns as required. In addition, due to the capability of broad area coherent oscillation, ultrahigh power stable single-mode lasers could be realized by extending these results.

SW: 6. What are the practical applications (or hoped-for applications) for photonic crystals? And, where do you see this field going in 10 years?

The photonic crystal lasers described in the answer to question #5 are one of the most important candidates for practical applications. These lasers have unprecedented features as described above: first, perfect, single longitudinal, and lateral mode oscillation can be achieved even when the lasing area becomes very large; and second, the polarization mode and the beam patterns can be controlled while keeping single mode oscillation by appropriate design of the unit cell and/or lattice phase in the photonic crystal; and thirdly the output can be emitted to the direction normal to the device surface (namely, the device has a surface-emitting function) and 2D arrays are straightforward. Very recently, we have succeeded in lasing oscillation in blue-violet wavelength region (*Science* 319: 445-447, 2008).

This would open the door to a much broader range of applications. For example, super-high-resolution light sources that could be focused to a spot smaller than blue-violet wavelengths could be made available by the use of doughnut beams. This would lead to the realization of post-blue lasers, as well as optical tweezers for ultra-fine manipulation. Furthermore, blue-violet surface emitting lasers could find uses in a variety of new areas, including micro-operation to nano-operation in biological and/or medical fields.

The ability of photonic crystals in light emission control is also very important for practical applications. Right now, solid lighting is one of the most important research fields, and the efficiency of light-emitting diodes should be as high as possible. The photonic crystal technology will definitely contribute to increase such light-emission efficiency.

It is expected that, over the next 10 years, nano-processing technology will further advance, and that more reliable and precise devices will continue to be developed. In the case of 2D photonic crystal slabs, there is the promise of remarkable advances in Si-based systems, together with progress in integration with electronic circuits. Further advances can be expected in combined optical and electronic circuits equipped with features such as optical switching, tuning, and delay functionality. It is expected that the main components of such circuits will be optical, and optical/electronic chips will be developed. There is no doubt that the size and power consumption of such devices will be more than hundreds of times smaller than they are now.

Advances in a large number of applications can also be expected, where ultra-high Q nanocavity would be utilized for one of the most important key elements for stopping light, quantum communications and informatics. Actually, currently, the studies on the combination of nanocavities and quantum dots are becoming the very active research fields. Dynamic control of photonic crystal nanocavity has also started to be achieved in very fast time range (see our paper *Nature Materials* 6: 862-865, 2007).

It is expected that the technology available for the fabrication of 3D photonic crystals, which are considered to be more difficult to fabricate than 2D crystals at the present time, will also advance over the coming decade, and that 3D crystals will witness completely new levels of light control that will also enable intricate 'complete control of fields."

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