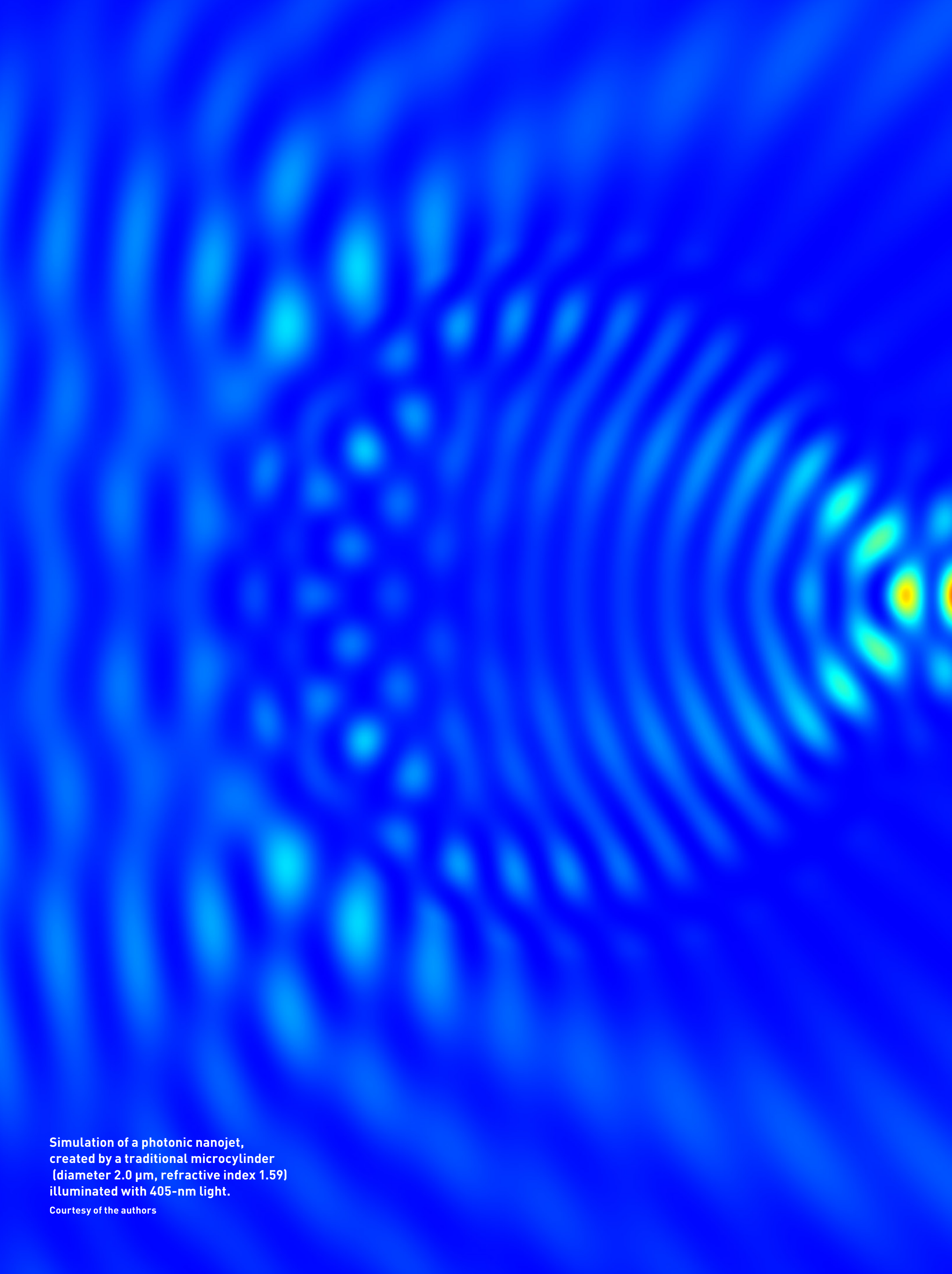


Simulation of a photonic nanojet, created by a traditional microcylinder (diameter 2.0 μm, refractive index 1.59) illuminated with 405-nm light.

Courtesy of the authors

Alexander J. Littlefield, Jinlong Zhu,
Jonah F. Messinger and Lynford L. Goddard

Photonic Nanojets

Microspheres, microcylinders and more complex dielectric structures can create nanoscale concentrations of directed energy. Thanks to progress in fabrication techniques, these optical jets could soon find their way into more advanced applications.

At least two millennia ago, it was known that small water droplets could cause "sunburns" to form on plants. The sunburns are the result of photonic nanojets (PNJs)—highly concentrated, propagating beams of light generated by certain types of dielectric structures (commonly spherical and cylindrical ones) on the order of a few wavelengths in size. Typically, the PNJ hotspot—the location of greatest intensity—is less than half a wavelength in width and extends more than a wavelength in length. In the case of the sunlit droplets, the concentrated energy created by each droplet has a typical intensity of 10 to 50 times that of the incident light.

Being only several wavelengths in size, a typical PNJ generator, such as a microsphere or microcylinder, differs from classical optical elements, such as thin lenses, in that the PNJ generator relies on near-field diffraction and interference effects to achieve its unusual characteristics. Because of this, PNJ generators need to be analyzed with wave optics, rather than the ray optics commonly used with classical elements. Unlike other near-field phenomena, PNJs are often composed of propagating waves—and, while evanescent waves may contribute to a PNJ produced very near a dielectric, most PNJ generators can create a small focus many wavelengths away.

While the theory of PNJs has been known and studied numerically for many years, and while simple dielectric spheres to produce them have been readily available, fabrication of more complex designs for PNJ generators remains a challenge. But new techniques are emerging that could soon make these tiny optical jets part of the device design toolkit.

From ordinary microspheres to GRIN structures

Traditionally, spherical and cylindrical dielectric microstructures have been the geometries of choice for producing point-focused and line-focused PNJs, respectively. A single-index (for example, silica) microsphere is one of the easiest ways to generate a PNJ, and a self-assembled layer of microspheres can be used to produce a 2D array of PNJ hotspots, simplifying alignment.

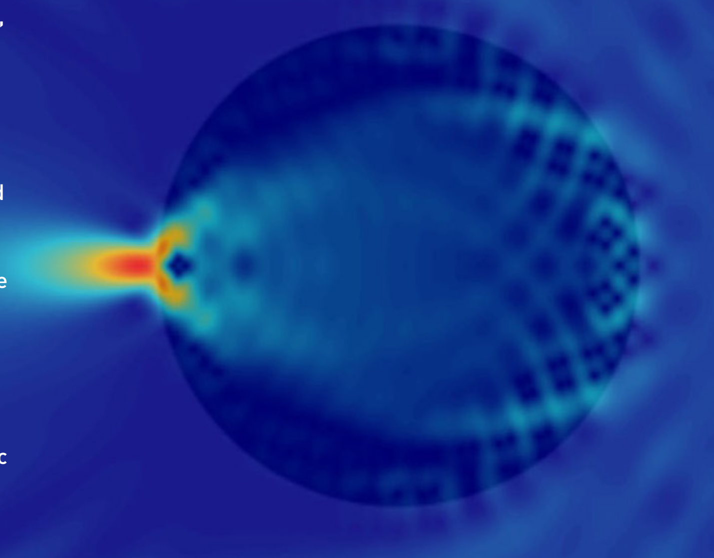
A vast assortment of geometrical and gradient-index (GRIN) microstructures can be engineered to produce PNJs from a plane-wave incident field. These structures, while more difficult to fabricate than conventional microspheres, can produce much narrower beams, and can significantly expand the design space by providing many more variables for precisely engineering the PNJ's shape. A commonly defined figure of merit for assessing such devices is the length of the PNJ divided by its full-width at half-maximum (FWHM), which can be optimized through inverse design to produce a fabricable design with reasonable manufacturing tolerances.

The theory behind PNJ design

Mie theory (see "Meta-Optics with Mie Resonances," OPN, January 2017, p. 24) accurately captures the key physics needed to explain the shape of the PNJ formed by a microsphere or a microcylinder, and why the PNJ is formed outside the surface when the refractive index, n, is less than two. The light entering the microsphere can be decomposed into a series of eigenfunctions that solve Maxwell's equations in spherical coordinates.

Using this theory, much of the focusing can be explained by the repeated reflections within the dielectric material. Eigenmode decomposition into the appropriate basis system and an analysis of near-field diffraction and interference effects can explain the operation of most other microstructure geometries. The decomposition and analysis are usually accomplished through numerical modeling.

Super-oscillatory theory may explain some PNJ designs in which the width remains sub-diffraction-limited, even far from the dielectric structure. Through the careful selection of the amplitudes and phases of lower-order modes, an oscillation faster than the highest-order harmonic can be sustained. Thus the classical diffraction limit can be bypassed through careful engineering of the geometrical or gradient-index profile, the materials used, and the phase front of incoming light.



1047-6938/21/01/34/8-$15.00 ©OSA

A vast assortment of geometrical and gradient-index microstructures can be engineered to produce PNJs from a plane-wave incident field.

One approach to maximizing the intensity, or the ratio of PNJ length to FWHM, is engineering a stepped-index profile to use refraction and interference at multiple interfaces. Although these designs can be difficult to manufacture, they often produce PNJs with excellent properties.

For example, in 2019, researchers at Sun Yat-sen University, China, proposed a design involving a high-refractive-index cylinder and cladding, with a section cleaved off. In numerical simulations assuming illumination with 633-nm light, the design produced an incredible 87-nm FWHM (0.14 wavelengths), with a maximum of 38 times intensity enhancement at the PNJ hotspot. The design presents many manufacturing challenges: the use of $n = 3$ materials, coating with a second material, and the carefully engineered cleaving at a well-defined interface. But if those challenges can be overcome, the resulting PNJ would rank among the best in the field in resolution as a fraction of a wavelength.

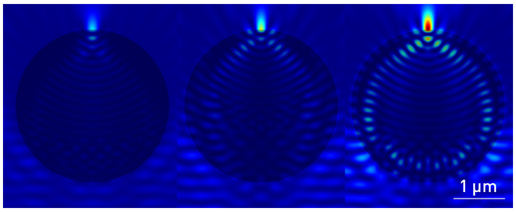
Even more precise control of PNJ properties can come from GRIN structures, which enable elaborate phase-front engineering. A series of spheres of constant index, all tangent to the point nearest the focus, for example, can produce a very high intensity PNJ—the incident plane wave slowly bends as it traverses the GRIN structure, producing constructive interference at the PNJ hotspot. When concentric spheres are used instead, an elongated PNJ can be created, with one design yielding a PNJ that is 20 wavelengths long. A nontraditional structure proposed in 2017 by researchers at Tomsk State University, Russia, involved a micro-cuboid with a GRIN profile. In numerical simulations, the researchers found that, by engineering the grading factor along the cross-section of the micro-cuboid, the resulting PNJ length could be tailored to be between 1 and 7 wavelengths. And the relatively simple micro-cuboid geometry could ease the path to a fabricable device.

Sawtooth, hook and trap

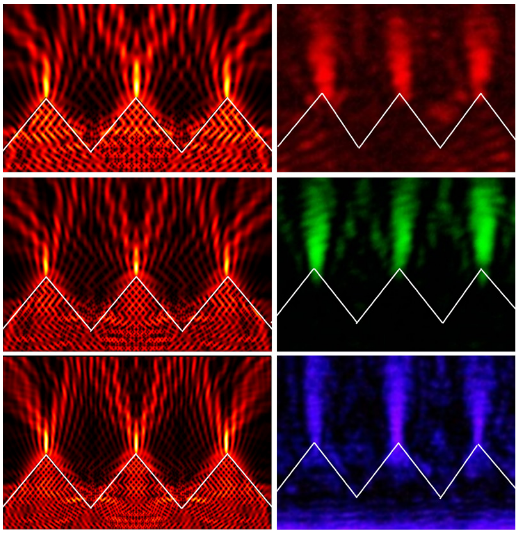
Other combinations of materials and geometry can produce more exotic PNJs. In 2018, for example, the Tomsk State University group mentioned above experimentally

A nanojet sampler

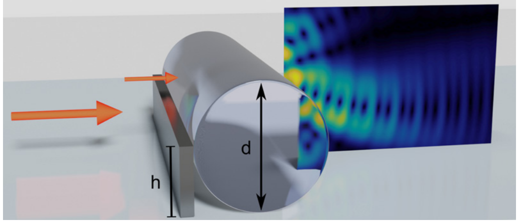
Innovations in modeling and materials fabrication are creating new opportunities for shaping PNJs.



Simulated PNJs at 520 nm from constant-index profile, stepped-index profile, and GRIN profile devices.
Adapted from A. Littlefield et al., META2020 (2021); CC BY 4.0



PNJs created by illuminating sawtooth-pattern phase diffraction gratings with different colors of light.
C.-Y. Liu et al., Europhys. Lett. **123**, 54003 (2018)



Partial masking of a dielectric microcylinder can enable creation of a curved "photonic hook."
I.V. Minin et al., Opt. Lett. **45**, 4899 (2020)

In envisioning new structures for creating and tuning PNJs, actual applications require the ability to manufacture these structures. Emerging techniques are showing the way.

realized a near-field PNJ generator using phase diffraction gratings in a dielectric sawtooth pattern. Each triangular tooth can produce a PNJ with significant sidelobes; combining many periods into a single structure creates an array of PNJs (each centered above a tooth) with much weaker sidelobes.

Experimentally, this structure was fabricated via lithography and replica molding—a potentially significant advantage, as it means that the structure can be easily and inexpensively produced in a large, precisely defined array, unlike most spherical designs. The PNJ generators were spaced close together (at a minimum tested spacing of 5 μm), yet still produced a similar focal profile to standard dielectric spheres. The measured PNJ width was still subwavelength, and the length extended to 5 wavelengths.

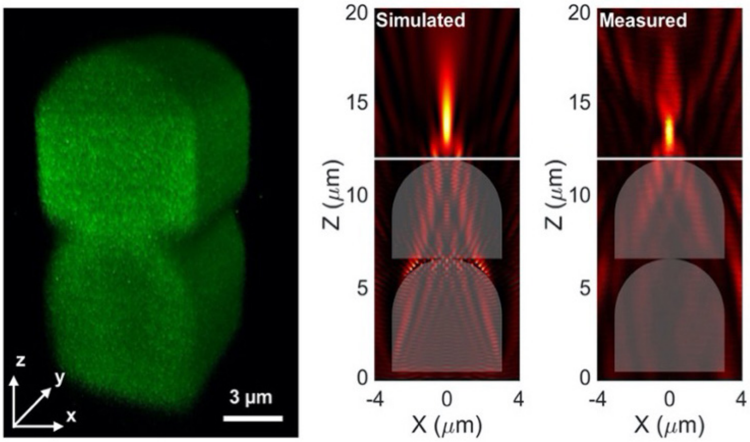
Still more recently, the Tomsk State University team has reported an experimental demonstration of a tunable device for generating a "photonic hook"—a PNJ with an asymmetric field profile, which results in a beam of light whose hotspot has a radius of curvature on the order of a wavelength. The demonstrated device consisted of a standard microcylinder with a transverse metallic sheet that blocked a portion of the illumination. Adjusting the height of this metal mask allowed tuning of the hook's radius of curvature. Physically, the hook arises because the partial illumination of the microcylinder no longer results in complete cancellation of the component of the wave vector parallel to the translational direction of the mask.

Finally, by applying metal behind a PNJ generator, interference of the forward and backward waves will create a standing-wave PNJ. For optical-trapping applications, one advantage of a standing-wave PNJ over a conventional travelling-wave PNJ is that the standing-wave PNJ balances out axial scattering forces, which would otherwise push the object to be trapped along the beam's propagation direction. This advantage means that a wider class of objects, including metal nanoparticles, can be trapped and manipulated using standing-wave PNJs. Although a similar PNJ can be produced between two microspheres, that requires precise alignment of two microspheres; the proposed structure—which requires only a single microsphere, anywhere on the metal sheet—may be easier to fabricate.

Advances in fabrication

As some of the discussion above suggests, while much exciting work has advanced in envisioning new structures for creating and tuning PNJs, actual applications require the ability to manufacture these structures easily and en masse. Emerging techniques are showing the way toward such scalable fabrication.

Silica microspheres are readily available from numerous vendors. An individual microsphere can be extracted and used as an isolated PNJ generator; microspheres can also be arranged into regular patterns—typically a hexagonal close-packed, single-layer arrangement—using self-assembly. In April 2020, researchers at the Shenzhen Institutes of Advanced Technology, China, introduced a technique called template-assisted self-assembly that uses photolithography and reactive ion etching to create microwells into which the microspheres



A capped multimode waveguide structure created with SCRIBE (left) generated a highly concentrated PNJ in close agreement with simulated results (center and right).

C.R. Ocier et al., Light Sci. Appl. **9**, 196 (2020); CC BY 4.0

can self-assemble. The technique allows the microsphere arrangement to be set arbitrarily, a potential advantage in production-scale fabrication.

More advanced planar and 3D topographic PNJ generator structures have been successfully made using standard lithography. However, emerging PNJ generator structures, which include complicated and volumetric step-index and GRIN structures, require full 3D manipulation of optical properties that's difficult to realize with traditional fabrication approaches. One emerging alternative is direct laser writing (DLW), a maskless lithography process used to define 3D polymer structures (see, for example, "3-D Laser Nanoprinting," OPN, October 2019, p. 28).

Recently, our team at the University of Illinois at Urbana-Champaign, USA, has developed an enhanced DLW process, subsurface controllable refractive index via beam exposure (SCRIBE). The technique utilizes a porous substrate to mechanically support a photoresist, allowing suspended optical elements to be reliably defined without the need for a printed polymer scaffold. Furthermore, by adjusting the laser power and beam exposure, SCRIBE can control the fill-fraction of polymerized photoresist in the substrate pores, and thus locally set the effective refractive index.

We have found that SCRIBE can vary the refractive index across a wide continuous range ($\Delta n > 0.3$), in all three dimensions, with sub-micron resolution, and in a single processing run. It avoids the need for multiple photoresists and writing steps to achieve GRIN optics. We have demonstrated use of the technique not only to create PNJ generators but also other optical elements such as Luneburg lenses, compound achromatic lenses, planar axicons, 3D waveguides and microrings, and variable-color distributed Bragg reflectors, with the devices created both in porous silicon (PSi) and porous silica ($PSiO_2$).

The ability to define volumetric optical elements that are a few micrometers in size with SCRIBE enabled the realization of a previously proposed PNJ generator design, consisting of two cascaded multimode waveguides each having a half cylinder cap. The dimensions of each waveguide, the curvature of each cap and the gap between the two elements are used to control modal interference, and thereby to engineer the PNJ hotspot location and shape and to minimize the strength of the sidelobes.

Toward applications

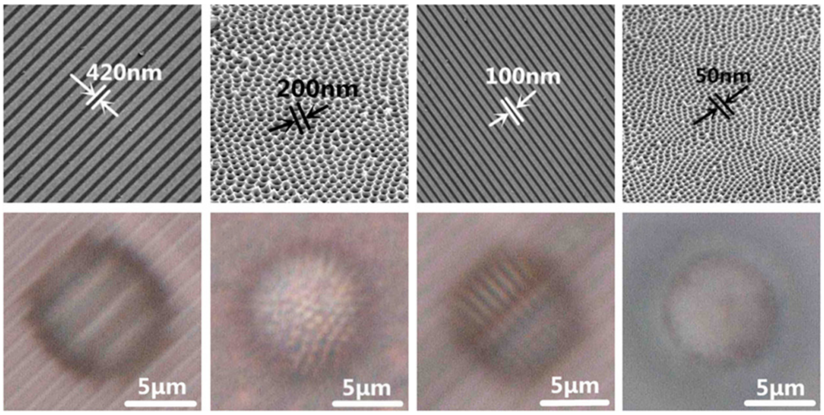
As fabrication approaches continue to improve, we expect the unusual characteristics of PNJs to find new uses in real-world applications. In the rest of this feature, we look at a few PNJ application areas being explored in research labs today.

Super-resolution imaging

Under an ordinary microscope, the diffraction limit prevents distinguishing features that are spaced by less than 200 nm with visible light. By placing PNJ generators on the surface of the substrate of interest, high-resolution near-field images of nanoscale objects can be translated into a resolvable virtual image in the far field.

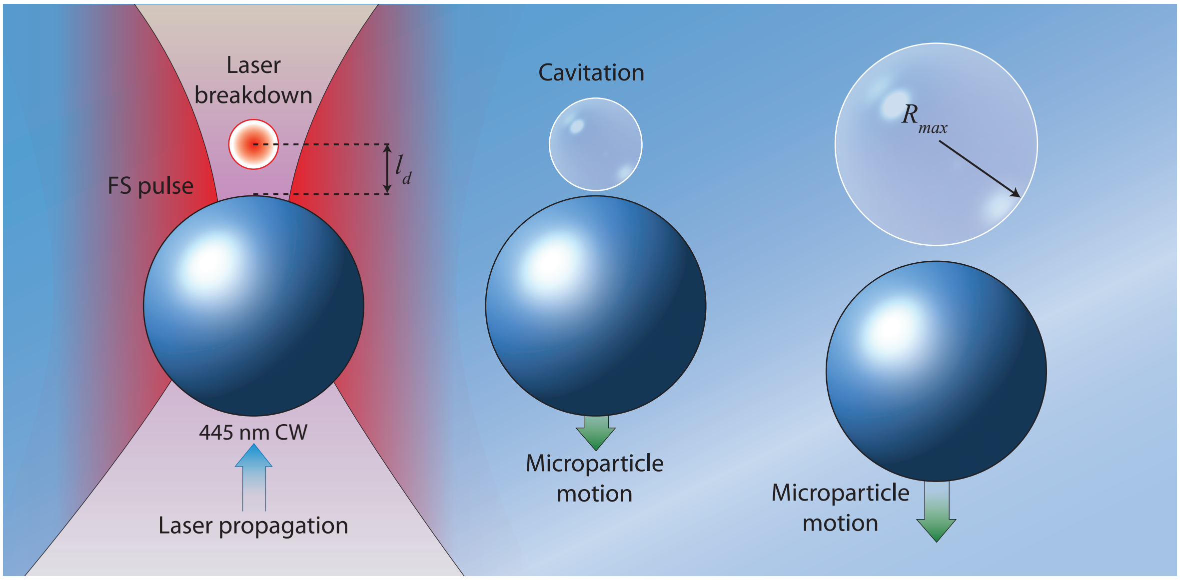
Nearly a decade ago, researchers showed experimentally that PNJs combined with a standard microscope were capable of measuring features with spacings as small as 50 nm using 600 nm illumination, owing to the evanescent wave coupling from the substrate into the PNJ generator structure. The resolution depends closely on the PNJ width, while a longer PNJ length can increase depth of field and mechanical-positioning tolerances.

Another interesting approach, reported in April 2020 by researchers at the Institute of Optics and Electronics, Chinese Academy of Science, is using PNJs to combine optical trapping with super-resolution imaging. The team employed a single laser beam to position a



A PNJ-assisted microscope enabled super-resolution images of a variety of features.

B. Du et al., J. Phys. Chem. A **124**, 7211 (2020)



The PNJ from a microsphere focusing a femtosecond pulsed laser causes cavitation in the water—and pushes the microsphere backwards relative to the laser propagation direction.

Illustration by Phil Saunders / Adapted from A. Shakhov et al., Opt. Lett. **43**, 1858 (2018)

microsphere against the sample, collecting the reflected light to image features with super-resolution. This approach enabled multiple parts of a sample to be independently and quickly viewed without disturbing or damaging the sample itself. In August 2020, still another group, at Southeast University, China, used DLW (via a Nansocribe 3D printer) to write PNJ generators directly atop a substrate to image features of interest. Assisted by the substrate PNJ generators, the team could resolve gratings and structures with pores smaller than the classical resolution limit using a conventional microscope.

Chemical sensing

Researchers from the Far Eastern Federal University in Russia have recently experimentally explored chemical sensing using PNJ-based fluorescence imaging. The group used an array of Al_2O_3 microspheres covered in a layer sensitive to Au^{3+} both to generate the fluorophore excitation with PNJs and to collect the fluorophore emission and thereby detect the local analyte concentration. The tight concentration of light in the PNJ enhanced the fluorescence intensity of the sensitive layer, enabling a lower minimum detection limit for the analyte. The PNJ approach was able to activate a significantly larger volume of the sensitive layer than plasmonic approaches, which enhance fluorescence in the very small region that's in contact with the plasmonic structure.

Improving microendoscopy

In May 2020, a research group from Le Centre National de la Recherche Scientifique (CNRS), France, showed that nonlinear effects of PNJs can improve microendoscopy, which involves inserting optical fiber into the body to image tissue via local excitation and collection of the resulting emission. A silica microsphere, placed at the tip of a high-numerical-aperture double-clad fiber, created a high-intensity PNJ that both concentrated pulses from a tunable 700-to-1000-nm femtosecond laser and efficiently collected the scattered light. The system enabled two-photon excitation fluorescence and second- and third-harmonic generation nonlinear imaging of collagen, green fluorescent protein (GFP)-tagged neurons, and human skin stratum corneum.

Particle trapping and manipulation

PNJs can enable extremely high-intensity fields and localization to nanoscale volumes. In 2018, researchers from Semenov Institute of Chemical Physics, Russia, reported using silica microspheres to concentrate femtosecond laser pulses and induce breakdown and cavitation in water. The large effective band gap of water necessitates five photons from the laser for ionization; such a high-order nonlinear process was achieved only at the PNJ hotspot. Further, the cavitation from the highly directional PNJ could be used to propel the microsphere antiparallel to the direction of light propagation, with micronewtons of

The concepts born in the study of PNJs seem likely to expand into new realms as novel materials and device geometries, fabrication methods and applications emerge.

force—significantly greater than the force produced using conventional optical trapping. Particle speeds of up to 100 m/s were reported.

Last year, researchers in Hong Kong and Singapore observed a force in the same reverse direction, but due to a different physical effect, when dissolved particles were illuminated with a picosecond laser. Solvent molecules in the PNJ hotspot on the shadow side of the dissolved particles experienced local heating via the photothermal effect. Although the incident photons impart momentum upon the particles via the optical scattering force, the thermally generated fluidic force was four orders of magnitude larger. Therefore, the net force experienced by the particles was in the opposite direction of light propagation. This approach required only a single laser source and did not cause breakdown of the medium, but the imparted force was relatively small (on the order of piconewtons), and the maximum particle speed detected was approximately 1 mm/s. The team envisions use of the technique in biophotonics applications such as cell sorting and classification.

A nanojet future

As the foregoing, selective survey indicates, emerging fabrication techniques may soon enable the realization of many recently proposed advanced PNJ generator designs. SCRIBE and other emerging techniques are beginning to unlock additional degrees of freedom for engineering PNJ generators—potentially enabling increased fabrication tolerance, new functionality, simple mass manufacturing and ubiquitous integration of PNJ generators that enhance the performance of chip-scale lasers, modulators, photodetectors and imaging sensors.

In principle, an engineered structure with a refractive-index difference of 2 to 3 can produce a PNJ with a FWHM of one-tenth the wavelength. New materials science techniques to artificially increase the refractive index, coupled with extending operation to the extreme UV region, could conceivably decrease the FWHM to the sub-nanometer level.

The theory and application space for PNJs are also rapidly expanding beyond the field of optics. The tools used to understand optical focusing can be used more generally for studying waves focusing on the scale of a few wavelengths. PNJ operation in the terahertz and millimeter-wave ranges is an emerging area of exploration, and sound wave focusing via "acoustojets" has been theorized and demonstrated in recent years. Thus, the concepts born in the study of PNJs seem likely to expand into these and other new realms as novel materials and device geometries, fabrication methods and applications emerge. OPN

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For additional references and resources, go online: **www.osa-opn.org/link/photonic-nanojets**

Correction

The authors of the article "Photonic Nanojets" (OPN, January 2021, p. 34) apologize for not providing historical context on the concept's development. In 1998, Kawata et al. observed optical field enhancement from laser irradiation of spherical polystyrene particles of size $d \leqslant \lambda$ on a photosensitive film.[1] In 2000, Mosbacher et al. used Mie theory and experiments to show how the enhancement scales with particle size across a wide range ($0.4\,\lambda \leqslant d \leqslant 3.2\,\lambda$) and to explain that it is due to focusing.[2] In 2004, the Backman–Taflove group at Northwestern University showed that in addition to field enhancement, light generated on the shadow side of a microcylinder can propagate with a sub-diffraction width over a distance of several optical wavelengths, and named the effect a photonic nanojet.[3]

The authors also regret any confusion caused by the title of the OPN feature, which is the same as a previously published review paper.[4]

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