On-chip Infrared Spectroscopic Sensing

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Infrared (IR) spectroscopy probes the phonon vibrational states of molecules by measuring wavelength-dependent optical absorption in the mid-infrared regime (2.5-25 μm wavelength or 400-4,000 cm^{-1} in wave number). It is widely recognized as the gold standard for chemical analysis given its superior specificity. Traditional IR spectroscopy relies on fragile bench-top instruments located in dedicated laboratories, and is thus not suitable for emerging field-deployed applications such as in-line industrial process control, environmental monitoring, and point-of-care diagnosis. Recent strides in photonic integration technologies provide a promising route towards enabling miniaturized, rugged platforms for IR spectroscopic analysis. It is therefore attempting to simply replace the bulky discrete optical elements used in conventional IR spectroscopy with their on-chip counterparts. This size down-scaling approach, however, cripples the system performance as both the sensitivity of spectroscopic sensors and spectral resolution of spectrometers scale with optical path length.

To address this challenge, we present the development of two novel photonic device designs uniquely capable of reaping performance benefits from microphotonic scaling [1]. Firstly, we leverage strong optical and thermal confinement in judiciously designed microcavities to circumvent the thermal diffusion and optical diffraction limits in conventional photothermal sensors and achieve parts-per-billion (ppb) level gas molecule limit of detection. Photothermal spectroscopy has been predicted as a technique 10^4 times more sensitive than conventional microcavity absorption spectroscopy [2, 3]. We propose a new technique that monitors the shift in cavity resonance as a result of heating. Resonant absorption of cavity light by the gas molecules thermally heats the cavity, producing a large resonant shift in a suitably designed microdisk cavity, as schematically illustrated in Fig. 1.

In the second example, a novel spectrometer technology based on on-chip digital Fourier Transform InfraRed (dFTIR) is proposed to overcome the aforementioned spectral resolution limit facing current on-chip spectrometers. As schematically depicted in Fig. 2, the dFTIR spectrometer consists of an interferometer with arms comprising a series of cascaded optical switches connected by waveguides of varying lengths. Each permutation of the switches modifies the physical waveguide path lengths and thus spectrometer configurations. Such a dFTIR approach is far more effective for varying the optical path length than index modulation and hence enables perform metrics comparable or even superior than conventional benchtop instruments. The spectrometer design fulfills Fellgett's advantage offering dramatically-improved SNR and enables sub-nm spectral resolution (as projected in Fig, 3) on a millimeter-sized, fully-packaged photonic integrated chip without mechanical moving parts.

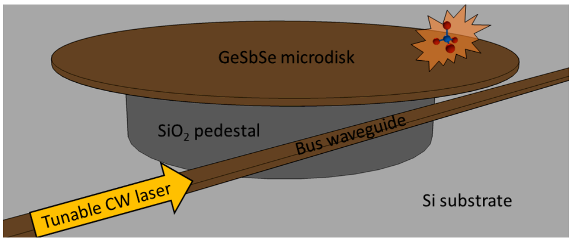

Fig.1 Schematic of a suspended microdisk cavity structure for sensing a target gas molecule in the surrounding air. Brown denotes a 30 μm radius $Ge_{23}Sb_7Se_{70}$ microdisk coupled to a bus waveguide, all suspended 10 μm above a Si substrate by SiO_2 supports.

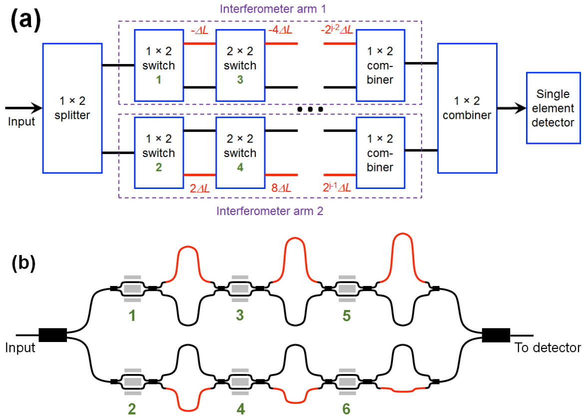

Fig. 2 (a) Block diagram of the dFTIR spectrometer design; (b) schematic layout of a 64-channel dFTIR spectrometer: the waveguide segments of varying lengths different from the standard length are shown in red (not drawn to scale). The green numbers label the 1 × 2 or 2 × 2 switches.

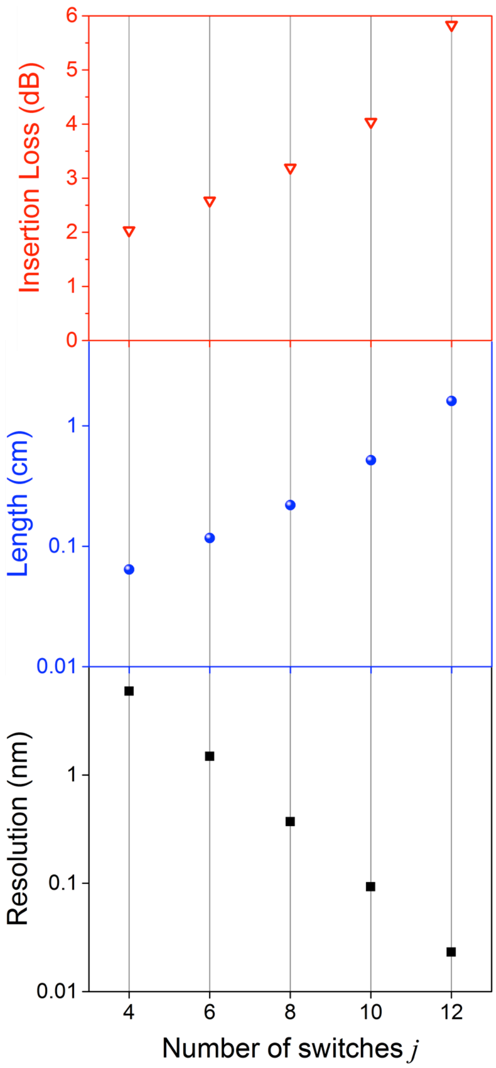

Fig. 3 Projected spectral resolution, interferometer arm length and insertion loss of the dFTIR spectrometer.

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