On-chip Raman spectroscopy with a Triplex dual-waveguide trap

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We present a new approach to on-chip Raman spectroscopy based on the dual-waveguide trap geometry. In the device counter-propagating interfering beams emanate from opposing TripleX waveguides to produce a confined optical field in a fluidic channel. The field is used to induce optical trapping of microparticles supplied by a flow. The transparency window of TripleX allows application of the standard Raman wavelength of 785 nm, thereby making an additional laser path for Raman excitation redundant. With the device we generate Raman spectra of trapped polystyrene beads and bacterial spores. This approach is promising for on-chip fingerprinting of bacteria and other cells.

Introduction

There is a strong interest in lab-on-a-chip devices capable of identifying biological samples, including devices that make use of Raman spectroscopy. This technique already has many off-chip applications to identify biological samples. With Raman spectroscopy one measures the chemical composition of the sample by obtaining information on its molecular vibrations which can therefore yield a spectroscopic fingerprint [1]. Samples need to be kept stationairy during a Raman measurement and for small samples, such as single cells, this can be achieved by using laser light in a technique called optical trapping. Off-chip this is often performed by creating a tightly focussed laser beam [2] or by opposing two laser beams [2, 3], whilst on-chip waveguides [4] or photonic crystal cavities [5, 6] are used. Using the trapping light for Raman generation is a method called Laser Tweezers Raman Spectroscopy (LTRS) [7]. On-chip trapping and Raman generation could be performed by using two opposing waveguides as a dual-beam optical trap as first proposed by van Leest *et al.* [8] where simulations were shown of the trapping potential of such a device. So far, one device has been reported on that uses an integrated dual-beam optical trap consisting of opposing waveguides [4, 9]. The reported devices are very well capable of optical trapping[4, 9], however, the waveguide material Ta_2O_5 is not transparent for the Raman wavelength 785 nm and cannot use the trapping light for Raman excitation and requires an additional off-chip Raman laser. Furthermore, Ta_2O_5 is a research material in photonics and therefore not suitable for mass-production.

We now report on a dual-waveguide device capable of optical trapping and Raman generation. The dual-waveguide device is fabricated in TripleX waveguide technology [10, 11]. TripleX waveguides are highly transparent in the visible and NIR range (405-2350 nm), contrary to other waveguide materials, such as SOI, InP and Ta_2O_5. As a result, the standard Raman wavelength of 785 nm can be used for the trapping light, in

contrast with [9]. TripleX is an established waveguiding platform [11] and is suited for mass-production and compatible with CMOS technology.

Methodology

The dual-waveguide device consists of a fluidic channel, an entry waveguide and a Y-junction splitting the waveguides into two semi-circles which terminate oppositely in the walls of the integrated fluidic channel (see Figure 1a). The waveguide has a base and top width of 1.1 and 1.0 μm, respectively, and height of 1.0 μm (see Figure 1c) and consists of 50 nm thick Si_3N_4 and an inner region of SiO_2. The fluidic channel is 5 μm wide and 15 μm long, which tapers up to 1 mm wide in two steps (see Figure 1b) and is created by dry etching successively through the upper cladding (12 μm SiO_2), the waveguide and the lower cladding (8 μm SiO_2). Finally, the fluidic channel is sealed by bonding onto the structure a glass wafer with pre-etched holes for access to the fluidic channel.

Laser light of 785 nm is coupled via a single mode polarization maintaining fibre, butt coupled to the TripleX input waveguide, exciting the lowest TE mode. An immersion objective placed above the optical trap collects the Raman photons. Polystyrene beads of 1 μm diameter or bacterial spores (*Bacillus Subtilis*) dispersed in water are made to flow through the channel with a syringe pump. Flow velocities for the experiments, in the range 7 - 90 μm/s, are obtained by stabilizing the flow without pump activity.

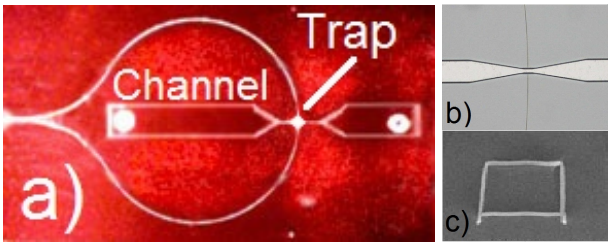

Figure 1: a) the integrated Raman trapping device fabricated in TripleX waveguide technology. A Y-junction splits the entry waveguide into half-circular arms (diameter = 7mm) that terminate in the walls of the fluidic channel. b) The middle tapered section of the fluidic channel with opposing waveguides (top and bottom). c) Cross-section of a TriPleX waveguide.

Dual-waveguide optical trapping and Raman spectroscopy

Using the light from the opposing waveguides, we have demonstrated optical trapping of polystyrene beads that are transported through the fluidic channel. Stable trapping can be performed for at least 10 minutes, provided that there is no collision with another bead transported through the fluidic channel. One or more beads can be trapped at one given time. These multiple beads are usually trapped in a necklace perpendicular to the flow direction. Images of one or more beads trapped are shown in Figure 2.

The light in the trap can be used to generate Raman photons off the trapped particles. Therefore, we have studied the capability of using our device for on-chip Raman Spectroscopy by measuring photons inelastically scattered from trapped single polystyrene (PS) beads or bacterial spores (*Bacillus Subtilis*) with a spectrometer. This is first demonstrated by the measured spectra of PS shown in Figure 3a, taken for five different integration times in the range of 0.25 - 15 s. We observe that with increasing integration time

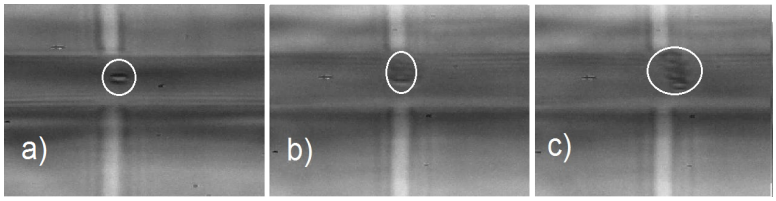

Figure 2: Trapped beads inside the fluidic channel (left to right) between the waveguides (top and bottom).

distinctive peaks develop in the spectra. The labeled peaks in Figure 3a agree with the literature values. The peaks at 1003 and 1033 cm^{-1} are clearly discernible for an integration time as short as 0.25 s. This is useful for experiments concerning fingerprinting of bio-objects such as single cells, that have a relatively weak Raman signal and therefore will unavoidably lead to longer integration times. In addition, we have trapped and measured bacteria spores, the spectrum is shown in Figure 3b. Bacteria spores are more difficult to trap due to their lower refractive index and higher transparity. This unavoidably leads to longer integration times, which in this case is 10 minutes. However, the obtained spectrum is a first of its kind in on-chip trapping and Raman generation and could lead to a multitude of applications, including on-chip biological Raman identification.

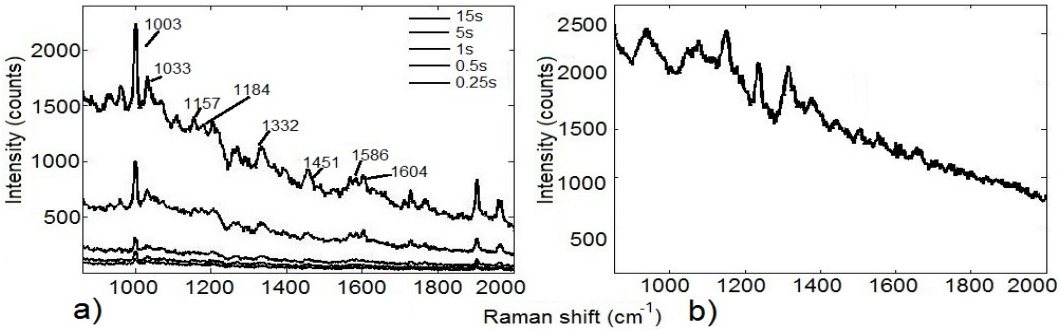

Figure 3: a) Raman spectra of an optically trapped PS bead, for integration times as indicated. Typical PS peaks are indicated with the 15 s spectrum. b) Raman spectrum of optically trapped bacteria spore Bacillus Subtilis for integration time 10 min. Measurements were performed using an estimated optical power between the 7 and 10 mW.

To further characterize the device, we performed finite-difference time domain (FDTD) simulations of the optical fields, using commercial software (FDTD solutions 8.5.3, Lumerical Solutions Inc., Canada). Simulated intensity profiles between the waveguides are shown in Figure 4a, both for the xz-plane and the yz-plane (x is along the flow direction, y is the height and z is the gap axis). The simulated profiles show an interference pattern that is well confined between the waveguides, hereby creating a strong field for optical trapping resulting in strong optical forces. The forces that act on these trapped particles have been calculated for the x-, y- and z-axis using the Maxwell stress tensor. In Figure 4b we give the resulting forces (in one direction for x and z due to symmetry, however, in two directions for y due to lack in symmetry, y_1 is towards to top of the waveguide).

The graph in Figure 4b shows the optical forces for x and y that pull the particle back to the centre point when it is moved away. The F_z shows a sinusoidal dependence on the bead position, which is in agreement with stable trapping points being located at the interference maxima (shown in Figure 4a). This explains why multiple beads can be trapped along the z-axis (see Figure 2). The calculated forces shown in Figure 4b are high and comparable to [4]. Therefore our trap can be characterized as a strong trap.

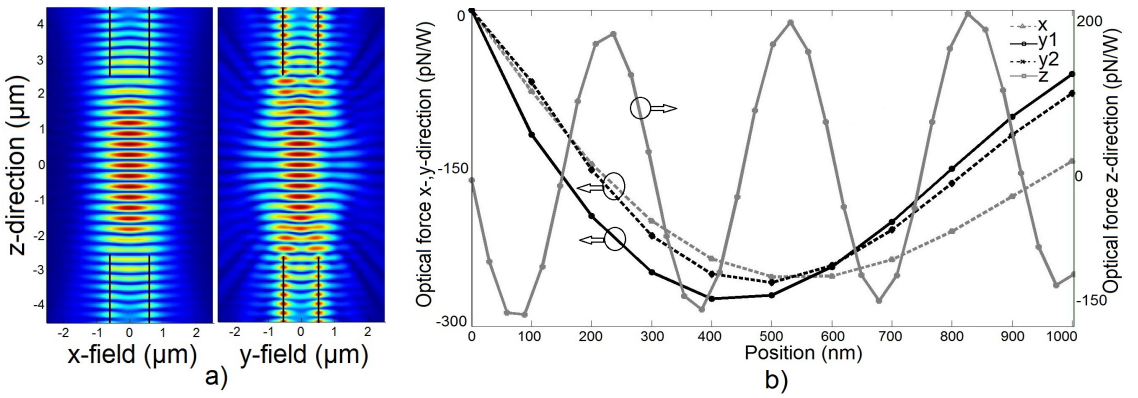

Figure 4: On left: Simulated intensity patterns in the *xz*- and the *yz*-plane. On right: Calculated forces of the trap as a function of bead position on the *x*-, *y*-, and *z*-axis.

Conclusion

We have presented a TriPleX dual-waveguide device capable of generating Raman spectra from on-chip optically trapped polystyrene beads or bacteria spores that are supplied through an integrated fluidic channel. We succesfully and reproducibly trapped particles and obtained Raman spectra from them. The results presented are the first of its kind. The dual-waveguide device could lead to, amongst others, on-chip biological identification.

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