

MONOLITHIC WAVEGUIDE ARRAY PLATFORM FOR PHOTONIC CHARACTERISATION OF BIOLOGICAL SAMPLE

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ABSTRACT

We report an innovative lab-on-a-chip (LOC) system in which waveguide arrays, fibre-to-waveguide couplers and microfluidic channels are integrated to form a complete microchip for photonic characterisation of micron-sized samples. Sample properties are deduced from near-field diffraction pattern resulted from scattering in the microfluidic channel which is collected by the high density waveguide arrays.

KEYWORDS

Lab on a chip, waveguides, optofluidic, photonics, near-field diffraction, flow cytometry.

INTRODUCTION

Performing flow cytometry in a LOC setting is highly desirable and much effort has been put into developing semi- and fully optically integrated LOC systems. [1] Degrees of integration vary, from individual fibres coupled to a microfluidic channel [2] to waveguides fabricated onto substrates including PDMS[3], SU8[4] and photo-patternable acrylate-based polymers. [5] Spatial resolution is determined by a combination of factors, such as coupling- and propagation loss, waveguide density, wavelength and beam spot size. Polymer based waveguides typically have a core dimension between 40–135 μm and with a propagation loss of the order of 1dB/cm. [5,6] Silica on silicon (SOS) waveguides on the other hand can achieve propagation loss as low as 0.01dB/cm [7] and a dimension of 4–8 μm . [8]

Using diffraction imaging to obtain 3D morphology of cells as part of a flow cytometry routine allows high throughput and label-free interrogation of single cells. [9] To conduct such operation in LOC systems, high spatial resolution is necessary to capture the details of diffraction pattern resulting from scattering.

In addition, because of the length scale of microfluidics, optical phenomena could be considered far- or near field depending on the wavelength, feature dimensions and location of the particles. Measuring in the near field regime allows us to access information which is unavailable in the far field[11]. Kostner et al. [10] has demonstrated how morphological information can be deduced with forward scattering (FS) signal.

In this work, a LOC system is developed to utilise the dimension and attenuation advantage of SOS waveguides which in turn allows diffraction patterns of samples to be measured.

EXPERIMENTAL

The device, shown in Figure 1, was fabricated using SOS planar waveguide technology which allows a high waveguide count and density. It consists of 32 interchangeable inputs and outputs, fibre pigtailed to allow easy user interface. The SOS waveguides were designed to operate in single-mode at 1550nm and were fabricated by doping silica with Germanium, Boron and Phosphorus to achieve a refractive index of 1.4561 and 1.4452 for waveguide core and cladding respectively. Each waveguide has a cross section of 8x8 μm . At the interrogation region where the waveguides and the microfluidic channel intersect, it has a centre to centre spacing of 14 μm between individual waveguides and a 250 μm spacing at the fibre pigtail interface. The propagation loss of the waveguides varies depending on which input and output is tested. Overall, it is of the order of 0.8dB/cm which includes propagation loss and loss due to the 50 μm gap microfluidic channel. The crosstalk between adjacent waveguides is less than 0.1%. The microfluidic channel is fabricated using standard wet etch technique and has a width of 50 μm . Altogether two masks were used in a three step photolithography process.

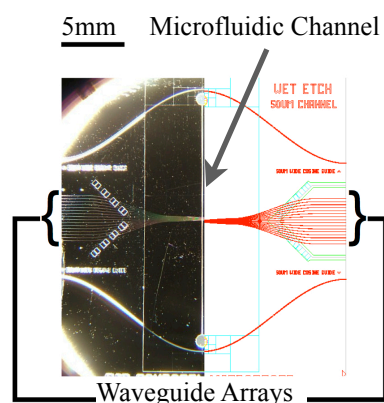


Figure 1: Top view and design of device

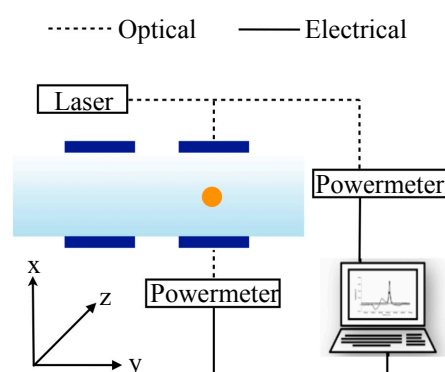


Figure 2: Schematic of experimental setup

We used one waveguide as an optical input into the device which was connected to a diode laser with a maximum power of 28mW. The optical power out of the remaining waveguides were measured whilst a sample was placed at a specific position by mounting it on translation stages travelling along y and z axis with an increment of 0.5 μm as illustrated in Figure 2. This enables both forward scattered (FS) and backward scattered (BS) to be measured. A

differential optical measurement was obtained by acquiring reference reading from the laser output and signal reading from waveguides simultaneously. The samples were fabricated using Focused Ion Beam (FIB) technique to obtain a well defined size of $\sim 3\mu\text{m}$ and shape.

To study human erythrocytes, we generated a fluidic flow into the device by either infusion or withdrawal through the inlet and outlet. The scattering due to erythrocytes was measured in a similar fashion as described above.

RESULTS AND DISCUSSION

Figure 3 shows the intensity due to FS of a sample and read out from waveguides on the output side, at 0° and a second adjacent waveguide on the opposite side. Sample position is the sample displacement relative to the centre of the input beam. At position 0, the sample sits right in front of the input beam. At 0° , the impulse response of the system can be estimated by deconvoluting the sample function, in this case a rectangular function, from the signal. Figure 4 shows the comparison between the experimental data and the model of sample size $2.3\mu\text{m}$, $3.3\mu\text{m}$ and $3.7\mu\text{m}$. The discrepancy at the tail might be due to the sharp edges. Hence the diffraction is more pronounced. This is a limitation of the approach. However, for biological samples for instance cells, the round edge means such features will be less prominent.

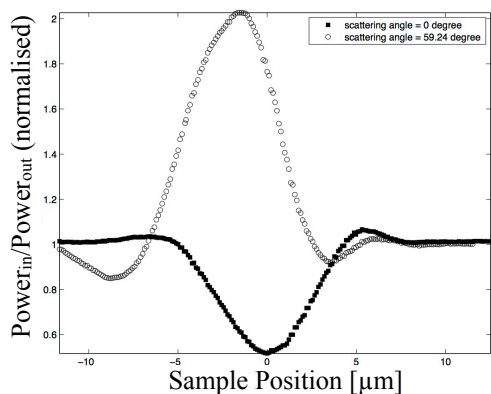


Figure 3: Intensity plot of forward scattering.

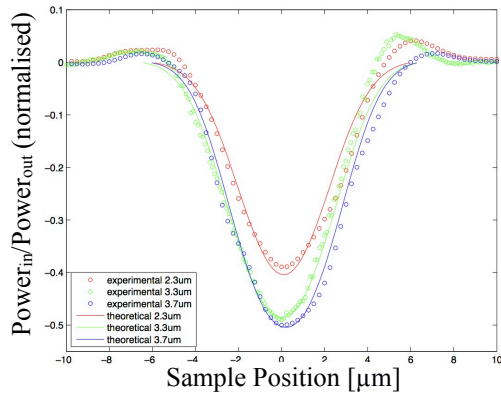


Figure 4: Comparison of experimental and theoretical results at 0° scattering output.

Figure 5 is the intensity due to BS of a sample and readout from waveguide located on the same side as the input waveguide, second adjacent to the input beam. Each data point is a measurement of the diffraction as a result of back scattering, either a constructive or destructive interference. This is highly sensitive to any displacement where a $0.5\mu\text{m}$ displacement can lead to a 5% change in intensity. We are still in the process of having better control in BS measurement as the signal-to-noise ratio is low and working on interpreting the BS data. By combining individual intensity plots, a pixel plot shown in Figure 6, can be established where a horizontal line scan depicts the diffraction pattern of the sample at a particular position. The dark blue line represents a faulty waveguide.

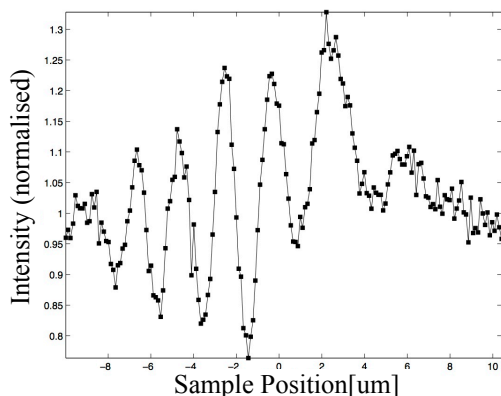


Figure 5: Intensity plot of backward scattering. The solid line is a guide to the eye.

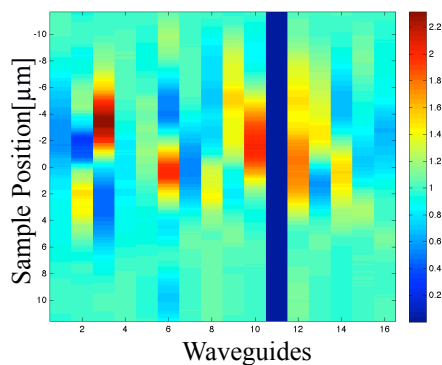


Figure 6: Pixel plot of forward scattering.

Lastly Figure 7 shows the intensity of FS when erythrocytes travel along the microfluidic channel. Each minima is due to a cell crossing the input beam. It demonstrates that the device can easily perform cell counting. When the minima are studied carefully, they all have a consistent form illustrated in Figure 8(Bottom). Figure 8(Top) shows a finite element method (FEM) simulation of a dielectric sphere travelling along waveguide structures in the $+y$ direction indicated in Figure 2. The simulation is able to model the scattered electric field which gives a good fit to the experimental data.

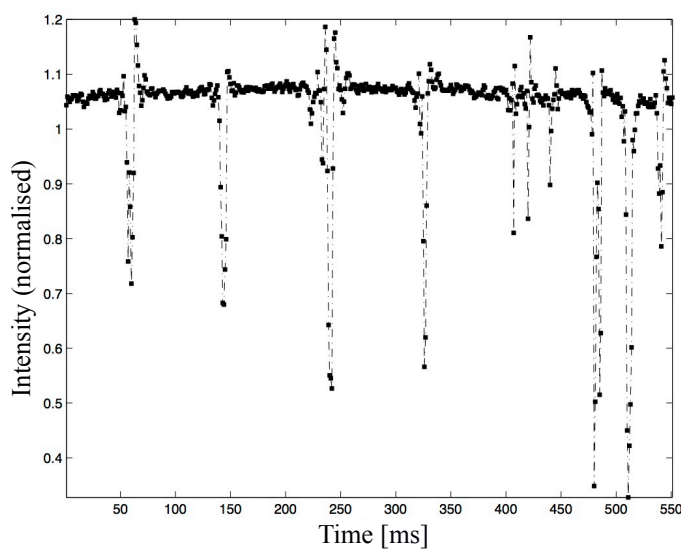


Figure 7: Forward scattering of erythrocytes.

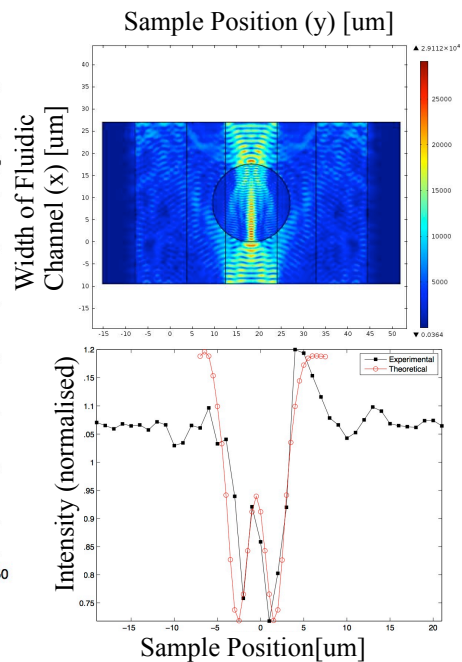


Figure 8: (Top) FEM simulation of a dielectric sphere travels along waveguide structures. (Bottom) Experimental and FEM comparison.

CONCLUSION

In summary, high density waveguide arrays and microfluidic channels have been fabricated. We have demonstrated that simple morphological properties can be deduced from the optical signal. We have shown that near field diffraction pattern can be captured with the waveguide arrays.

To our knowledge, this is the first time the diffraction pattern within the size regime of microfluidic systems has been measured using integrated optics. Applications to this technique are broad, including carrying out on-chip photonic characterisation of single cells and label free classification of cells. The understanding of diffraction patterns of different biological targets could eventually lead to more sophisticated monolithic miniaturised visualisation capability which would have applications in label free single cell detection.

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