All-silicon standing-wave microspectrometer with tunable spectral resolution

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Traditional multispectral sensing systems are burdened with enormous information generation and processing requirements [1], largely due to implementation of a maximum spectral resolution that is not necessarily required for all sensing tasks. Devices designed with the flexibility to adapt to a particular sensing task could dramatically reduce operation requirements and information volume. Whereas most microspectrometers (commonly grating-based devices with a detector array) have fixed spectral resolution, our standing-wave microspectrometer can be easily configured for a particular sensing task by tuning its spectral resolution, allowing real-time optimization of device sensitivity. Here we demonstrate continuous resolution tuning from 72 nm to 6 nm ($\lambda = 633$ nm), for adaptive spectral discrimination throughout the visible range.

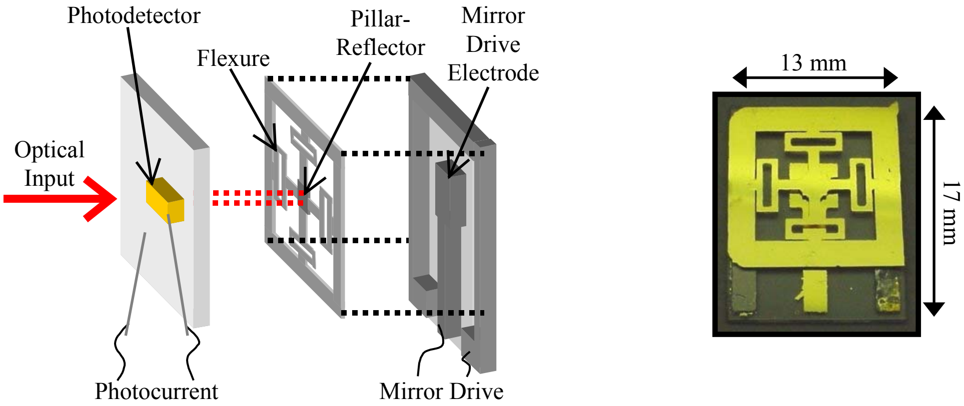

Fig. 1. Left: Microspectrometer schematic. Light traverses the photodetector and reflects off the MEMS mirror pillar back to the detector. Right: photo of MEMS component packaged with electrode.

In the standing-wave spectrometer (Fig. 1), incident light reflects off a micromirror, creating an optical standing wave that is continuously sampled by a partially-transmitting photodetector. As the mirror scans along the optical beam axis, an interferogram is generated. After conversion of the data from interferogram vs. time to interferogram vs. mirror displacement, a Fourier transform yields the optical spectrum of the incident light. Here the mirror component is a parallel-plate electrostatically driven MEMS actuator. This 13 × 13 mm Si device consists of a 2 × 2 mm reflective mirror pillar connected to four rectangular flexures [2]. High-amplitude continuous harmonic motion is accomplished by driving with a DC-offset sinusoidal voltage at the mechanical resonance frequency. We achieve a mirror scan length of 31 μm for peak-to-peak drive voltage $V_{pp} = 100$ V at 547 Hz. The detector is a Si *p-i-n* photodiode with transparent ZnO contacts. The active region is 30 nm thick [3], allowing for partial transmission of the optical input. Electrical bandwidth was limited to $f_{3dB} \approx 30$ kHz due to large geometric capacitance and low ZnO layer conductivity.

Due to the parallel-plate architecture of our MEMS oscillator, the mirror scan length L can be expressed as $L = bV_{pp}^2$ for some scaling coefficient b. Combining this with the Rayleigh spectral resolution criteria, the spectrometer resolution $\Delta\lambda$ can be expressed as $\Delta\lambda = \lambda^2/2bV_{pp}^2$ for wavelength λ; here b is measured as $\sim 3.0 \times 10^{-9}$ m/V^2. For a sensing task requiring a particular spectral resolution, a change in V_{pp} optimally reconfigures the spectrometer in real-time. In spectrometers, better spectral resolution generally implies worse signal-to-noise ratio (SNR); here a number of factors contribute, dominated by detector performance degradation with increased mirror scan length. For a given mirror scan frequency, increased scan length implies a higher frequency of fringes in the interferogram, which is attenuated for frequency components above the detector f_{3dB}. Thus operating at the lowest acceptable spectral resolution optimizes sensitivity or SNR.

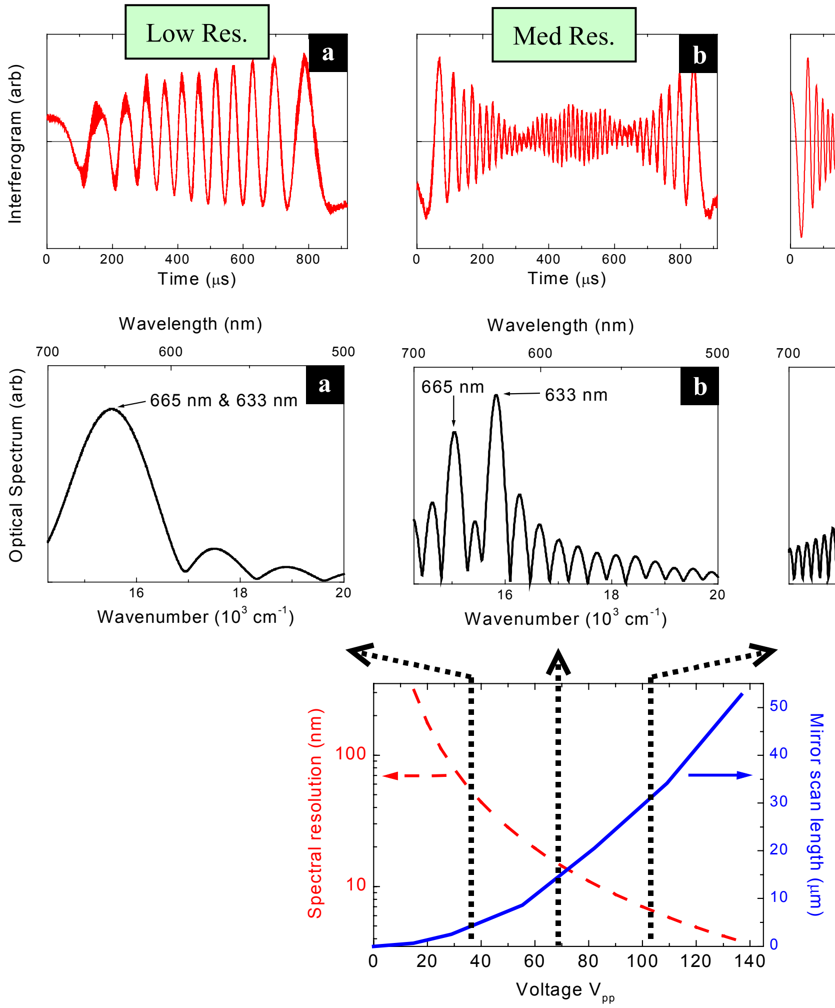

Fig. 2. Top: Interferograms (AC-coupled photocurrent) for mirror scan lengths of a) 3.8 μm, b) 14 μm, and c) 31 μm. Middle: Optical spectra derived from interferograms, with resolutions (peak full-width at half-maximum, at 633 nm) of a) 1800 cm^{-1} = 72 nm, b) 340 cm^{-1} = 14 nm, and c) 140 cm^{-1} = 5.6 nm. Bottom: Spectral resolution (dashed line) and scan length (solid line) vs. actuator drive amplitude *Vpp*. Vertical dotted lines mark operating points for low, medium, and high resolution data in a), b), and c), respectively.

For input lasers at 633 nm (363 μW) and 665 nm (716 μW), data at low, medium, and high resolution are shown in Fig. 2 with a graph depicting the device operating points. When it is not necessary to resolve the two shades of red, the low resolution operating point minimizes required actuator drive power, interferogram sampling rate, and generated data. Medium resolution clearly resolves the two lasers. High resolution yields the narrowest peak at 633 nm (FWHM = 6 nm), but requires a higher optical power (3.05 mW) for detection. Decreased sensitivity at this resolution prevents detection of lower power sources; here, the 665 nm laser had no higher power setting and therefore could not be detected. Spectral discrimination was accomplished across the visible range, with sources at 543 nm (green) and 488 nm (blue) in addition to those mentioned above.

In summary, with an all-silicon standing-wave microspectrometer we have demonstrated continuously tunable spectral resolution, offering real-time optimization of device sensitivity and system operating requirements.

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References

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