

Low divergence photonic nanojets from Si₃N₄ microdisks

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Abstract: High intensity sub-wavelength spots and low divergence nanojets are observed in a system of Si₃N₄ microdisks illuminated from the side with laser light of wavelengths 488 nm, 532 nm and 633 nm. The disks are of height 400 nm with diameters ranging from 1 μm to 10 μm. Light scattered from the disk and substrate is observed by imaging from above. In free space light is focused inside the disks and a sub wavelength spot is observed, whereas in water the refractive index contrast is such that photonic nanojets are formed. The angular distribution of the intensity compares well to the analytical solution for the case of an infinite cylinder. Two distinct cases of scattering pattern are observed with even and odd numbers of lobes. Finally when the disks are illuminated with a focused Gaussian beam perpendicular to the substrate an extremely low divergence beam is observed. This beam has a divergence angle over 10 times smaller than a focused Gaussian in free space with the same waist.

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1. Introduction

Scattering of light by spherical and cylindrical particles has been of interest for over 100 years now since the popular derivation of the analytical solution for a sphere by Mie in 1908 [1]. It has lead to a better understanding of many optical phenomena, and has resulted in important technological developments in areas such as communication, metrology, meteorology, and astronomy [2].

In general, light scattering from an object depends on its size relative to the incident wavelength, characterized by the size parameter $x_s = 2\pi R / \lambda$, and also the ratio of the refractive index of the object to the surrounding medium, known as the refractive index contrast (m). If a particle has a small size parameter ($x_s \ll 1$), it is said to be in the Rayleigh regime and approximate solutions can be found by assuming the particle is in a static field. If it has a large size parameter geometrical optics can be used. In the intermediate regime where the diameter of the particle is of the order of 1-10 times the incident wavelength these approximations do not apply [3], and the EM field can only be calculated by solving Maxwell's equations either using analytical or numerical techniques.

Light with optical frequencies that is incident on particles with diameters in the range of 1 μm to 10 μm falls into this intermediate range. Studies in this regime can be found as far back as 1985, where numerical techniques were used to calculate the analytical Mie solutions. At that time scattering of water droplets in fog or cloud was of interest for high energy laser propagation in the atmosphere [4, 5]. Lately however, with increased computational power available, the properties of light scattering in this regime have been explored with high resolution using numerical techniques such as Finite Difference Time Domain (FDTD) and Finite Element Methods (FEM). This has lead to the prediction in 2004 that light scattered from an infinite cylinder would produce an interesting scattering distribution [6]. This distribution has a high intensity main lobe, with weakly sub-diffraction waist, and very low divergence angle. This results in a high intensity beam which persists with a sub-wavelength waist over a distance of micrometers. A similar distribution was shown to exist for the case of a sphere [7]. These distributions were termed Photonic Jets or Photonic Nanojets (PNJ) and

were shown to exist for a range of size parameter x_s , as long as the refractive index contrast is close to $m = 1.7$ [6, 7].

Since then the properties of these scattering distributions have been explored both analytically and numerically [8–12]. They have been experimentally observed directly with centimeter scale spheres at microwave frequencies (30 GHz) [13], at optical frequencies using a scanning con-focal microscopy technique [14], and indirectly using reflection from a substrate [15].

These computational techniques combined with the commercial availability of high quality mono-disperse microspheres has led to a substantial amount of literature since 2004 on both the intrinsic properties of the PNJ and applications [16, 17]. The importance of the PNJ is evidenced from the numerous applications which have been proposed and experimentally verified. For example a metallic nanoparticle passing through the PNJ creates a large backscattering perturbation, which depends on the third power of the nanoparticle diameter as opposed to the sixth power in standard Rayleigh scattering [6, 7]. This effect has been exploited to detect a 50nm gold particle using a BaTiO₃ microsphere embedded in a PDMS matrix [18]. The PNJ effect has been used in direct write lithography, producing features with minimum sizes ~100nm with light of wavelength 355nm [19]. PNJs have been proposed for optical data storage, with resolution higher than BluRayTM [20], single molecule detection and fluorescence enhancement [21], and super-resolution optical microscopy [22]. They have also been used for low loss optical transmission [23], and as a precise cutting tool for medical applications [24].

Much of the experimental work thus far has focused on PNJs from dielectric spheres, despite the original predictions being in cylindrical geometries. This is due to the fact that the intensity enhancement for a sphere is greater than that of a cylinder. The use of a planar disk based system however offers many advantages over the case of a sphere. The disks size and shape and position can be easily controlled to high precision in the fabrication process. Higher refractive index materials can be used. These disks can be made cheaply in large volumes, and in arrays that could then be integrated on chip with micro-fluidic channels to produce on chip solutions for single molecule fluorescence detection, nano-particle detection, or bio-sensing applications.

This paper provides a study of the properties of light scattering from Si₃N₄ ($n=2.1$) microdisks of height 400nm on an SiO₂ ($n=1.45$) substrate. The scattering distribution depends on both parameters x_s and m . Microdisks with diameters ranging from 1 to 10 μ m in 500nm steps are fabricated and incident wavelengths of 488 nm, 532 nm and 633 nm were used in order to fully probe the size parameter space. The disks were then immersed in water in order to change the refractive index contrast m from 2.1 to $2.1/1.33=1.58$. By simply imaging the disks, many of the properties of light scattering in this regime are confirmed. The angular dependence of the scattering distribution compares well with the analytical solution for an infinite cylinder. This simple non invasive approach allows us to indirectly measure the total near field intensity distribution. Finally the case of perpendicular illumination with a focused Gaussian beam is shown to produce an extremely low divergence jet with a divergence angle over ten times smaller than possible with a focused Gaussian beam in free space.

2. Material system and fabrication

A 400nm layer of stoichiometric Si₃N₄ was deposited on a 2 μ m layer of thermally grown SiO₂ using LPCVD (Si-Mat). The 2 μ m thick low refractive index oxide layer acts as an optical spacer between the high refractive index Si₃N₄ and the Si base wafer. The microdisks were patterned using a 25 kV Zeiss SUPRA 40 E-beam lithography system, using AZ 2070 nLof negative tone resist (Microchemicals GmbH), with a voltage of 20 kV and a dose of 40 μ C/cm². The resist was developed leaving a 550 nm layer of nLof resist which was used as a mask in the etching process. The sample was etched using an Oxford Instruments ICP plasma

etch tool with a mixture of SF_6 and CHF_3 gases to create disks with smooth sidewalls. Finally an oxygen plasma step was used to clean the remaining resist from the surface. Single microdisks of diameters ranging from 1 to 10 μm were fabricated. Cross sectioning using a focused ion beam (FIB) milling method showed a significant sidewall angle of 56° from the substrate. This means that the diameter of the disk changes by 540 nm from the top of the disk to the bottom. The sidewall is also convex as shown in Fig. 1(b).

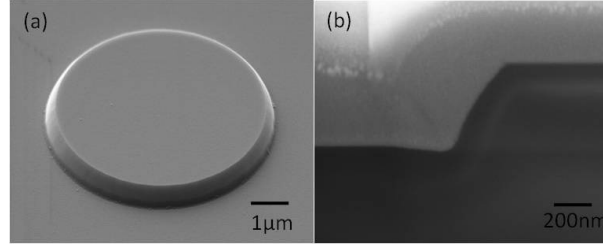


Fig. 1. (a) SEM image of a single microdisk of diameter 8 μm . (b) FIB milling was used to cut through the disk. The disk was covered in a thin layer of Pt in order to protect the dimensions of the structure. The side profile shows the disks are of height 400 nm with a sidewall angle of 56° .

3. Experimental setup and analysis

The experimental setup is depicted in Fig. 2(a). Light from a source laser is introduced with a high angle of incidence at 80° from the normal. The laser produces linearly polarised light with a Gaussian profile of width 2 mm, much larger than the size of an individual disk. This means that the light incident on a single microdisk is effectively a plane wave. Continuous wave (CW) excitation at wavelengths of 488 nm, 532 nm and 633 nm was used in this study. All the results in this paper are for the TM case, where the incident polarisation is along the axis of the cylinder as in Fig. 2(a). Differences between the TE case and the TM case are too small to be detected with this method. The scattered light is observed from above using a long working distance, flat field corrected, 100x microscope objective with an NA of 0.7 (Mitutoyo). The objective is infinity corrected, thus a tube lens of focal length 200 mm is used to form the primary image directly on the CCD. The result is a gray-scale pixel image of the scattered light distribution as shown in Fig. 2(b).

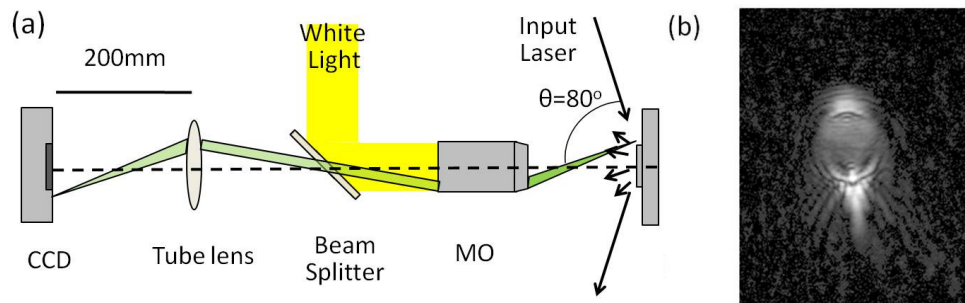


Fig. 2. (a): Laser light is introduced with an angle of incidence of 80° . Most of the light is reflected specularly, but a small percentage is scattered at large angles by the disk. The scattered light from the structure is collected using the microscope objective (MO) and imaged onto a CCD as indicated by the marginal ray bundle in green. The input beam is a Gaussian with a large beam diameter of 2 mm, making the excitation effectively a plane wave on the scale of the microdisk. Images of the disk can be obtained by introducing white light through the beam splitter. (b) Raw image from a microdisk of diameter 6.5 μm , with 532 nm incident wavelength. Light is incident from the top.

The images were recorded with a Sony CCD with a resolution of 1024x768 and 4.6 μ m physical pixel size. In order to determine the image pixel size accurately, the diameter of the disk was measured to within ± 40 nm using SEM, and this was used as a calibration for the optical image. Error is introduced in determining the exact boundary of the disk, due to the diffraction limited collection optics. By taking the maximum and minimum values of diameter from the image and dividing by the number of pixels, a value for each pixel can be obtained with a corresponding uncertainty. From this method it was established that the image was over sampled with an image pixel size of 110 $\pm$ 1nm. The imaging system is diffraction limited, thus the smallest dimensions of the scattered intensity resolvable, R , will be limited by the Rayleigh criterion $R = 0.61\lambda / NA$. This gives values of R of 425 nm, 464 nm, and 552 nm for input wavelengths of 488 nm, 532 nm and 633 nm respectively. This effect could be accounted for by processing the image using a deconvolution step, however the parameter of interest is the divergence angle of the main lobe and is not affected by the blurring. Deconvolution is not used in order to avoid introducing unnecessary uncertainty to the measurement. When measuring the properties of the scattering distribution it is important to remember that the image is blurred due to diffraction. Thus figures quoted like the FWHM and axial falloff are always larger than the actual dimensions present in the system. The angular quantities will not be affected though, as the blurring is equal in both dimensions. The error quoted on these quantities is error introduced by uncertainty in calculating the individual image pixel size.

The position of best focus was determined by taking the position with the sharpest image of the disk under white light illumination. This image was used to superimpose the disk circumference on the scattered images. Due to the high angle of incidence and low surface roughness of the substrate the input light is almost completely specularly reflected. This results in a negligible background far from the disks. The observed light is thus a combination of scattered light from the Si₃N₄ and reflected / scattered light from the SiO₂ surface just outside the disk. Therefore the image we observe does not correspond to a map of the total intensity distribution, but is primarily made up of the scattered field. Only light which is scattered into the cone of the MO is observed in the image. Due to the large range of intensity in the image, four images were taken of each disk with different exposure times and recombined in order to increase the dynamic range. This allowed us to plot the log plots in of the intensity distribution over three orders of magnitude.

4. Analytical model: Mie theory

In this size regime the EM field can be solved for using either numerical or analytical techniques. Numerical techniques such as FDTD and FEM are well established [6], and can give reliable field distributions for specific disk diameters. In this paper the analytical solution for light scattering from an infinite cylinder is used. Although this doesn't exactly match the geometry, it gives physical insight into the origin of the lobes in the scattering distributions. The derivation of the solution is well known and can be found in many light scattering textbooks [25, 26]. The form of the solution is outlined below. In this method the field is split into three parts; the incident field (E_i), the internal field (E_{int}), and the scattered field (E_s). The total field outside the cylinder is given by vector addition of E_i and E_s and the total field inside the cylinder is given by E_{int} . Using the co-ordinate system depicted in Fig. 3, the incident field is a time harmonic plane wave, polarised along the z-axis and propagating along the x-axis, which is given in cylindrical co-ordinates by Eq. (1).

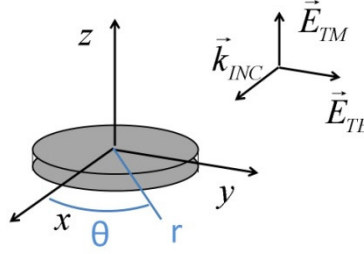


Fig. 3. Co-ordinate systems used in specific form of the analytical solution. Incident light is linearly polarised along the z-axis in the TM case, and propagates along the x-axis.

The solution is obtained by expanding the electric field in terms of circular cylindrical functions (Bessel and Hankel functions) and then imposing boundary conditions to find the expansion coefficients. For the TM case the electric field has components only along the z-axis (along the axis of the cylinder). The analytical expressions for the incident, scattered and internal electric field are then given by:

$$E_z^i(kr) = E_0 \sum_{n=-\infty}^{\infty} i^n J_n(kr) \exp(in\theta) \quad (1)$$

$$E_z^s(r, \theta) = -E_0 \sum_{n=-\infty}^{\infty} i^n b_n^{cyl} H_n^{(1)}(kr) \exp(in\theta) \quad (2)$$

$$E_z^{int}(r, \theta) = E_0 \sum_{n=-\infty}^{\infty} i^n d_n^{cyl} J_n(mkr) \exp(in\theta) \quad (3)$$

$$b_n^{cyl} = \frac{m J_n'(mx_s) - J_n(x_s) J_n'(x_s)}{m J_n'(mx_s) H_n^{(1)}(x_s) - J_n(mx_s) H_n^{(1)}(x_s)} \quad (4)$$

$$d_n^{cyl} = \frac{1}{J_n(mx_s)} [J_n(x_s) - b_n^{cyl} H_n^{(1)}(x_s)] \quad (5)$$

E_0 is the incident electric field amplitude. The refractive index contrast m is the ratio of the refractive index of the cylinder to the surrounding medium. The size parameter $x_s = 2\pi R / \lambda = kR$ is fixed for a particular case by the ratio of the cylinder radius R to the incident wavelength λ . This is the natural parameter to use as the analytical solution does not depend on the radius and diameter independently, but on their ratio. J_n is the Bessel function of order n , and $H_n^{(1)}$ is the Hankel function of the first kind of order n , where the prime refers to the derivative of these functions with respect to their argument. The expansion coefficients b_n^{cyl} and d_n^{cyl} are complex scalars given by Eq. (4) and Eq. (5). They depend only on the size parameter x_s and the refractive index contrast m . The expression for the scattered field can be reduced further to:

$$E_z^s(r, \theta) = -E_0 b_0 H_0^{(1)}(kr) - 2E_0 \sum_{n=1}^{n_c} i^n b_n^{cyl} H_n^{(1)}(kr) \cos(n\theta) \quad (6)$$

It has been shown empirically that the summation in Eq. (6) converges for a finite value of n given by: $n_c = x_s + 4.05x_s^{1/3} + 2$ [27]. From Eq. (6) it is evident that the radial dependence of the scattered field is a combination of different orders of weighted Bessel functions, whereas the angular dependence is contained in a weighted sum of $\cos(n\theta)$ terms. Only a finite number of terms in the sum are non zero and the main contribution comes from values of n

less than x_s . Thus the scattered field is dominated mainly by these components. This results in a fixed number of lobes in the scattered field which increases with the size of the disk. These vary from even to odd numbers of lobes, which results in either a single central lobe or two symmetric ones either side of the centre line of the disk respectively. The expression $I = E_s \cdot E_s^*$ is proportional to the scattered intensity. Equation (6) is used to calculate this scalar field at fixed points on a Cartesian grid. The solution is then interpolated using tri-linear interpolation to create a smooth surface map for comparison with experimental results.

5. Results

5.1 Scattering in air

For a refractive index contrast of 2.1, (Si_3N_4 in air) incident light is focused to a sub-wavelength spot which is located just inside the opposite surface of the disk. Scattering distributions were recorded for disks ranging in diameter from 1 to $10\mu\text{m}$ in 500nm steps, with incident wavelengths of 488 nm, 532 nm and 633 nm. Representative results of three microdisks of diameter $1.5\mu\text{m}$, $4.5\mu\text{m}$ and $8.5\mu\text{m}$ are shown in Fig. 4. The scattering distribution depends only on the size parameter and the refractive index contrast, so changing the wavelength is equivalent to changing the diameter of the disk. The experimentally measured distribution is compared with the internal and scattered fields from theory. The top row of Fig. 4 is an interpolated map of the experimental results over a $20\mu\text{m}$ by $14\mu\text{m}$ area with a pixel size of 110 nm, for the three different disk sizes. Linear and $\log_{10}$ plots are shown. The linear plot is normalised to 1 and the log plot is over 3 orders of magnitude. The bottom row of Fig. 4 is an interpolated map of intensity for an infinite cylinder using a Cartesian grid of 40 nm spacing over the same area. The log scale allows us to see the higher angle lobes in more detail. These lobes are an order of magnitude lower in intensity than the main lobe, but are the most important element in creating this unique low divergence main lobe [10].

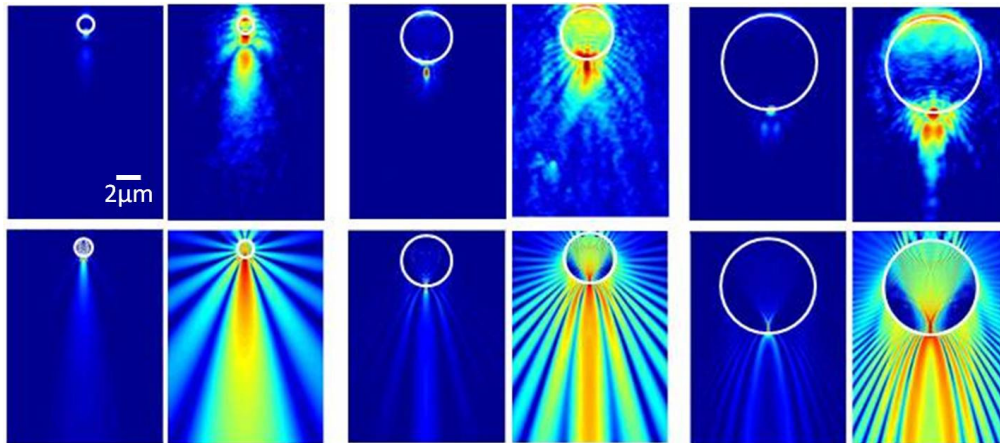


Fig. 4. Experimental images and analytical results of the scattered intensity for individual disks. All images are normalised to the maximum intensity. Light is incident from the top of the images at a wavelength of 532 nm. Top row from left: Experimental linear image, and $\log_{10}$ of $1.5\mu\text{m}$ diameter disk, $4.5\mu\text{m}$ diameter disk and $8.5\mu\text{m}$ diameter disk. Bottom row from left: Analytical results for infinite cylinder of same dimensions as above experimental results, plotted in linear and log scales. The scale is the same for all images with a scale bar given in the top left experimental image.

From Fig. 4 the angles of the secondary lobes compare well with the analytical theory for an infinite cylinder. Due to the fabrication process a sidewall angle of 56° was present. It was found that the best match with theory was found by using value of diameter half way between

the top and bottom diameter of the disk. This sidewall angle also contributes to some scattering at the edges of the disk which accounts for the high intensity at the edge of the disks seen in the experimental results and not in the theory. In the experimental images out of plane divergence results in the scattering distribution being truncated in the radial direction. This out of plane divergence is not accounted for in the simple infinite cylinder model. The angle of divergence out of the plane of the disk is expected to be 35° , similar to the case of light emitted from a planar waveguide with the same materials and dimensions. The scattering distribution can be understood as a linear combination of a finite number of terms in the sum of Eq. (6). In Fig. 5 the norm of the expansion coefficient $b_n^{(cyl)}$ as a function of n shows the relative contribution of each term in the sum for a $1.5\mu\text{m}$ diameter disk (Fig. 5(a)), and an $8.5\mu\text{m}$ diameter disk (Fig. 5(b)).

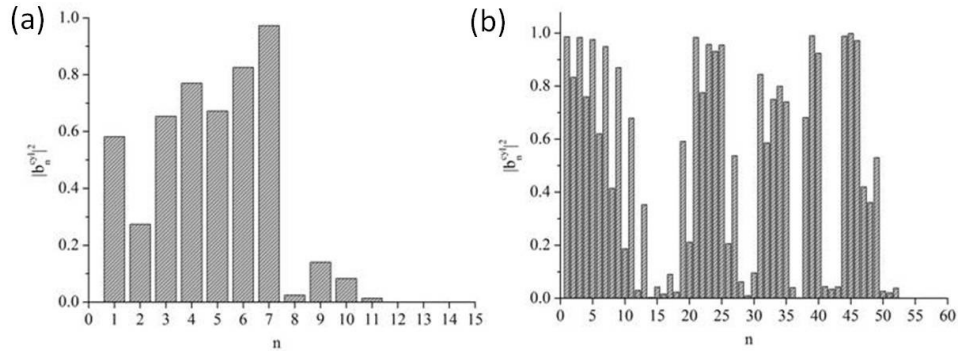


Fig. 5. Norm of expansion co-efficient of the scattered field $\mathbf{E}_s$ for disk of diameters (a) $1.5\mu\text{m}$, (b) $8.5\mu\text{m}$.

For a $1.5\mu\text{m}$ diameter disk 14 lobes are visible, and we see that the main contribution is from terms up to the $n=7$ term. As the diameter of the cylinder increases more terms become significant, resulting in a more complex scattering distribution. Two distinct cases were observed experimentally: An even number of lobes and a single lobe in the centre at $\theta=0$, and an odd number of lobes with two symmetric lobes either side of the $\theta=0$ line. For the $1.5\mu\text{m}$ and $4.5\mu\text{m}$ cases there are an even number of lobes (14, and 38 respectively), and a central peak, whereas for the $8.5\mu\text{m}$ case there was an odd number of lobes (63) with a local minimum in at $\theta=0$ and a symmetric distribution around this line. A further example of these two cases is shown for comparison in Fig. 6. These are two disks with diameters $9\mu\text{m}$ and $9.5\mu\text{m}$ respectively. The incident light is a plane wave of wavelength 532nm with TM polarisation from the bottom left-hand corner of the image. A change of only 500nm results in a very different distribution. As the diameter of the disk increases the number of scattering lobes changes between even and odd, adding one lobe at a time.

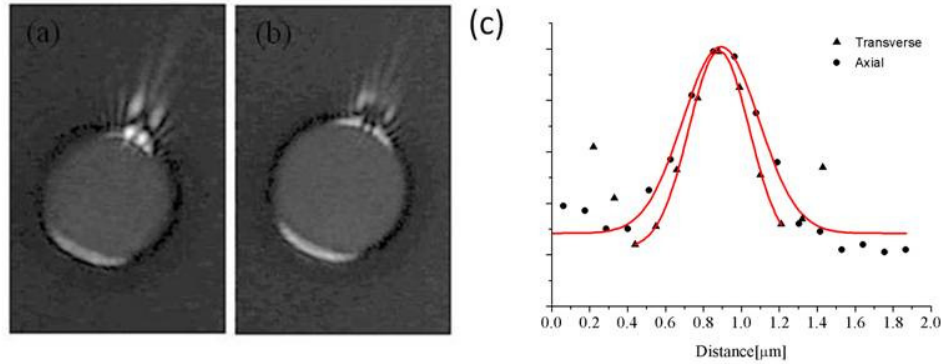


Fig. 6. Raw experimental images. Incident light of wavelength 532nm from bottom left corner of image. (a) Disk of diameter $9\mu\text{m}$ (b) Disk of Diameter $9.5\mu\text{m}$. (c) Axial and transverse profile of the central peak in (b) fitted with Gaussians. This gives a diffraction limited spot of FWHM $460\text{nm} \pm 60\text{nm}$ by $508 \pm 65\text{nm}$.

For some disk diameters a small spot of high intensity was observed just inside the disk along the $\theta = 0$ axis, as in Fig. 6(b). Cross sections of the profile are taken and plotted in Fig. 6(c). The circles represent pixel values along the $\theta=0$ axis, and the triangles are values from a cross section perpendicular to this. The points are fitted with a Gaussian and the FWHM are found to be $508 \pm 65\text{nm}$ along the $\theta=0$ axis and $460 \pm 60\text{nm}$. The error quoted here is from the uncertainty in determining the size of each individual image pixel. These values are of course limited by the MO used to record the image. The smallest resolvable distance for this MO given by the Rayleigh criterion is 460nm at 488nm . Even a perfect MO will cause blurring due to diffraction. The above dimensions are therefore an upper limit on the spot size

The total intensity outside of the disk is not observable directly using our experimental method, however since the incident field is known to be a plane wave, and the observed scattered field matches reasonably to the analytical solution, it follows that the total local intensity can be calculated based on the vector addition of the incident and scattered electric fields. Figure 7 shows the total intensity inside and outside the disk for the case of scattering in air. This is the intensity that would be actually seen by a particle close to the disk. Interference from the incident field and the scattered field outside the disk create a small sub-wavelength spot on its surface. These images are quite different from those in the second row of Fig. 4, which shows only the scattered field. The maximum intensity is inside the disk, but there is a small sub-wavelength spot on the surface of the disk.

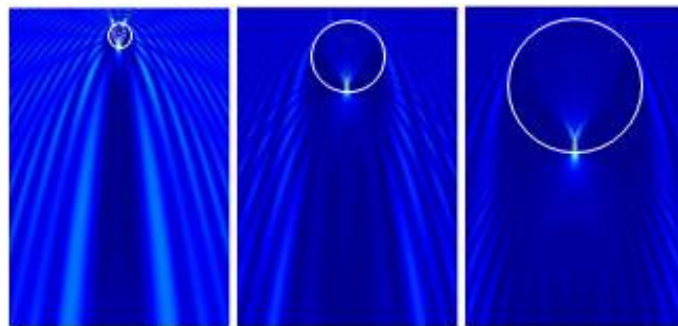


Fig. 7. Calculated total intensity for an infinite cylinder of index 2.1 in air for diameters of $1.5\mu\text{m}$, $4.5\mu\text{m}$ and $8.5\mu\text{m}$ plotted on a linear scale.

5.2 Microdisks in water: Photonic jets

When the disks are immersed in water the refractive index contrast m is reduced to 1.5. In this case conditions are controlled to observe a scattering distribution termed a photonic jet where the maximum intensity is outside the disk, and the main lobe is long and narrow with a low divergence. The experimental setup used in shown in Fig. 8. The optical system after the MO is the same as the one described in Fig. 2(a). The same MO was used as for the images of scattering in air, for comparison between the two cases. The introduction of a coverslide and water between the MO and the object introduces spherical aberration which results in some blurring of the image. This is accounted for in calculating the image pixel size. Each pixel in this case is measured to be $135 \pm 8 \text{ nm}$ using the SEM calibrated disk diameter. The results of scattering for disks of diameter $1.5 \mu\text{m}$, $3 \mu\text{m}$ and $6 \mu\text{m}$ with an incident plane wave illumination of 633 nm are shown in Fig. 9. Note that the incident wavelength is effectively reduced to $\lambda/1.33$ (475 nm) in water. Images are taken over a $20 \mu\text{m} \times 14 \mu\text{m}$ area, and tri-linear interpolation is used to smooth them.

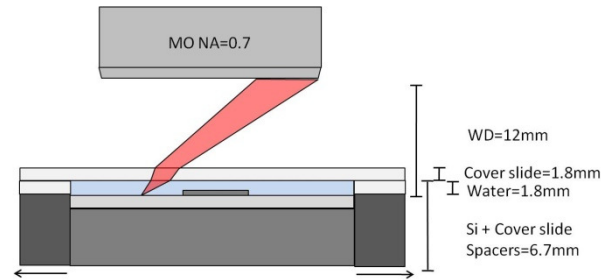


Fig. 8. Experimental setup used to measure the scattering properties of the microdisks in water. Some spherical aberration is introduced in this setup, but is accounted for in the scaling of the image pixel size. The rest of the optical system from the back of the MO is identical to that of Fig. 2(a). The laser is input at 80° angle of incidence through the cover-slip. The shaded red region indicates a marginal ray bundle.

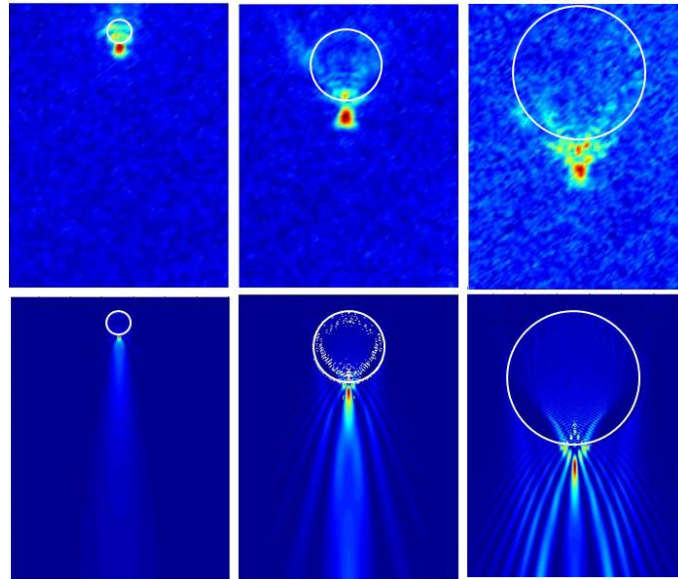


Fig. 9. Scattering distribution from microdisks in water. The incident wavelength is 633 nm which is effectively reduced to 475 nm in water. The refractive index contrast is now 1.5. In this case the maximum of the scattered light is outside of the disk and we see the photonic nanojet effect. The normalised intensity plots are shown for 3 different disk diameters (a) $1.5 \mu\text{m}$ (b) $3 \mu\text{m}$ (c) $6 \mu\text{m}$ on a normalised linear scale.

The intensity maximum in Fig. 9 is now outside the disk. This configuration could have applications for biological sensing or nanoparticle detection in solution.

5.3 Non planar excitation

Another interesting case is with Gaussian illumination perpendicular to the substrate. Lately it has been shown that the properties of the PNJ can be controlled by shaping the input beam intensity and phase [28]. Using the experimental setup in Fig. 10(a), focusing the incident light on the edge of the disk is shown to produce a low divergence beam on the opposite side of the disk, as shown for the case of a $9\mu\text{m}$ diameter disk in air and 488nm incident illumination in Fig. 10(c).

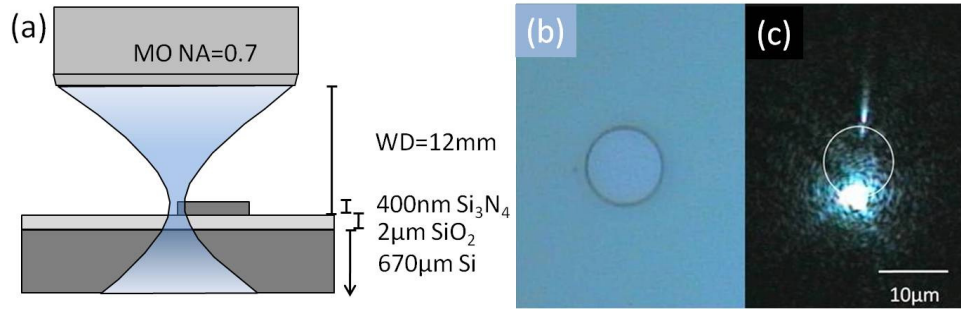


Fig. 10. (a) Experimental setup. Laser light of wavelength 488nm is focused onto the rim of the disk (b)The white light image of the $9\mu\text{m}$ diameter microdisk before illumination. (c) Image with 488nm CW laser illumination. The Nanojet forms in air on the opposite side of the disk to the illumination.

Due to the high NA of the MO, light incident at high angles is scattered by the disk and focused into the jet. Only a small portion of the total intensity is focused into the nanojet. The exposure time of the image in Fig. 10(b) is chosen such that the jet is clearly visible, and the incident spot is over exposed. The transverse profile at the surface of the disk is plotted in Fig. 11(a) and fitted with a Gaussian. The main lobe only is fitted as this corresponds to the nanojet. The FWHM of the jet at the point of maximum intensity is 510nm . This corresponds to a w_0 value of 205nm (w_0 = half the $1/e$ waist). The profile along the $\theta = 0$ line is shown in Fig. 11(b). The axial profile of the PNJ has been shown to be best fitted with a Lorentzian function. The parameter used to characterise the length of the jet is then half the FWHM of the Lorentzian, which is labelled Z_r , and represents the distance from the point of maximum intensity to the point of half maximum intensity along the $\theta = 0$ axis.

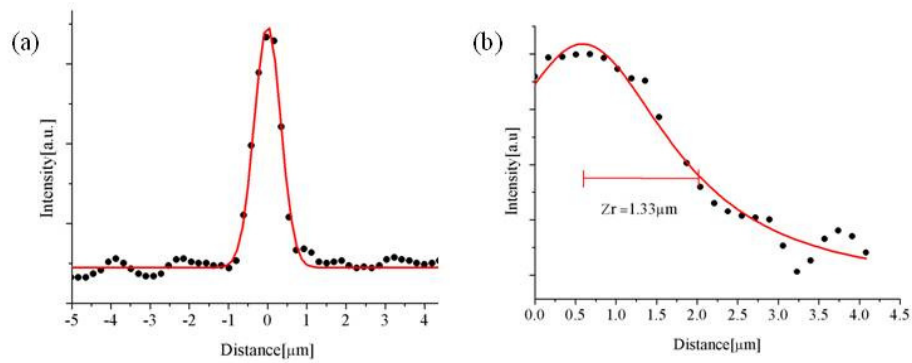


Fig. 11. (a) Standard fitting of the nanojet to extract FWHM. The FWHM is this case is 510nm corresponding to a w_0 value of 205nm. (b) The profile of the intensity along the $\theta = 0$ axis. The data was fitted with a Lorentzian function.

In any focused beam there is a relationship between the minimum beam waist and the divergence angle due to diffraction. The smaller the beam waist the larger the angle of divergence. The figure of merit is then the product of the beam waist and the divergence. In free space this is smallest for a focused beam with a Gaussian distribution. In Fig. 12 w_0 is plotted as a function of distance with zero corresponding to the position of the point of maximum intensity outside of the disk. The straight line fit defines the angle of divergence of the main beam. There is a very low angle of divergence of only $3.3 \pm 0.2^\circ$ and a waist $w_0 = 205\text{nm}$.

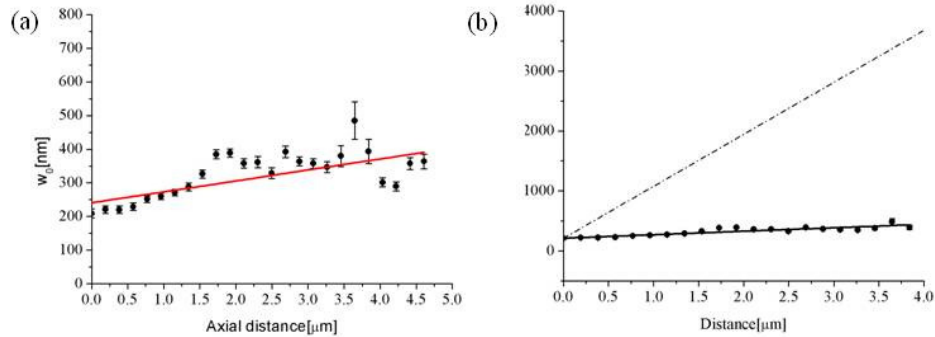


Fig. 12. The transverse FWHM is plotted as a function of distance, with 0 corresponding to the point of highest intensity (smallest FWHM). We can see the extremely low divergence angle. (b) Comparison between the divergence angle of the experimentally measured Jet and that of a Gaussian with the same waist. The dashed line represents the Gaussian divergence with an angle of 47° . This is over 10 times the divergence angle of the nanojet.

Comparing this angle with the paraxial approximation for focusing of a Gaussian beam gives good insight into the unique properties of the nanojet. For a focused Gaussian the beam waist describes a hyperboloid with an angle of θ . The relationship between the beam waist and the divergence angle is given by $\theta \approx \lambda / \pi w_0$ [29]. Of course the paraxial approximation is only valid for small θ , however it has been shown to be correct to within 10% for the high angle case [29]. This is useful as it allows us to use this analytical expression to compare the divergence of a Gaussian in free space to the photonic jet in Fig. 12 (b). The divergence angle of a focused Gaussian in free space with the same waist as the nanojet is 47° . Thus the divergence angle of the nanojet observed is over 10 times smaller than a classically focused

Gaussian beam with the same waist. This corresponds to an M^2 value of 0.07, which is much less than 1. This low divergence is possibly the most distinguishing feature of a photonic nanojet and is one of the properties which exhibits the most potential to be exploited for applications.

6. Conclusions

The scattering properties of a microdisk are fully explored and compare well with the analytical model for an infinite cylinder. For the case of microdisks in air small sub wavelength spots are formed inside the disk. These were measured to be oval in shape and have a FWHM of $460\text{nm} \pm 60\text{nm}$ by $508 \pm 65\text{nm}$. These values are limited by the effect of microscope blur and are an upper limit for the true size of the intensity spot. The match between the experimental images and the analytical scattered intensity distribution allows us to postulate that the total intensity distribution matches that of the analytical model. This suggests that using the microdisks in air can create a very small sub-wavelength spot on the surface of the disk. This would be useful for sensing applications.

Photonic Nanojets were observed in water when the refractive index contrast was 1.5. These PNJ provide a small interaction volume outside of the disk and could be used for bio-sensing and nanoparticle detection in liquids. The disks can produce interaction volumes on the same scale as MOs for a fraction of the price. The planar fabrication process means that large arrays of these cylinders could be fabricated easily and at very low cost.

Changing the illumination from the case of a plane wave offers a method to produce a nanojet even though the refractive index contrast is not in the optimum range. With perpendicular focused illumination a sub-wavelength waist beam can be created with a divergence angle over 10 times smaller than expected from Gaussian focusing. This beam can be created in a planar system which offers exciting prospects for integration.

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