Networked Swept-Source Raman Sensors

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Abstract: Raman spectroscopy with large-area, spectrally-selective detectors and tunable lasers enables distributed chemical sensing where excitation light can be delivered via optical datacom networks. Distributed sensing over 100's of meters and multiple locations is demonstrated. © 2021 The Author(s)

Fiber-optic probes for spontaneous Raman spectroscopy are widely used in pharmaceutical manufacturing [1], clinical applications [2,3], and environmental monitoring due to Raman's non-destructive nature and high chemical specificity. In the heart of traditional Raman systems lies a dispersive spectrometer that separates the weak Raman signal into its different wavelengths but also acts as the Signal to Noise Ratio (SNR) bottleneck of the system. The spectrometer's entrance slit and optics (f/#) determine the light gathering power of the system (etendue) and in most applications the collection fiber is chosen so its core diameter matches the slit width. An intrinsic tradeoff exists between the spectral resolution of the spectrometer and the light gathering, and so in order to achieve high resolution for accurate chemical fingerprinting, SNR is compromised. Moreover, the vertical dimension of the slit is also constrained and limits the number of input channels. Commercial systems usually offer up to 4 input channels and have limited multiplexing ability. Since there are no available optical switches or splitters for standard multimode 200μm core collection fibers, these systems are at their limit.

Here, we demonstrate a highly multiplexed, distributed Swept-Source Raman system that replaces the fixed wavelength laser and spectrometer with a tunable laser and a large-area, low-cost, spectrally-selective detector operating at room-temperature, see Fig 1a. The spectral selectivity is accomplished by placing a high-index, thin-film filter in front of a silicon photoreceiver. The filter's large area and wide acceptance angle are compatible with collection fibers that have significantly greater core diameters and larger Numerical Aperture (NA). Here we use a 600μm core fiber with NA=0.5, improving the light collection by a factor of x30 compared with standard 200μm core, 0.22 NA fibers. This enhancement of signal collection allows us to acquire Raman spectra with uncooled, low-cost silicon photoreceivers.
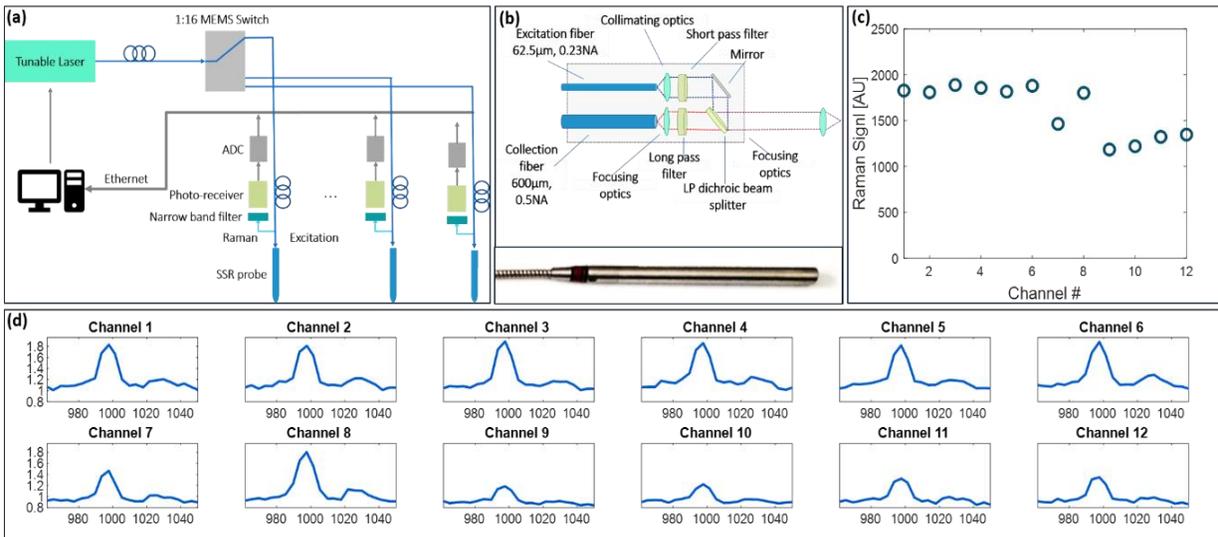

Fig.1 (a) Illustration of a multiplexed Swept-Source Raman network. (b) Image of the custom multimode probe we had designed and used to acquire the spectra with the internal optical components. (c) Comparison of the Raman signal power of 12 of 16 switch channels. (d) Spectra of polystyrene collected with 80mW, 2 sec integration time with 23 data points using the multimode probe through 12 of the 16 channels of the datacom switch. All 16 ports are functional and the in signal is dominated by variability in the probe to sample alignment.

In this Swept-Source Raman architecture, as the wavelength is tuned, the spectral features in the Raman spectra are sequentially sampled by the wavelength-selective photoreceiver and the spectrum is constructed. While the simplicity of the receiver is offset by the complexity of the excitation, this architecture supports significant multiplexing. The photoreceiver can be integrated with probes (Fig.1b) and the laser is considered a shared resource, allowing simultaneous or sequential acquisitions of spectra using an optical switch (Figs. 1c-d, 2a).

In our probes optical design, we chose an excitation tuning range of 780-835nm, that is typical for both clinical and industrial applications [4]. Fortunately, this wavelength range is also compatible with data communications fiber optic components. Indeed, we utilize standard 62.5μm multimode fibers and a 1:16 fiber datacom switch to distribute the tunable excitation to the various probe locations. Fig. 1d shows spectra of polystyrene sampled sequentially through each of the switch channels with our probe, exciting with 80mW of power and collecting over 2 seconds of integration time on each of the 23 wavelengths. The switch insertion loss varies somewhat for each channel but is lower than 1dB for all 16 channels. The variation in spectra intensity stems from both channel variability but is dominated by sample placement.

The system demonstrated here further enables sequential or simultaneous collection of spectra remotely with either single mode or multimode excitation (Fig. 2a). We measure the spectrum of Tylenol located approximately 100 meters away from the tunable laser (Fig. 2b) while simultaneously acquiring silicon spectrum with the multimode switched probe (Fig. 2c). Both spectra are acquired using 80mW of power, 2s integration time and 250 wavelengths.
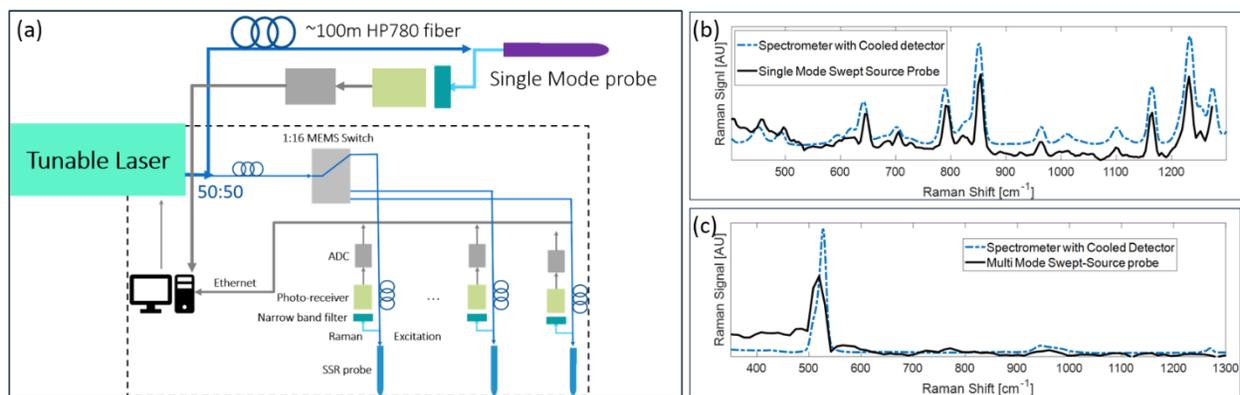

Fig.2 (a) Illustration of a multiplexed Swept-Source Raman network with the optional simultaneous single mode probe. (b) Image of Tylenol spectra acquired with Single mode probe, 2s integration 250 data points, and compared with cooled detector benchtop spectrometer Raman system. (c) Image of silicon spectra acquired with a multimode probe, 2s integration 250 wavelengths compared with cooled detector benchtop spectrometer Raman system.

Our proposed system can significantly enhance the use of Raman spectroscopy for continuous monitoring and control. In an industrial application this means that nearly every unit process can be simultaneously monitored. For clinical applications, it is feasible to switch between multicore fiber probes to realize lens-free, compressive sensing as has been demonstrated recently for endoscopic fluorescence imaging [5]. Finally, the scale and range of such a highly networked, fiber optical Raman spectroscopy system enables applications that are cost-prohibitive today: for example, monitoring water quality in rivers and treatment facilities, monitoring plant growth in indoor farms and many more.

References

[1] Paudel, A., Raijada, D. Rantanen, J. "Raman spectroscopy in pharmaceutical product design" Advanced drug delivery reviews **89**, 3–20 (2015).
[2] Baker, M. J. et al. "Clinical applications of infrared and raman spectroscopy: state of play and future challenges" Analyst **143**, 1735–1757 (2018).
[3] Kong, K., Kendall, C., Stone, N. & Notingher, I. "Raman spectroscopy for medical diagnostics from in-vitro biofluid assays to in-vivo cancer detection" Advanced drug delivery reviews **89**, 121–134 (2015).
[4] Cordero E, Latka I, Matthäus C, Schie I, Popp J. "In-vivo Raman spectroscopy: from basics to applications" J Biomed Opt. **23** (7) ,1-23 (2018)
[5] Pengfei Zhang, Guiwen Wang, Xiujuan Zhang, and Yong-qing Li, "Single-Acquisition 2-D Multifocal Raman Spectroscopy Using Compressive Sensing" Analytical Chemistry **92** (1), 1326-1332 (2020)