***Japan Academy Prize to:***

Susumu Noda
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for "Exploration of Ultimate Light Control Based on Photonic Crystals and its Application for Advanced Semiconductor Lasers"

***Outline of the work:***

"Light" plays important roles in various fields, including measurements, communications, illumination and material processing. Advanced research and development to better control light waves have been extensively and globally conducted. Dr. Susumu Noda has played pioneering and leading roles in the exploration of photonic nanostructures called "photonic crystals" in order to develop new methods to ultimately control light waves and in the application of these photonic crystals to the advancement of semiconductor lasers. Photonic crystals are man-made structures with periodic refractive index distributions, having periods of the order of the wavelength of light. Photonic crystals allow the control of light waves and the generation of optical functions, just as the control of electron waves in regular crystals results in various material properties and functions. Dr. Noda succeeded in developing a three-dimensional (3D) photonic crystal with a complete bandgap at optical wavelengths for the first time in the 1990s, which had been a veritable pie in the sky until then; he also showed that 3D photonic crystals, if properly modified, allow one to suppress or enhance spontaneous emission processes and to control the light propagation [Refs. 1–8].

Dr. Noda then extended his research to two-dimensional (2D) photonic crystals, which are formed by the periodic modulation of in-plane refractive index distributions in free-standing dielectric slabs, to show that 2D photonic crystals allow far superior control of light over the 3D counterparts [Refs. 9–20]. He demonstrated that artificial line defects, carefully designed and introduced in 2D photonic crystals, work as lossless waveguides. He also showed that artificial point defects in 2D photonic crystals work as nanocavities that can trap light in the ultrasmall volume of the order of cubic wavelengths; by tuning the nanocavity structure, he achieved an ultrahigh $Q$ factor (more than $10^7$ at present) while maintaining the ultrasmall volume of the nanocavity. These nanocavities, designed according to his design principle, are called "Noda's cavities" and are widely used in various fields of basic optical sciences, such as cavity electrodynamics and quantum optics. Silicon-based ultrasmall Raman lasers have also been developed using ultrahigh $Q$ nanocavities.

Dr. Noda has also invented and developed new semiconductor lasers, in which photonic crystals are embedded to control oscillation modes of laser light for the stable operation of broad-area high-power semiconductor lasers [Refs. 21–35]. It is well known that when the size of the light emission area of conventional semiconductor lasers is broadened to increase their output power, multiple oscillation modes appear, resulting in a significant deterioration of the laser beam quality; this deterioration is one of the most serious bottlenecks toward high-power semiconductors lasers. Dr. Noda has demonstrated that by embedding a 2D photonic crystal inside of a semiconductor laser and using a singularity point (Γ point, etc.) of the photonic-crystal band structure, oscillation can predominantly occur in a single mode even when the size of the laser is broadened, resulting in stable oscillation over the broad area and consequently leading to high-power, high-beam-quality operation. Semiconductors lasers of this type are called photonic-crystal surface-emitting lasers (PCSELs) and stay stable when the diameter of light emission area gets as large as five hundred micrometers or even several millimeters. In particular, he has developed unique “double-lattice” photonic-crystal structures, in which a pair of photonic-crystal lattices are overlapped and separated by a distance of approximately one-fourth of their periods, and enabled 10–100-W-class high-power, high-beam-quality operation.

By taking advantages of the high power and high beam quality of these PCSELs, and also their extremely narrow beam divergence, he has succeeded in realizing a lens-free, high-resolution light detection and ranging (LiDAR) system. This system is expected to significantly enhance the performance of robots and autonomous vehicles. Furthermore, he has developed lasers with “dually modulated photonic crystals,” in which lattice points are modulated both in position and size, to enable 2D beam scanning and the generation of structured light, which are important for non-mechanical LiDAR and face-recognition systems.

In light of these advantages, photonic-crystal surface-emitting lasers are expected to serve as key next-generation light sources with performances surpassing those of not only conventional semiconductor lasers but also $CO_2$ and fiber lasers; they are likely to play important roles in expanding a variety of fields, such as sensing, communications, material processing, transportation, lighting, and medicine, and unlocking the door to an ultra-smart society called “Society 5.0.”

Dr. Noda has also applied his achievements on photonic crystals to explore their new possibilities in the fields of thermal radiation and photovoltaics [Refs. 36–40]. He has devised a new concept for the control of thermal radiation processes, which are known for their undesirable wide emission spectra and slow response speeds, to enable the concentration of their wide spectra into a very narrow band without losing energy and also their high-speed modulation.

As previously stated, Dr. Noda has made significant contributions to the field of photonic crystals by developing 3D photonic crystals and advanced light-wave control based on 2D photonic crystals, and by inventing photonic-crystal surface-emitting lasers. He has also played a leading role in the global research community, making significant contributions to the advancement of optical science and technology. His contributions are projected to fuel the advancement of basic science and the social application of photonic technology. Dr. Susumu Noda is eminently qualified to receive the Japan Academy Prize based on his exceptional achievements.

Dr. Noda’s research accomplishments have been published in over 500 academic journal papers and/or presentations in major international conferences, with over 30,000 citations. He has earned accolades, including Joseph Fraunhofer Award / Robert M. Burley Prize from the Optical Society of America, IEEE Nanotechnology Pioneering Awards, the Leo Esaki Prize, the Medal with Purple Ribbon, and the Japan Society of Applied Physics Achievement Award.

## List of Main Publications

### A. Complete Three-Dimensional (3D) Photonic Crystals and Light Control


[1] S. Noda, N. Yamamoto, M. Imada, H. Kobayashi, M. Okano, "Alignment and stacking of semiconductor photonic bandgaps by wafer-fusion," ***Journal of Lightwave Technology***, Vol. 17, No. 11, pp. 1948–1955 (1999).

[2] A. Chutinan and S. Noda, "Highly confined waveguides and waveguide bends in three-dimensional photonic crystal," ***Applied Physics Letters***, Vol. 75, No. 24, pp. 3739–3741 (1999).

[3] S. Noda, K. Tomoda, N. Yamamoto, and A. Chutinan, "Full three-dimensional photonic bandgap crystals at near-infrared wavelengths," ***Science***, Vol. 289, No. 5479, pp. 604–606 (2000).

[4] S. Ogawa, M. Imada, S. Yoshimoto, M. Okano, and S. Noda, "Control of light emission by 3D photonic crystals," ***Science***, Vol. 305, No. 5681, pp. 227–229 (2004).

[5] S. Noda, M. Fujita, and T. Asano, "Spontaneous-emission control by photonic crystals and nanocavities" (review paper), ***Nature Photonics***, Vol. 1, No. 5479, pp. 449–458 (2007).

[6] K. Ishizaki and S. Noda, "Manipulation of photons at the surface of three-dimensional photonic crystals," ***Nature***, Vol. 460, No. 7253, pp. 367–370 (2009).

[7] S. Takahashi, K. Suzuki, M. Okano, M. Imada, T. Nakamori, Y. Ota, K. Ishizaki, and S. Noda, "Direct creation of three-dimensional photonic crystals by a top-down approach," ***Nature Materials***, Vol. 8, No. 9, pp. 721–725 (2009).

[8] K. Ishizaki, M. Koumura, K. Suzuki, K. Gondaira, and S. Noda, "Realization of three-dimensional guiding of photons in photonic crystals," ***Nature Photonics***, Vol. 7, No. 2, pp. 133–137 (2013).


### B. 2D Photonic Crystals Surpassing 3D Crystals


[9] S. Noda, A. Chutinan, and M. Imada, "Trapping and emission of photons by a single defect in a photonic bandgap structure," ***Nature***, Vol. 407, No. 6804, pp. 608–610 (2000).

[10] Y. Akahane, T. Asano, B. S. Song, and S. Noda, "High-Q photonic nanocavity in a two-dimensional photonic crystal," ***Nature***, Vol. 425, No. 6961, pp. 944–947 (2003).

[11] B. S. Song, S. Noda, and T. Asano, "Photonic devices based on in-plane hetero photonic crystals," ***Science***, Vol. 300, No. 5625, p. 1537 (2003).

[12] B. S. Song, S. Noda, T. Asano and Y. Akahane, "Ultra-high-Q photonic double-heterostructure nanocavity," ***Nature Materials***, Vol. 4, No. 3, pp. 207–210 (2005).

[13] M. Fujita, S. Takahashi, Y. Tanaka, T. Asano, and S. Noda, "Simultaneous inhibition and redistribution of spontaneous light emission in photonic crystals," ***Science***, Vol. 308, No. 5726, pp. 1296–1298 (2005).

[14] Y. Akahane, T. Asano, B. S. Song, and S. Noda, "Fine-tuned high-Q photonic-crystal nanocavity," ***Optics Express***, Vol. 13, No. 4, pp. 1202–1214 (2005).

[15] S. Noda, "Seeking the ultimate nanolaser" (perspective paper), ***Science***, Vol. 314, No. 5797, pp. 260–261 (2006).

[16] Y. Tanaka, J. Upham, T. Nagashima, T. Sugiya, T. Asano and S. Noda, "Dynamic control of the $Q$ factor in a photonic crystal nanocavity," ***Nature Materials***, Vol. 6, No. 11, pp. 862–865

(2007).
[17] M. Yamaguchi, T. Asano, and S. Noda, "Photon emission by nanocavity-enhanced quantum anti-Zeno effect in solid-state cavity quantum-electrodynamics" ***Optics Express***, Vol. 16, No. 22, pp. 18067–18081 (2008).
[18] Y. Sato, Y. Tanaka, J. Upham, Y. Takahashi, T. Asano, and S. Noda, "Strong coupling between distant photonic nanocavities and its dynamic control," ***Nature Photonics***, Vol. 6, No. 1, pp. 56–61 (2012).
[19] Y. Takahashi, Y. Inui, M. Chihara, T. Asano, R. Terawaki, and S. Noda, "A micrometre-scale Raman silicon laser with a microwatt threshold," ***Nature***, Vol. 498, No. 7455, pp. 470–474 (2013).
[20] T. Asano, Y. Ochi, Y. Takahashi, K. Kishimoto, and S. Noda, "Photonic crystal nanocavity with a $Q$ factor exceeding eleven million," ***Optics Express***, Vol. 25, No. 3, pp. 1769–1777 (2017).

## C. Photonic-Crystal Surface-Emitting Lasers

[21] M. Imada, S. Noda, A. Chutinan, T. Tokuda, M. Murata and G. Sasaki, "Coherent two-dimensional lasing action in surface-emitting laser with triangular-lattice photonic crystal structure," ***Applied Physics Letters***, Vol. 75, No. 3, pp. 316–318 (1999).
[22] S. Noda, M. Yokoyama, M. Imada, A. Chutinan, and M. Mochizuki, "Polarization mode control of two-dimensional photonic crystal laser by unit cell structure design," ***Science***, Vol. 293, No. 5532, pp. 1123–1125 (2001).
[23] M. Imada, A. Chutinan, S. Noda, and M. Mochizuki, "Multidirectionally distributed feedback photonic crystal lasers," ***Physical Review B***, Vol. 65, No. 19, paper 195306 (2002).
[24] E. Miyai, K. Sakai, T. Okano, W, Kunishi, D. Ohnishi, and S. Noda, "Lasers producing tailored beams," ***Nature***, Vol. 441, No. 7096, p. 946 (2006).
[25] H. Matsubara, S. Yoshimoto, H. Saito, Y. Jianglin, Y. Tanaka, and S. Noda, "GaN photonic-crystal surface-emitting laser at blue-violet wavelengths," ***Science***, Vol. 319, No. 5862, pp. 445–447 (2008).
[26] Y. Kurosaka, S. Iwahashi, Y. Liang, K. Sakai, E. Miyai, W. Kunishi, D. Ohnishi, and S. Noda, "On-chip beam-steering photonic-crystal lasers," ***Nature Photonics***, Vol. 4, No. 7, pp. 447–450 (2010).
[27] Y. Liang, P. Chao, K. Sakai, S. Iwahashi, and S. Noda, "Three-dimensional coupled-wave model for square-lattice photonic crystal lasers with transverse electric polarization: A general approach," ***Physical Review B***, Vol. 84, No. 19, paper 195119 (2011).
[28] S. Iwahashi, Y. Kurosaka, K. Sakai, K. Kitamura, N. Takayama, and S. Noda, "Higher-order vector beams produced by photonic-crystal lasers," ***Optics Express***, Vol. 19, No. 13, pp. 11963–11968 (2011).
[29] Y. Liang, C. Peng, K Sakai, S. Iwahashi, and S. Noda, "Three-dimensional coupled-wave model for square-lattice photonic crystal lasers with transverse electric polarization: finite size effects," ***Optics Express***, Vol. 20, No. 14, pp. 15945–15961 (2012).
[30] K. Hirose, Y. Liang, Y. Kurosaka, A. Watanabe, T. Sugiyama and S. Noda, "Watt-class high-power, high-beam-quality photonic-crystal lasers," ***Nature Photonics***, Vol. 8, No. 5, pp. 406–411 (2014).

[31] S. Noda, K. Kitamura, T. Okino, D. Yasuda, and Y. Tanaka, “Photonic-Crystal Surface-Emitting Lasers: Review and Introduction of Modulated-Photonic Crystals,” ***IEEE Journal of Selected Topics in Quantum Electronics***, Vol. 23, issue 6, paper 4900107 (2017).
[32] M. Yoshida, M. De Zoysa, K. Ishizaki, Y. Tanaka, M. Kawasaki, R. Hatsuda, B. S. Song, J. Gelleta, and S. Noda, “Double-lattice photonic-crystal resonators enabling semiconductor lasers with high-brightness and symmetric narrow-divergence beams,” ***Nature Materials***, Vol. 18, No. 2, pp. 121–128 (2019).
[33] R. Sakata, K. Ishizaki, M. De Zoysa, S. Fukuhara, T. Inoue, Y. Tanaka, K. Iwata, R. Hatsuda, M. Yoshida, J. Gelleta, and S. Noda, “Dually modulated photonic crystals enabling high-power high-beam-quality two-dimensional beam scanning lasers,” ***Nature Communications***, Vol. 11, paper 3487 (2020).
[34] R. Morita, T. Inoue, M. De Zoysa, K. Ishizaki, and S. Noda, “Photonic-crystal lasers with two-dimensionally arranged gain and loss sections for high-peak-power short-pulse operation,” ***Nature Photonics***, Vol. 15, No. 4, pp. 311–318 (2021).
[35] M. Yoshida, M. De Zoysa, K. Ishizaki, W. Kunishi, T. Inoue, K. Izumi, R. Hatsuda, and S. Noda, “Photonic-crystal lasers with high-quality narrow-divergence symmetric beams and their application to LiDAR” (review paper), ***Journal of Physics: Photonics***, Vol. 3, No. 2, paper 022006 (2021).

## D. Thermal Emission Control and Solar Cells Based on Photonic Crystals

[36] M. De Zoysa, T. Asano, K. Mochizuki, A. Oskooi, T. Inoue, and S. Noda, “Conversion of broadband to narrowband thermal emission through energy recycling,” ***Nature Photonics***, Vol. 6, No. 8, pp. 535–539 (2012).
[37] T. Inoue, M. D. Zoysa, T. Asano, and S. Noda, “Realization of dynamic thermal emission control,” ***Nature Materials***, Vol. 13, No. 10, pp. 928–931 (2014).
[38] T. Asano, M. Suemitsu, K. Hashimoto, M. De Zoysa, T. Shibahara, T. Tsutsumi, and S. Noda, “Near-infrared-to-visible highly selective thermal emitters based on an intrinsic semiconductor,” ***Science Advances***, Vol. 2, No. 12, paper e1600499 (2016).
[39] K. Ishizaki, M. De Zoysa, Y. Tanaka, S. Jeon, S. Noda, “Progress in thin-film silicon solar cells based on photonic-crystal structures” (review paper), ***Japanese Journal of Applied Physics***, Vol. 57, No. 6, paper 060101 (2018).
[40] T. Inoue, K. Ikeda, B.-S. Song, T. Suzuki, K. Ishino, T. Asano, and S. Noda, “Integrated near-field thermophotovoltaic device overcoming blackbody limit,” ***ACS Photonics***: Vol. 8, No. 8, pp. 2466–2472 (2021).