Towards Background-Free Fiber-Optic SERS Using 2PP-Fabricated Micro-Optics

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Abstract: To leverage the high sensitivity and specificity of Raman spectroscopy in medical diagnostics, we present two fiber-tip micro-optical components - fabricated via 2-photon polymerization - to allow background-free fiber-optic surface-enhanced Raman spectroscopy. © 2025 The Author(s)

1. Introduction

Raman spectroscopy is a highly effective real-time analytical technique widely used in research and industry for material characterization, chemical analysis, and biological investigations [1]. It provides numerous opportunities for *in vivo* diagnostic and tissue classification applications, for example for *in situ* tumour detection [2].

In clinical applications of biomedical optics, minimizing the size of the device while ensuring high detection accuracy is crucial. Optical fiber-based devices enable minimally invasive procedures due to their microscale dimensions, flexibility, and biocompatibility, supporting applications such as guided optical biopsies and photodynamic therapy [3]. The major challenge persisting in optical fiber-based Raman spectroscopy is the weak signal and strong background noise generated by the composition of the optical fibers, typically silica [4]. To address this limitation, various methodologies have been developed, incorporating alternative fibers, probe designs or computational strategies (e.g. [5]).

Surface-enhanced Raman spectroscopy (SERS) is a widely adopted signal enhancement technique. It significantly amplifies the Raman signal of molecules adsorbed on micro/nanostructured metallic surfaces, typically noble metals, such as gold and silver [6]. The interaction of light with metallic nanostructures generates localized surface plasmon resonances, which create intensified electromagnetic fields around the surface. By enhancing inherently weak Raman scattering, SERS enables highly sensitive molecular detection.

SERS has previously been integrated with optical fibres (e.g. [8]), however, the challenge of silica background signals still persists. To further advance fiber-optic SERS, here we report development of two micro-optical components that can be incorporated onto optical fiber tips to facilitate reduction of background signals, thereby offering opportunities to enhance diagnostic capabilities.

2. Methods

To accommodate various surgical and in vivo diagnostic scenarios, we propose micro-optical components for fabrication of two types of SERS probes: a side-viewing SERS probe and a forward-viewing SERS probe. The side-viewing SERS probe comprises two optical fibers and two aligned mirrors for beam focusing, with a SERS array positioned on the side surface of the probe. The forward-viewing SERS probe is designed for use with hollow core fibers to reduce silica background while also minimising probe size, and entails a SERS array on the front surface of a fiber cap.

Micro-optical components were designed in Solidworks and fabricated using 2-photon polymerization (2PP; Photonic Professional GT, Nanoscribe). The side-viewing probe was fabricated in a 2-step procedure with printing followed by assembly of optical fibers into the micro-optics. The forward viewing probe was fabricated via direct 2PP printing of the micro-optical component onto the fiber tip. Details of the design and fabrication of both probes are provided below.

3. Results and Discussion

3.1. Side-viewing SERS probe

The side-viewing SERS probe is a dual-fiber probe in which two optical fiber tips are assembled within the probe structure. A previous design [7] used microfabrication to create a miniature Raman probe incorporating

mirrors, lenses and optical fibers. To facilitate SERS, we propose a amended probe design, which integrates a SERS array and gold film coating. The probe tip structure has dimensions of 5 mm (length) x 1.2 mm (width) x 0.4 mm (thickness; see Fig. 1(a)). It includes two grooves for assembly of excitation and collection fibers, with two parabolic mirrors to align the excitation and scattered beams. A SERS array is positioned on the side border to enhance Raman signals. The geometrical design of this probe is illustrated in Fig. 1(b). The positions of two parabolic mirrors were determined based on the location of the SERS array (f_1), the tips of the two optical fibers (f_2,f_3) and the numerical aperture of the multimode optical fibers (200/220 µm core/cladding diameter, 0.22 NA, FG200LEA, Thorlabs). In this configuration, the laser light emerges from f_2 and is reflected by the large mirror (e_1) toward f_1, positioned at the bottom surface of the SERS probe. Scattered light is then reflected by the small mirror (e_2) and directed toward f_3. Each mirror has two focal points, consistent with the properties of an ellipse:

$$\frac{((x-h)cos\theta+(y-k)sin\theta)^2}{a^2}+\frac{((x-h)sin\theta-(y-k)cos\theta)^2}{b^2}=1 \quad (1)$$

where h and k are coordinates of the central point of the ellipse along the the x-axis and y-axis respectively, a and b are the semi-major axis and semi-minor axis respectively, and θ is the rotation angle.

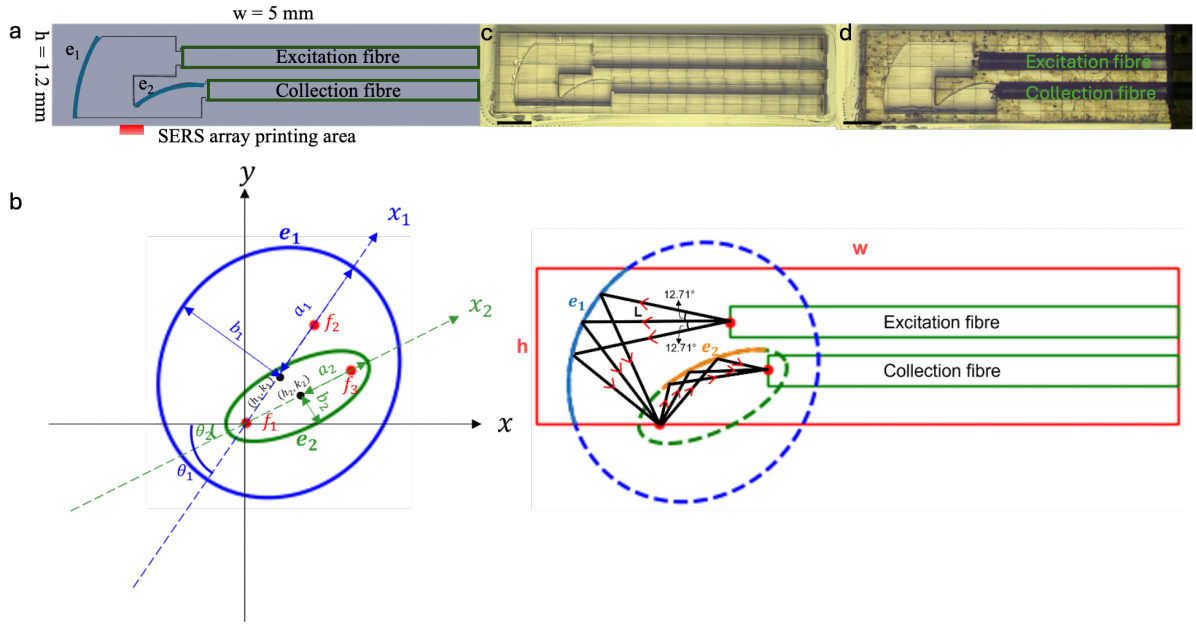


Fig. 1. Side-viewing SERS probe. (a) CAD model (top view) of the probe structure, featuring two parabolic mirrors (e_1, e_2), two grooves for optical fiber assembly and SERS array printed on side border. (b) Geometrical schematic illustrating the design of the parabolic mirrors in the side-viewing probe. (c,d) Microscopy images of 3D-printed side-viewing probe structure (c) and side-viewing probe assembled with two optical fibers (d). Scale bars - 500 μm.

The side-viewing probe structure was printed using 2PP on an ITO-coated substrate using 25x objective and IP-S resin (Nanoscribe GmbH; see Fig. 1(c)). Following this, two cleaved optical fibers were manually assembled into the probe structure, as depicted in Fig. 1(d). Ongoing work now involves probe validation to assess light collection, signal enhancement and background reduction capabilities.

3.2. Forward-viewing SERS probe

The forward-viewing SERS probe builds on our previous work, where a fiber-tip SERS probe was fabricated using 2PP [8]. This device provided effective Raman signal enhancement but suffered from high silica background [8]. To mitigate this issue, an improved design is proposed for use with hollow core fibers (instead of conventional silica fibers) to fundamentally reduce background. A fiber cap with a smooth and flat top surface was designed and printed at the fiber tip, allowing the SERS array to then be printed onto the cap. The cap was designed with a diameter of 250 µm, with four supporting legs incorporated to ensure the cap stands securely on the fiber tip, providing a stable surface for SERS array printing. The 3D model is illustrated in Fig. 2(a).

Both the cap and the SERS array were fabricated using 2PP. However, given the significant differences in size and resolution between the cap and the SERS array, a sequential fabrication approach was employed. Initially, the

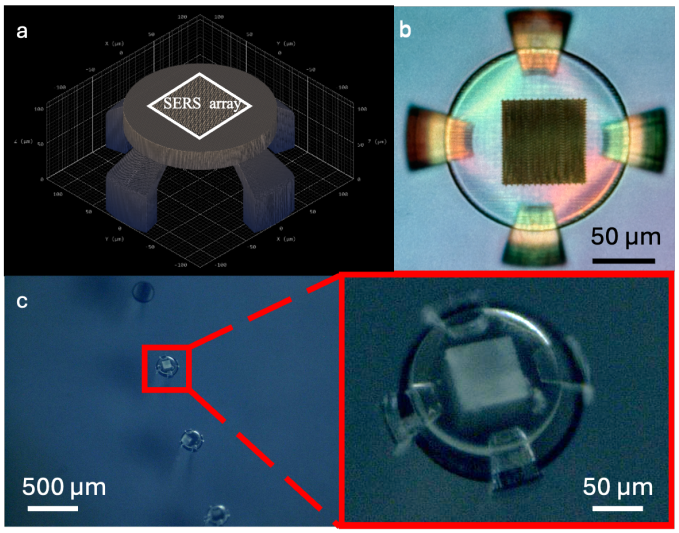


Fig. 2. Demonstration of cap design with SERS array for hollow core fiber. (a) CAD model of cap, designed as a floating platform with four legs, with SERS array printed on its top surface. (b) Microscopy image of the cap with SERS array printed on an ITO-coated substrate. (c) Microscopy images of the cap and SERS array printed on standard (silica) optical fibers.

cap was printed using 25× objective and IP-S resin. Following development of the printed cap, the 2PP objective was switched to 63×, and IP-Dip was used to print the SERS array onto the cap. This process was performed on both ITO-coated glass substrates (Fig. 2(b)) and optical fiber tips (using standard silica fibers for demonstration; Fig. 2(c)), thereby demonstrating successful fabrication of the forward-viewing SERS fiber probe.

4. Conclusion

Fiber-optic SERS incorporating 2PP-fabricated micro-optics can potentially address critical challenges for *in vivo* Raman spectroscopy including constrained space, low signal levels, and high fiber (silica) background. In this study, two SERS probe concepts were proposed and preliminary designs were developed and fabricated using 2PP. The side-viewing SERS probe will enable longitudinal and/or rotational sensing approaches, while the forward-viewing SERS probe will allow a more direct *en face* sensing method, thus addressing multiple possible *in vivo* diagnostic applications. Future work will now entail further optimisation of probe designs, integration of the forward-viewing cap structure with hollow core fibers, and laboratory validation of the fully assembled/fabricated probes.

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