# Power Budget Analysis for Waveguide Enhanced Raman Spectroscopy


Zilong Wang[1], Michalis N. Zervas[1], Philip N. Bartlett[2], James S. Wilkinson[1]

1. Optoelectronics Research Centre, University of Southampton, SO17 1BJ 2. Chemistry, University of Southampton, SO17 1BJ


## Introduction

Surface-enhanced Raman Spectroscopy (SERS) is a powerful tool for chemical analysis which can suffer from poor repeatability due to the sensitive nature of plasmonic interactions. Waveguide- enhanced Raman spectroscopy (WERS) is emerging as a competitive analytical tool which avoids nanostructured noble metal surfaces but which potentially provides comparable surface enhancements in a sensor format [1,2]. Comparison of these approaches suffers from ill-defined definitions of surface enhancement. We present a power budget analysis of WERS, relating the received power in a Raman emission line to the incident pump laser power, using waveguide surface intensity and Raman cross-section, allowing WERS optimisation and clear comparison of surface-enhanced techniques.

## Waveguide modelling and optimisation

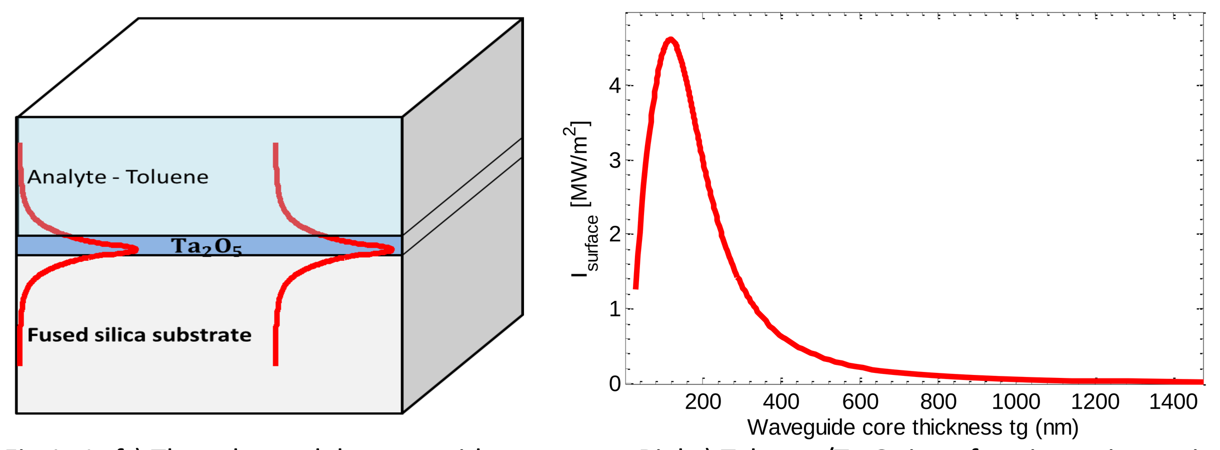


Fig 1 . Left) Three layer slab waveguide structure; Right) Toluene/$Ta_2O_5$ interface intensity against varied of core thickness

- ***Modelling methods***
1. Matrix method: formulate mode equation for multilayer slab waveguide structure.
2. Muller's method: calculate all the mode solutions.

- ***Waveguide design considerations***
1. High index contrast: n($Ta_2O_5$)/ n(SiO2) =1.465.
2. Both core and substrate assumed to have low loss.
3. Raman emission of waveguide materials are not in the range of interest.

- ***Optimised interface intensity***
1. Emitted Raman $P_{Raman} \propto I_{surface}$
2. The optimised core thickness is 120 nm @ 638 nm excitation wavelength.
3. Parameters such as wavelength, material index, number of layers and their thickness can be tuned to achieve the optimal performance.

## Instruments, apparatus & results

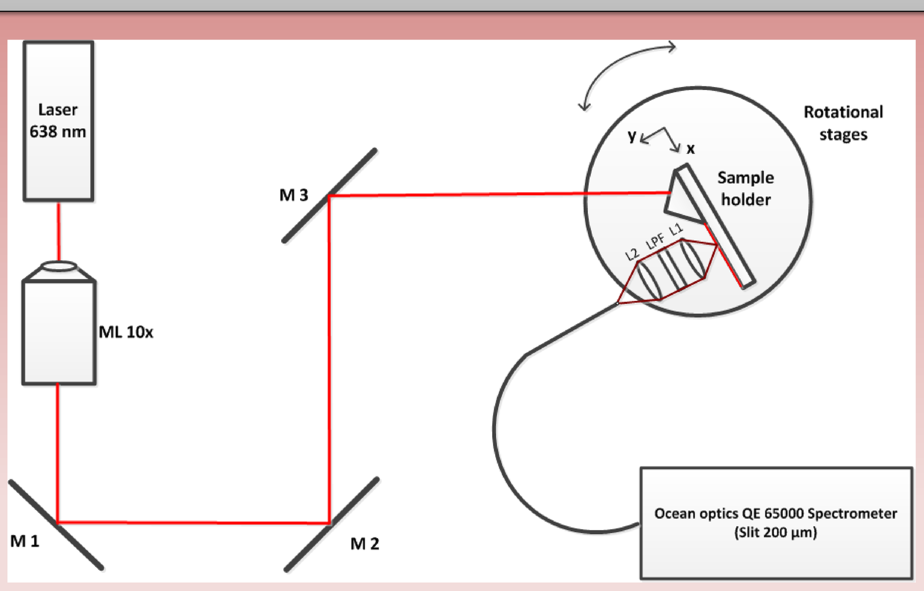


Fig 2. Instrument apparatus.

- M1, 2, 3 are mirrors.
- L1: lens with f1=25.4 mm;
- LPF: low pass filter with cutting edge at 650 nm;
- L2: lens with f2 = 30 mm.
- All lens with diameter 25 mm.
- Spectrometer: QE≈90%; slit width: 200 $\mu m$

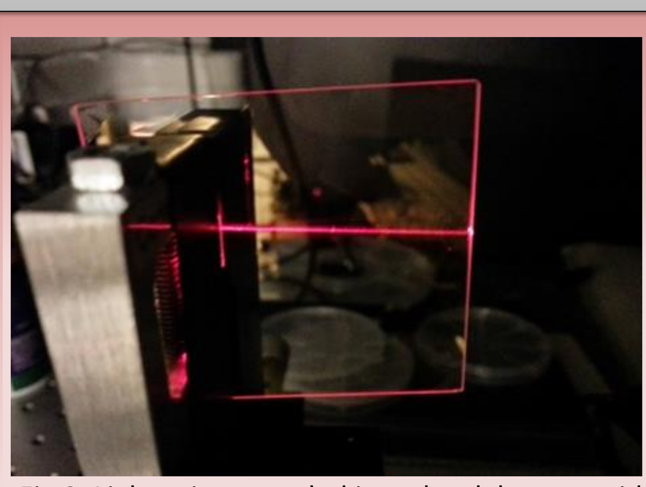

Fig 3. Light prism-coupled into the slab waveguide

A clean and clear streak of light observed indicates excellent waveguiding with low loss.

- Choice of Toluene: 1) known Raman cross-section; 2) random orientation as liquid.
- Raman peaks of Toluene can be observed at the right frequencies (Raman shifts).
- Feature broadening due to spectrometer slit width.
- Area under each peak gives collected Raman energy.

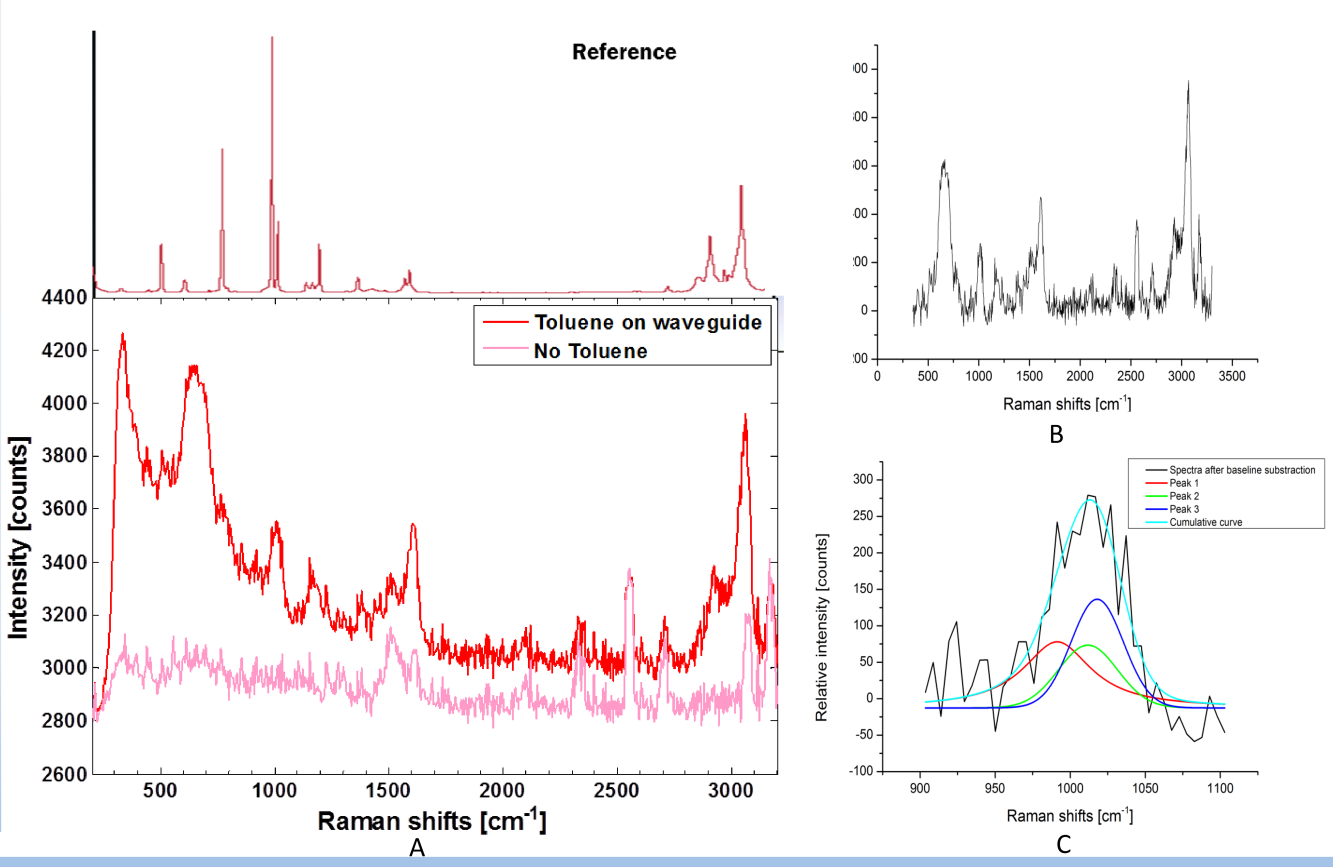


Fig 4. A. Raman spectra collected from waveguide surface, integration= 60 s; B. After baseline subtraction; C. Peak fitting to spectrum feature at around 1, 000 $cm^{-1}$ region.

## Power budget analysis

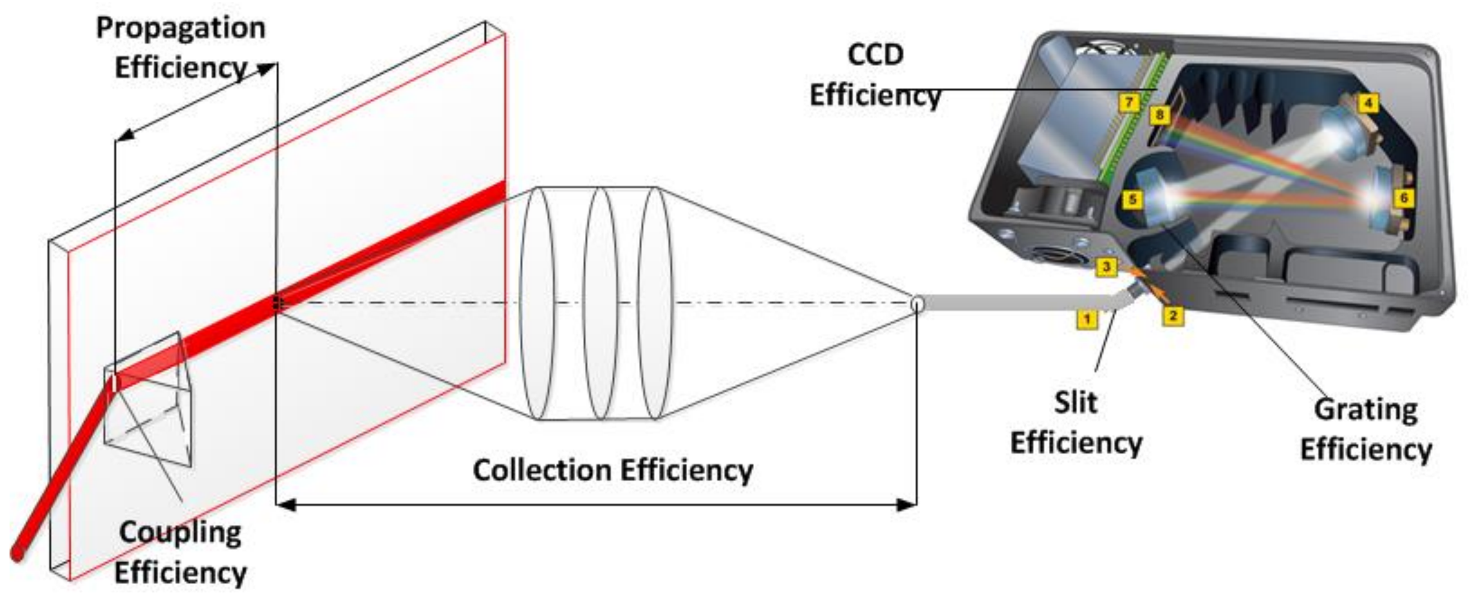


Fig 4. Loss illustrated in the instrument system

- 70mW unpolarised light arriving at the prism base, and half of them 35 mW of light will excite TM mode in waveguide.
- The waveguide loss is estimated to be 1 dB/cm
- Differential Raman cross section of Toluene $\frac{d\sigma}{d\Omega}$ is $350 \times 10^{-32}\ cm^2 \cdot sr^{-1}$ [3].
- The total emitted power from waveguide excitation in the collection region is calculated to be $2.24 \times 10^{-13}$ W
- The effective collection area[1]: Length: 1.16 mm; and width: 700 µm.

1. These length and width are within the collection cone by using a multi-mode collection fibre with 1 µm core diameter and NA of 0.58. The collection cone both depends on image system (L1, L2) and collection fibre.

Table 1. Summary of efficiencies and their corresponding methods and values

| Efficiency | Method | Value |
|---|---|---|
| Coupling efficiency ($\eta_1$) | Measured & calculation | 10% |
| Propagation efficiency ($\eta_2$) | Measured | 70.1% |
| Excitation efficiency ($\eta_3$) | $\eta_3 = \frac{\int \frac{\rho \cdot A}{M} \cdot N_A \cdot I(x) \cdot 4\pi \cdot \frac{d\sigma}{d\Omega} \cdot dx}{P_{pump}}$ | $7.45 \times 10^{-9}$% |
| Collection efficiency ($\eta_4$) | $\Omega = 2\pi \times (1 - \sqrt{1-(sin\theta)^2})$ $\eta_4 = \frac{\Omega}{4\pi}$ | 1.2% |
| Entrance slit efficiency ($\eta_5$) | Datasheet & calculation | 40% |
| Grating efficiency ($\eta_6$) | Spectrometer datasheet | 60% |
| Quantum efficiency ($\eta_7$) | Spectrometer datasheet | 90% |

***Theoretical analysis***: $P_{det} = P_0 \cdot \eta_1 \cdot \eta_2 \cdot \eta_3 \cdot \eta_4 \cdot \eta_5 \cdot \eta_6 \cdot \eta_7 \approx 5.80 \times 10^{-16}\ W$

***Experimental data***: $P_{det}{}' = 5.02 \times 10^{-16}\ W$

### Conclusion

- **Very good agreement between theoretical value and experimental data.**
- **The knowledge of how much power in and out as well as the efficiency of each part in between makes it suitable for making direct comparison with other configurations.**

## References & Acknowledgement


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