Subwavelength Optical Probing of Fluidic Microparticles

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Photonic jets with waists on the order of wavelength were generated by focusing 1550nm illumination with tapered optical fibers with different diameter. They were then applied to scanning fluid motions inside fabricated microfluidic channels. Intensity of the backscattering from the photonic jet was observed to be varying with fluidic motion. The generated photonic jet waists were measured with Shadow Image Measurement technique and Knife-edge Scanning Measurement technique. The narrowest jet measured was one-wavelength in waist, i.e. 1.51μm with +/- 0.25μm error, which was generated with fiber of 40μm in diameter. For photonic jet generated with 125μm optical fiber, the measured jet waist was 7μm and its working distance was around 50μm. With ultra-high resolving power and its compactness, the photonic jets can potentially enhance the performance of optical microscopes employed in various sensing applications, including the microfluidic bio-chips.

Introduction

Microfluidic bio-chips are getting attention in the medical and biochemical industries for its potential as a speedy and compact bio-fluid analyzer. Having the size as small as a stamp, the bio-chips have fluidic channels with channel width less than 1mm built on it. By inputting tiny amount of fluidic sample, built-in electro and magneto sensors together with the crossings of channels provide means for rapid analysis for scientists.

Since the fluids are flowing in miniature channels, the flow will be largely governed by surface tension and fluidic resistance. Some interesting properties such as zero velocity at the channel walls will be observed. Optical sensing of micro and nano-scaled particles flowing in such fluids is promising because of its high sensitivity. Yet at present optical imaging of microfluidic channels still relies heavily on bulky microscopes, contrasting the compactness of the bio-chip itself. In view of this, we propose the application of the novel photonic nanojet in microfluidic bio-chips.

The photonic nanojet is essentially a very narrow beam of light with a waist less than half the wavelength of the light, thereby breaking the theoretical diffraction limit in traditional geometrical optics. This idea was first demonstrated by a research group at Northwestern University by computer simulation [1] [2]. The simulation shows that a photonic jet can be generated at the shadow-side of a circular micro-particle illuminated by plane waves of light. When the microsphere is less than 10μm in diameter, the nanojet will be formed (Fig. 1).

The extremely narrow spot size of the nanojet has aroused interests of researchers because of its potential as a better imaging tool. The resolving power in traditional optical microscopes has always been limited by the diffraction limit, making it difficult to produce sharp images of small particles. Now with the nanojet, researchers have the chance to observe these particles in a more detailed way.

In 2006, another research group from Northwestern University scaled up the nanojet proposal from light waves to microwave and successfully demonstrated experimentally the existence of such nanojet [3]. When this microwave nanojet was used to scan across some particles, enhanced backscattering was observed. This further provides evidence for the existence of the nanojet phenomenon; however, the nanojet has never been successfully demonstrated in an optical dimension due to the difficulties in measuring the waist of such a narrow jet.

Our group has been proving this nanojet phenomenon in an optical level and developing its application model for analysis in microfluidic bio-chips. In this report we will detail our experimental measurements of photonic jets and the proof of theory for scanning...
of microfluidic channels.

**Scanning of Microfluidic Channels**

The strength of photonic nanojet is its subdiffractional accuracy in detecting tiny objects of interest. By integrating the nanojet into the microfluidic bio-chip, the bio-particles that are flowing through the focusing point of the nanojet would interact with the jet and would be imaged with ultra-high resolution. Here we propose 3 different ways of integrating nanojet onto the microchips.

1. A line of nanojet is produced across the microfluidic channel as laser strikes from top. The nanojet interacts with the bio-particles that are flowing through the channel, giving various backscattering patterns which are collected by a beam-splitter and a photo-detector for analysis purpose. This implementation will allow efficient 1-D localized scanning of the fluid (Fig. 2).

![Fig. 2 1-D scanning of microfluidic channel](image)

2. A line of nanojet is produced at the side of the microfluidic channel. The nanojet interacts with the particles that flow pass and form backscattering patterns. These patterns are collected by a beam-splitter and a photo-detector for analysis. The backscattering of those particles which pass through the line is collected for analysis. This implementation will allow efficient 1-D localized scanning of the fluid (Fig. 3).

![Fig. 3 1-D Scanning on side of microfluidic channel](image)

3. A spot of nanojet is produced at the spherical probe. The nanojet interacts with the particles that are at the spot to give scattering patterns. These patterns are collected by a photo-detector for analysis. The probe can be moved around along the x-y plane easily as a 2-D scan to observe the area of interest (Fig. 4).

![Fig. 4 2-D probe scanning of microfluidic channel](image)

**Fabrication of Microfluidic Bio-chips**

Commercially available bio-chips usually have channels that have at least one-dimension of its cross-sectional area less than 1 mm. Capillary forces will principally govern the velocity of the fluids flowing in the channels; therefore the flow will exhibit special characteristics such as zero velocity at the channel walls.

![Fig. 5 Lab-on-a-Chip from Agilent](image)

In order to prove our theory of applying nanojet on bio-chips, we had fabricated bio-chips using microscope glass plates. The height of the channels was 3 mm and the widths were 125 \( \mu m \), 400 \( \mu m \) and 600 \( \mu m \). Using optical fiber and syringe needles as masks made these dimensions. Optical fibers with diameter of 125 \( \mu m \) were put on chips for generating photonic jets.

Controlling the flow of fluids inside the channels was proved to be particularly challenging. Commercially available bio-chips use built-in electric field or magnetic field to control the fluidic motion; however, these require complex nanofabrication processes. In our proof of theory, syringes were used instead to pump fluids into the channels. For chips with channel widths 400 \( \mu m \) and 600 \( \mu m \), the syringe needle was
Fig. 6 Fabricated glass-plates-made fluidic channel; (a) schematic of cross-section; (b) schematic of top view; (c) fabricated fluidic chip of 600µm channel width; (d) fabricated fluidic chip of 400µm channel width

Fig. 7 Fiber on channel and syringe needle inside channel as viewed under microscope

put inside the channels to pump the fluids. (Fig. 7)
For chips with channel width 125µm, the fluid was injected from outside the chip into the channel.

Experimental Setup

The experimental setup for scanning microfluidic channel had a collimated 1550nm laser source reflected at a beam splitter and then focused onto the microfluidic chip. The backscattering was collected through the beam splitter to an imaging system (Fig. 8) (Fig.9).
Fig. 8  Schematic of experimental setup for scanning fluidic channel
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(b) y-z translation for CCD camera

(c) x-y-z translation for imaging lens

(b) x-y-z translation for focusing lens

(c) x-y translation for fluidic chip

(c) x-y-z translation for focusing lens
**Experimental Results**

The fluidic glass plate was observed with the setup. A white light source was used at the side to help locating the channel-fiber intersection.

De-ionized water (DI water) was injected into the 600μm-wide channel. As the DI water flowed through the channel, the backscattering from the 1550nm laser illumination markedly decreased in intensity. This was mainly due to the light absorption of the water, which was particularly strong around wavelength 1.4μm. The DI water flowing away from the fiber was also reflected by the white light illumination. The water flowing motion was uncontrollably overflowed when the capillary force inside the channel was not enough to push the fluid forward.
Fig. 10  Fiber on channel as observed with white light; (a) 125μm-wide channel with 125μm fiber under white light illumination (b) 1550nm laser illumination at 600μm-wide channel-fiber intersection; (c) 1550nm laser illumination and syringe needle inside 600μm-wide channel under white light illumination
Fig. 11 Injecting DI water into fluidic channel; (a) Backscattering from 1550nm illumination before injecting DI water; (b) Backscattering from 1550nm illumination after injecting DI water
Coke was then injected into the 400µm-wide channel. The flowing motion was captured in serial images with time intervals of 20ms. As Coke flowed through the channel, the backscattering from the 1550nm laser illumination varied in intensity. This variation could be contributed to the carbonated bubbles inside Coke. The variation in backscattering intensity is as shown in Fig. 13.

![Overflowed 600µm-wide channel](image)

**Fig. 12** Overflowed 600µm-wide channel

**Fig. 13** Backscattering light intensity variation as Coke Zero passes through the photonic jet
Generating Photonic Nanojets
To generate nanojet, previous research groups have suggested striking plane waves at circular dielectric of diameter smaller than 10µm, which are difficult to handle in experiment. Our group has instead been using single-mode optical fiber (diameter of 125µm) as the dielectric, which is then tapered down in a stepwise manner to approach 10µm in diameter as suggested by the computer simulation previously stated. The photonic jets generated by these fibers of different diameter were then measured using Shadow Image Measurement and Knife-edge Scanning Measurement, which are to be discussed in later sections.

Tapering was done by taking advantage of the localized heating from fusion splicer which is originally used for fusing optical fibers. The sparks generated by strong electric fields inside the machine locally heat up a point on the fiber and then pull at the two ends of the fiber. By carefully repeating this process along the length of the fiber, we could get tapered fibers with various diameters.

Fig. 14 Fiber tapering process; (a) fiber put inside the fusion splicer was shown on display; (b) localized heating; (c) localized heating was done over the length of the fiber; (d), (e) curvature at the end of the tapering
Experimental Setup
The experimental setup for generating the photonic jets had a collimated 1550nm laser source passing through an iris and then focused at a piece of optical fiber. The fiber was positioned inside the focal volume of the focused beam to make sure the light striking the fiber is well-collimated and most focused. The image at the shadow side of the fiber was then captured by an imaging system for the Shadow Image Measurement. A knife-edge was added right behind the fiber for the Knife-edge Scanning Measurement (Fig. 15).

Fig. 15 Schematic of experimental setup for generating and measuring photonic jets

Shadow Image Scanning Measurement
A shadow image of an illuminated fiber (diameter of 67µm) is shown in Fig. 16. The patterns at the two sides are the side walls and the central line of light is the focused photonic jet. Because the diameter of the fiber is known, by taking the ratio of the side walls to photonic jet we can estimate the waist of the photonic jet. Although the accuracy of this indirect measurement method was largely limited by the sensitivity of the CCD camera used, it can nevertheless give a quick and easy approximation of the real beam waist.

The measured Full Width Half Maximum (FWHM) beam waists are as shown in Fig. 18, Fig. 19 and Fig. 20.

Fig. 16 Shadow image of fiber (diameter of 67µm)
Fig. 18  Transmitted graph of line of photonic jet produced by striking optical fiber (diameter of 125µm) with 1550nm illumination and its intensity profile

Fig. 19  Transmitted graph of line of photonic jet produced by striking optical fiber (diameter of 67µm) with 1550nm illumination and its intensity profile

Fig. 20  Transmitted graph of line of photonic jet produced by striking optical fiber (diameter of 40µm) with 1550nm illumination and its intensity profile
**Knife-edge Scanning Measurement**

The knife-edge scanning technique is a direct measurement method to measure the size of a focused spot. A knife-edge was made to move across the spot in interest in a stepwise manner, blocking some of the light in every step (Fig. 21). The transmitted light intensity at every step was measured (Fig. 22). By differentiating the measured intensity as a function of scanning position, the light intensity profile can be obtained.

![Fig. 21 Schematic of knife-edge scanning of a light spot](image)

**Experimental Setup**

An experimental setup for the knife-edge scanning was integrated to the existing Shadow Image measurement setup. A small silicon chip coated with 1000Å of gold was used as the knife-edge (Fig. 23a). The coating was used because silicon is transparent to the 1550 nm source. The coating thickness of 1000Å was used because it was thick enough to block the light effectively but still able to give a reasonably sharp edge. A microscope was setup at the side to monitor the distance between the knife-edge and the optical fiber. Several fibers were firmly mounted on a C-clamp with wax, which was purposely aligned in a diagonal manner so that the switching between the delicate fibers of different diameters can be easily done.

![Fig. 22 Knife-edge Scanning of fiber (diameter of 125μm) at 3μm intervals](image)

![Fig. 23 (a) 1000Å gold-coated silicon chip; (b) a fiber (diameter of 40μm) mounted on C-clamp as viewed under microscope](image)

![Fig. 24 Schematic of knife-edge scanning experimental setup](image)
Fig. 25 Knife-edge scanning experimental setup
Experiment Results
The knife-edge was carefully tilted such that it was parallel to the fiber and was moved across the fiber with steps of 0.5µm. The step size and thus the accuracy of the measurement were limited by the translation stage knot which has smallest intervals of 0.5µm.

The knife-edge scanning measurement was done on photonic jets focused by optical fibers with diameter of 125µm, 67µm and 40µm. Their FWHM spot sizes were then calculated from the graphs. Since the generated photonic jet will diverge in a Gaussian manner, the knife-edge had to scan across the jet at the narrowest position to get the real spot waist. This position is found by repeating the scanning measurement along the y direction near the fiber. The measurement with the smallest value is the waist of the photonic jet.

Fig. 26 Knife-edge scanning across an optical fiber as observed under microscope

The knife-edge scanning measurements of the photonic jets generated with fibers of different diameter are as shown in Fig. 28, Fig. 29 and Fig. 30.

Fig. 27 Knife-edge scanning at different point of the beam

Transmitted intensity graph of knife-edge scanning of photonic jet produced by striking optical fiber (diameter of 125µm) with 1550nm illumination and its calculated intensity profile.
Fig. 29  Transmitted intensity graph of knife-edge scanning of photonic jet produced by striking optical fiber (diameter of 67μm) with 1550nm illumination and its calculated intensity profile.

Fig. 30  Transmitted intensity graph of knife-edge scanning of photonic jet produced by striking optical fiber (diameter of 40μm) with 1550nm illumination and its calculated intensity profile.

Fig. 31  Knife-edge Scanning Measurement results and its errors.
The measurement results here were compared to the ones from Shadow Image Measurement. As seen in the graph below, the two sets of results follow the same trend and approach the diffraction limit when the fiber diameter got narrower.

The FWHM spot waist of the photonic jet decreased sharply as the fiber diameter approached 10\(\mu\)m, i.e. the limit where the photonic jet can break the diffraction limit and have its waist get down to less than half the wavelength. However the trend was not linear and this contradicted the Rayleigh Criterion, which stated that the spot waist is inversely proportional to the lens' diameter. This can be explained by that the light focused by such a small lens (fiber) was affected by diffraction at the lens surface as its diameter approaches the wavelength of the light [5]. This non-linear trend was consistent with the simulations done by the group at Northwestern University.

**Measuring Working Distance of Photonic Jet**

The working distance of the photonic jet is defined by the Rayleigh range \(z_R\). It is the distance which a Gaussian beam has its cross-sectional area doubled. The focal volume \(b\) of the beam is defined as 2 times the Rayleigh range. Within this range the beam remains well focused and collimated.

Taking 7.0\(\mu\)m as the diameter of the smallest spot, the Rayleigh range \(z_R\) can be calculated as followed:

\[
z_R = \frac{\pi w_0^2}{\lambda}
\]

where \(n\) is the refractive index, \(w_0\) is the minimum Gaussian beam spot size, \(\lambda\) is the wavelength of the illumination.

From the above equation,

\[
z_R = 24.8287\mu m - 25\mu m
\]
Taking these measurements, the Rayleigh range can be estimated in another way as the spot size is a function of distance $z$ from the beam waist.

$$z_R = z / (w^2/w_0^2 - 1)^{1/2}$$

From the above equation,

$$z_R = 28.727\mu m \sim 29\mu m$$

The Rayleigh ranges calculated using the two methods were reasonably consistent with each other. The beam divergence is therefore following a Gaussian manner and the working distance of the photonic jet is around 25$\mu m$.

**Limitations of Knife-edge Scanning Measurement**

The accuracy of the Knife-edge Scanning Measurement is largely affected by the alignment of the knife-edge and fiber. If the knife-edge is not vertically parallel to the fiber, the measurement would be skewed and the calculated value would be enlarged (Fig. 35) (Fig. 36).

![Diagram of Knife-edge Scanning Measurement](image)

Fig. 35 Knife-edge making an angle with the fiber
The alignment process became more difficult as the fiber diameter got smaller. The knife-edge had to get closer to the fiber but the length of the curved part of the tapered fiber limited its distance from the fiber surface. In view of this we had tapered the fiber until it is broken into two pieces. The lower tip of the knife-edge can be made to scan across the upper tip of the fiber. With this method the alignment job was made easier and the knife-edge can get close enough to the fiber (Fig. 37).

In calculating the FWHM, only a part of the fiber-transmitted intensity was integrated to give the graphs for measurement. However, the measurement results were found to be unaffected by the dimensions of the part of image being integrated. This accuracy can be attributed to the fact that the Knife-edge Scanning Measurement relies on the change in transmitted light intensity instead of the light intensity value itself.

Comparing the Two Measurement Methods
The Knife-edge Scanning Measurement is a more accurate when compared to the Shadow Image Scanning Measurement because it is a direct measurement method. The Knife-edge Scanning Measurement does not depend on any other equipments but the knife-edge motion. The beam width is directly resulted from the spatial displacement of the knife-edge. On the contrary the Shadow Image Scanning Measurement has to depend on the resolution of the CCD camera used. The narrower the photonic jet, the less accurate the measurement is.

Yet the Knife-edge Scanning Measurement becomes more difficult as the fiber diameter become smaller.
The waist of the generated photonic jet becomes smaller and the measurement is severely affected by the alignment of the knife-edge and the fiber. At the present stage, the narrowest fiber we had successfully measured is the 40μm fiber. Further work will be done on measuring the photonic jets generated by narrower fibers.

**Integrating Photonic Jet on Microfluidic Channel**

The fluid motion in the fluidic channel was successfully observed as a variation in backscattering intensity of the photonic jet. Yet the channel depth (1mm) is much larger than the measured working distance of the photonic nanojet, which is on the order of a few microns. This makes it uncertain whether the backscattering was due to the interaction of photonic jet with the particles or due to reflection from the channel walls. We can verify if the variation in backscattering is coming from objects by having a control imaging system that synchronically monitor the fluid flow.

Besides our current implementation of using optical fiber as dielectric to generate photonic jets, we suggest another possible implementation using polystyrene beads with diameters on the order of micron and nanometer, which are now commercially available in both liquid form and dry form. A polystyrene bead can be hold at the tip of an optical fiber through electrostatic forces and light can be shined through the fiber to reach the polystyrene bead. The resulting focused photonic jet can be probed to wherever places to detect the micro-objects in concern (Fig. 39). This method allows more flexible probing of micro-objects and the photonic jet waist can be easily adjusted by using polystyrene beads of different diameter. Polystyrene beads of 1μm in diameter were purchased and are to be tested in the near future (Fig. 40).

**Conclusion**

Photonic jets with waists on the order of wavelength were generated with optical fibers of different diameters as micro-lenses. They were applied onto the scanning of fluidic motion in microfluidic bio-chips. Variation in backscattering light intensity was observed as the fluid flows. The scanning of microfluidic motion and micro-objects flowing in the fluid can be further investigated by adding a synchronized imaging system as control.

The photonic jet waists generated by fibers of different were measured using the Shadow Image Measurement and the Knife-edge Scanning Measurement. The jet waists for photonic jets generated by 125μm, 67μm and 40μm fibers are 7.0μm, 4.5μm and 1.5μm respectively as determined by the Knife-edge Scanning Measurement, which is a direct measurement evidence for the existence of photonic jet of one-wavelength in size. The two measurement methods showed very similar trend of jet waists decreasing sharply as fiber diameters are narrowed down to tenths of microns. Further work can be done on generating photonic jets using narrower optical fibers to attempt breaking the theoretical diffraction limit.

**References**