

# The performance of High-Index-Contrast Photonics Platforms for On-Chip Raman Spectroscopy

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Various photonic platforms exist that may be suitable for on-chip Raman spectroscopy. Here we compare 4 of them focusing on their intrinsic photon background and their capability for collecting Raman signal from liquid analytes. These two parameters define the complete figure of merit for waveguide enhanced Raman spectroscopy.

**Keywords:** Raman spectroscopy, Waveguide enhanced Raman sensing, HIC waveguides

Enhancing the light matter interaction is highly desirable for Raman spectroscopy because of the fundamentally weak Raman scattering cross sections. Hollow optical fibers and more recently nanophotonic waveguides have exhibited enhancement in Raman signal by many orders of magnitude over traditional Raman microscope [1, 2]. Rib waveguides can be used as easily as cover slides and have therefore been used for Raman spectroscopy of various analytes such as bulk liquids [3-5], adsorbed monolayers [6] as well as in gaseous state [7]. Many photonics platforms exist that may seem suitable for a Raman spectroscopy sensor, but a good waveguide-based Raman sensor requires qualities that may contradict each other. The waveguide need to be low loss to maximize the effective interaction length. At the same time, it needs to have a large index to be able to push a significant part of the field into the analyte out of the waveguide while still keeping good guiding properties. The waveguide must also handle large optical power. Finally, it should not induce any photon background that may overlap spectrally with the Raman signal. All these properties impact directly on the signal to noise ratio and may relax strongly the otherwise tight specifications required for light sources and photodetectors of a Raman spectroscopy system. In this report, we compare 4 photonic platforms and present measurements of their broadband photon background. The four platforms under investigation are PECVD Si<sub>3</sub>N<sub>4</sub>, ALD grown TiO<sub>2</sub>, sputtered Ta<sub>2</sub>O<sub>5</sub> and reactive co-sputtered Al<sub>2</sub>O<sub>3</sub>. To measure the Raman background of these waveguide materials, strip waveguides were fabricated on top of a silica substrate using traditional fabrication techniques e.g. Al<sub>2</sub>O<sub>3</sub>, Si<sub>3</sub>N<sub>4</sub> and Ta<sub>2</sub>O<sub>5</sub> waveguides were fabricated using deep UV lithography while ALD grown TiO<sub>2</sub> were patterned using e-beam lithography. The fabrication details of each waveguide can be found in [8-11]. The fabricated waveguide geometries, refractive indices and corresponding waveguide losses are presented in Table 1. It is worth noting that those geometries are not optimized for a use in Raman spectroscopy that typically requires smaller dimensions so that the field couples evanescently to an analyte. Therefore, scattering loss for an optimized waveguide may be underestimated. The total backscattered background P<sub>s</sub> normalized by total guided power P<sub>0</sub> can be estimated by assuming it has a Raman origin. In a waveguide of length L, width w and height h and propagation loss α can be computed using

$$\frac{P_s}{P_0} = \frac{1}{2} \times \rho \sigma \eta_{BG} \gamma^2 \times \left( \frac{e^{-2\alpha L} - 1}{2\alpha} \right)$$

where ρ and σ are respectively the molecular density and Raman cross section of the waveguide material, γ is the coupling efficiency. η<sub>BG</sub> is background conversion efficiency that quantifies the amount of a background signal collected in a waveguide mode. The values of η<sub>BG</sub> depends on the geometry and the index contrast of the waveguide. Using COMSOL Multiphysics mode solver, we deduced η<sub>BG</sub> for the 4 waveguides assuming 785 nm pump wavelength and 820 cm<sup>-1</sup> Stokes shift (Table 1).

The background spectra are measured from the 4 waveguides using a confocal setup [12]. A 785 nm pump is used to excite the TE fundamental mode in a waveguide using high NA 0.9/100× objective. The backscattered signal is collected using the same objective and the Raman Stokes scattered signal is sent to -73°C cooled Andor

IDUS 401 CCD camera after the remaining pump is rejected by a spectral filter. Furthermore, an integrating sphere at the output side of the waveguide is used to measure the transmission and the coupling efficiency.

Waveguide	Cross section (width (nm) × (nm) height)	Refractive index	Waveguide loss (dB/cm)	$\eta_{BG}$
Al <sub>2</sub> O <sub>3</sub>	2400 × 550	1.64	2.2	0.2114
Si <sub>3</sub> N <sub>4</sub>	700 × 220	1.90	4.3	0.5405
Ta <sub>2</sub> O <sub>5</sub>	1000 × 550	2.11	4.0	0.6321
TiO <sub>2</sub>	1000 × 450	2.36	8.2	0.6901

Table 1. The optical properties of different photonics platforms under discussion.

The measured Raman spectra  $\sigma^*$  are plotted in Fig. 1 and are normalized by  $\gamma$ ,  $\eta_{BG}$  and length factor. The error bar in Fig 1. represents the deviation of signal over five different waveguide on same chip. TiO<sub>2</sub> exhibits a large Raman background that is an order of magnitude stronger as compared to other three materials. The other three waveguide materials are in close competition and outperform each other depending on the Raman frequency under interest. Therefore, Al<sub>2</sub>O<sub>3</sub> may suffer from low collection efficiency from an analyte lying uniformly over the waveguide length. However, Si<sub>3</sub>N<sub>4</sub> and Ta<sub>2</sub>O<sub>5</sub> seem to have similar performance in term of the Raman background.

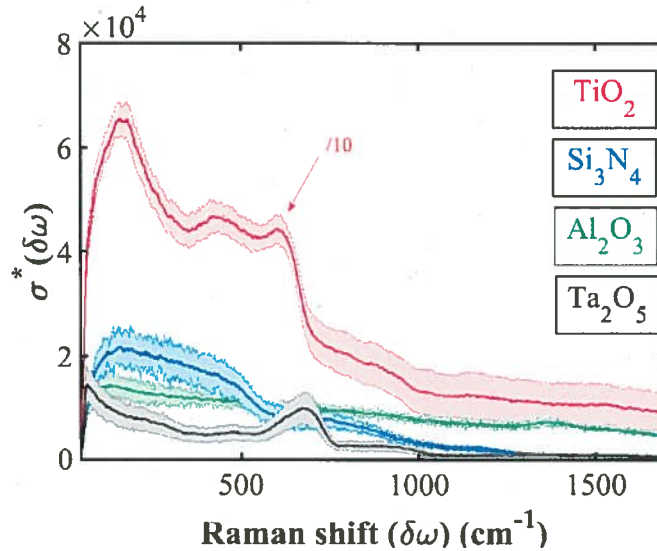


Figure 1. The normalized Raman background of four photonics platform. . The TiO<sub>2</sub> Raman spectrum is normalized by 10 for visual guidance.

In the latter part, we have computed the analyte signal collection efficiency  $\eta_{Analyte}$  [2] for all the four photonics platforms. For this purpose, we assume a uniform covering of the waveguides with an analyte having refractive index 1.37 and a Raman mode around 819 cm<sup>-1</sup> i.e. isopropanol [2]. The Raman collection efficiency  $\eta_{Analyte}$  for each material is maximized by adjusting the geometry of the waveguide assuming the same pump wavelength of 785 nm and 819 cm<sup>-1</sup> Raman shift. The results of these simulations are summarized in Table 2. Owing to high index contrast, TiO<sub>2</sub> waveguide leads to the high collection efficiency while the Al<sub>2</sub>O<sub>3</sub> waveguide suffers due to low index contrast. On the other hand Si<sub>3</sub>N<sub>4</sub>, and Ta<sub>2</sub>O<sub>5</sub> offers similar magnitude of collection efficiency.

Waveguide	Cross section (width (nm) × height (nm))	$\eta_{Analyte}$
Al <sub>2</sub> O <sub>3</sub>	325 × 1200	0.0395
Si <sub>3</sub> N <sub>4</sub>	200 × 550	0.1721
Ta <sub>2</sub> O <sub>5</sub>	175 × 425	0.2667
TiO <sub>2</sub>	150 × 375	0.3745

Table 2. The signal collection efficiency  $\eta_{Analyte}$  from an analyte lying uniformly on a waveguide.

As a conclusion, we have presented the performance of four different high index contrast photonic platforms in term of photon background and signal collection efficiency. TiO<sub>2</sub> has the higher collection efficiency but its performance suffers due to huge photon background. On the other hand, Al<sub>2</sub>O<sub>3</sub>, Si<sub>3</sub>N<sub>4</sub> and Ta<sub>2</sub>O<sub>5</sub> have same photon

background that is an order of magnitude less than  $\text{TiO}_2$ ,  $\text{Si}_3\text{N}_4$  and  $\text{Ta}_2\text{O}_5$  looks equally promising as their photon background is low and similar high index contrasts leads to high signal collection efficiency.

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