An Optofluidic Nanoplasmonic Sensor for Aerosols

Hao Jiang and Sophia Judge

Department of Biomedical Engineering, Lawrence Technological University, 21000 W 10 Mile Rd, 48075, Southfield, MI, USA
hjiang@ltu.edu; sjudge@ltu.edu

2023 IEEE Photonics Conference (IPC) | 979-8-3503-4722-7/23/$31.00 ©2023 IEEE | DOI: 10.1109/IPC57732.2023.10360531

***Abstract*—Direct optical sensing of ultrafine particles in aerosols is challenging due to the weak signals. We experimented on an optofluidic nanoplasmonic sensor chip based on a metal nanoaperture and successfully detected individual silica ultrafine particles in the aerosols.**

Keywords—metal nanoaperture, ultrafine particle, aerosol sensor, PM0.1, optofluidic sensor, nanoplasmonic sensor

I. Introduction

Optofluidic nanoplasmonic sensors combine microfluidics and plasmonic sensing into biosensing platforms with high-sensitivity label-free detection and great versatility in manipulating analytes [1]. Many such sensors have been demonstrated, but are limited to applications for liquids. This work introduces a new application of optofluidic nanoplasmonic sensors for aerosol detection.

For a given aerosol, of special interest are the airborne particles, in terms of their mass concentration, number concentration, and particle size distribution [2]. As shown in Fig. 1(a), in conventional optical measurement approaches, a laser beam is incident onto an aerosol and the light scattered from airborne particles is collected by a photodetector. The mass concentration of the ensemble of particles can be measured from the overall scattered light intensity. Individual particles can also be measured from the separate optical pulses from each particle. Conventional optical measurements can only detect particles with sizes comparable to the wavelength of light, typically larger than 300 nm. For airborne particles smaller than 100 nm, referred to as ultrafine particles (UFP) or $PM_{0.1}$, the scattered light is too weak, due to Rayleigh scattering. UFPs can pose severe health risks since they can be easily transported deep into the lung [2]. Recently, there have been growing interests in aerosol sensors that can detect UFPs with convenient, compact, and low-cost techniques.

To overcome this challenge in detecting UFPs in aerosols, we studied an optofluidic nanoplasmonic aerosol sensor chip shown in Fig. 1(b). The core component is a metal nanoaperture which has two main functionalities. Firstly, owing to the strong light confinement by the nanoaperture, the interaction of the laser beam with the UFPs can be significantly enhanced to give a strong optical signal in the transmitted light. When a nanoparticle is inside the nanoaperture, the light transmission increases due to dielectric loading [3]. Metal nanoapertures have proven successful in optical trapping and sensing of single biomolecules in liquids [3]. Secondly, the

This work was supported by National Science Foundation Engineering Research Initiation (ERI) program under Award Number 2138534.

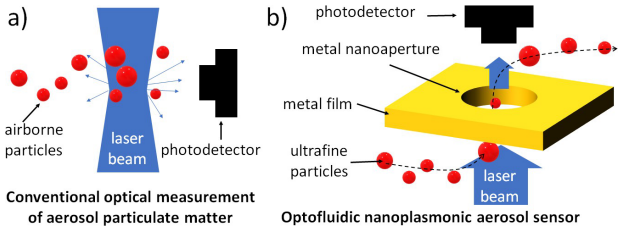

Fig. 1. Schematic of (a) conventional optical approach for measuring aerosol particulate matter concentration and (b) optofluidic nanoplasmonic sensor for detecting ultrafine particles in aerosols.

metal nanoaperture also serves as a nanofluidic channel for aerosols to flow through. Such flow-through strategy has been used in sensing analytes in liquids and is proven advantageous [1]. In our previous work, we have studied this configuration based on numerical simulations and demonstrated its potential [4]. In this work, we presented our experimental results on this optofluidic nanoplasmonic sensor for detecting spherical silica UFPs of different diameters.

II. Methods

The schematic and the photographs of the experimental setup are shown in Fig. 2 and Fig. 3(c)(d), respectively. The optical sensor chip is comprised of a silicon frame, a silicon nitride (SiN) membrane, and a metal film, with a nanoaperture through both the metal film and SiN membrane to allow aerosol to flow through. The sensor chip was installed inside a custom-built aerosol chamber with air-tight sealing rings.

Aerosols of silica nanospheres were generated using a constant output atomizer (TSI model 3076). Compressed N_2 gas, after being filtered and dried, was regulated into 32 PSI pressure to atomize the monodisperse silica nanospheres solution (from NanoComposix) loaded inside the atomizer. The generated aerosol was dried with a diffusion dryer and then an inline desiccant dryer to remove water from the aerosol to attain solid silica UFPs suspended in the aerosol. Then, the aerosol was processed by a soft X-Ray aerosol neutralizer (TSI model 3088) to remove the electrostatic charges on the particles, which is crucial for minimizing the loss of particles in the tubing. The generated silica UFPs are monodisperse and the diameters were controlled through silica nanoparticles in source solutions.

The generated aerosol was launched into the bottom sensor chamber and a very small portion of the aerosol flowed through the metal nanoaperture to enter the top chamber. Silica UFPs were transported through the nanoaperture under both the pressure-driven flow and Brownian diffusion. A pressure sensor

979-8-3503-4722-7/23/$31.00 ©2023 IEEE

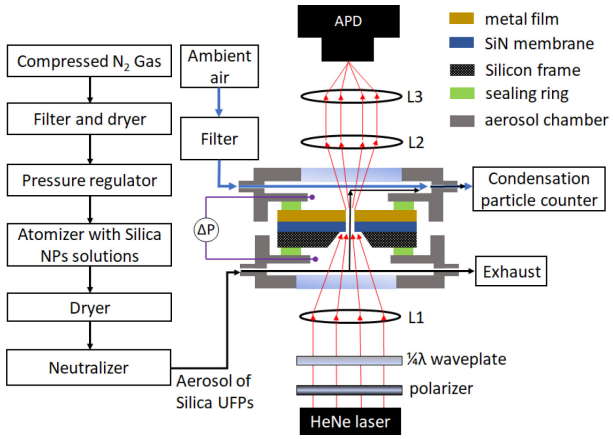

Fig. 2. Schematic of the optofluidic experimental setup for aerosols of monodispserse silica nanoparticles.

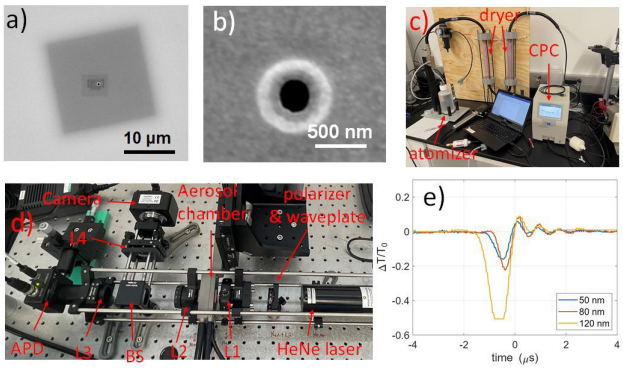

Fig. 3. Experimental results. (a) SEM image of metalized SiN membrane. The dark squre is the window of SiN membrane suspended on the frame. (b) Zoom-in SEM image of the fabricated metal nanoaperture with diameter of 300 nm. Photograph of (c) the aerosol generation and analysis setup and (d) the optofluidic experimental setup. (e) Acquired signal from single silica UFP of different diameters.

was connected with the top and bottom chamber to monitor the differential pressure, ΔP, which was kept between 15 kPa and 16 kPa in this work. Ambient air, after being filtered with a zero filter, was drawn into the top chamber to mix with the flow-through aerosol, and the mixture was analyzed by a condensation particle counter (CPC, TSI model 3750).

In the optical setup, a HeNe laser beam (632.8 nm wavelength, 15 mW power, continuous wave, linearly polarized, Thorlabs model HNL150LB) was first processed with a linear polarizer to control the transmitted laser power and then a quarter waveplate to convert the beam into a circularly polarized beam. Due to the circular symmetry of the metal nanoaperture, the circularly polarized beam can provide more uniform optical responses than a linearly polarized beam. The laser beam was focused by an aspheric lens L1 (f = 13.86 mm, Thorlabs C560TME-A) onto the nanoaperture, and the transmitted beam was focused by two plano-convex lens L2 (f = 30 mm), L3 (f = 50 mm) onto an avalanche photodiode (APD, Thorlabs model APD130A). A beam splitter (BS, 10:90/R:T) was inserted between L2 and L3, and the reflected light is focused by a lens L4 (f = 75 mm) onto a CMOS camera to acquire images of the nanoaperture lighted by the laser.

The optical sensor chip with a metal nanoaperture was manufactured based on a commercially available SiN nanopore device purchased from Norcada. The original nanopore device is comprised of a 200-μm-thick silicon frame with a 50-nm-thick SiN membrane. There is a 20 μm × 20 μm window area at the center of the SiN membrane, which gives a suspended membrane to allow access to aerosols from both sides. At the center of the window, there is a through-hole nanopore with diameter around 600 nm in the SiN membrane. Metal films were deposited on top of the SiN membrane using sputtering deposition (DC sputtering, Ar gas). A 100 nm chromium (Cr) film was sputtered first, followed by a 100 nm gold (Au) film. Such a bilayer configuration of metal film can minimize the stress in the film and achieve an optically thick metal film (total thickness of 200 nm). Due to the metal deposited on the sidewall of the nanopore, the fabricated metal nanoaperture is significantly smaller than the nanopore in the original SiN membrane. Fig. 3(a)(b) shows SEM images of the metalized SiN membrane window area (the dark square) and the fabricated metal nanoaperture with diameter about 300 nm.

III. Results and Discussion

Our initial experimental results of the sensor's response to single silica UFPs is shown in Fig. 3(e). In our experiments, we can acquire about one signal over every few minutes. Each UFP triggers a strong resonance in the optical signal, which lasts about 2 μs duration. With increasing silica NP diameter, the amplitude of the signal grows significantly. The CPC measures the particles collected from the top chamber, which indicates about 5-10 particles collected over a duration of 20 minutes. We hypothesize the signal is caused by the mechanical resonance induced by the turbulent flow of the silica UFP travelling through the nanoaperture. Futher studies are underway to confirm this hypothesis.

Acknowledgment

This work was performed in part at the University of Michigan Lurie Nanofabrication Facility.

References

[1] C. Escobedo, A.G. Brolo, R. Gordon, and D. Sinton, "Optofluidic concentration: plasmonic nanostructure as concentrator and sensor," *Nano Letters*, vol. 12, no. 3, pp. 1592-1596, 2012.

[2] H.S. Kwon, M.H. Ryu, and C. Carlsten, "Ultrafine particles: unique physicochemical properties relevant to health and disease," *Experimental & Molecular Medicine*, vol. 52, no. 3, pp. 318-328, 2020.

[3] Y. Pang, and R. Gordon, "Optical trapping of a single protein," *Nano Letters*, vol. 12, no. 1, pp. 402-406, 2012.

[4] H. Jiang, and S. Judge, "Numerical study of metal nano-orifices for optical sizing of ultrafine particles in aerosols," *Plasmonics*, 2023. (Accepted. In press. https://doi.org/10.1007/s11468-023-01959-x)