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Compact standing-wave transform spectrometer based on integrated MEMS mirror and thin-film photodetector

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We demonstrate an integrated standing-wave Fourier-transform spectrometer, 17 × 13 × 2 mm, with 32 nm spectral resolution at 665 nm. The compact, 1-D system design offers mirror stability, guarantees relative component alignment, and should enable simple fabrication of imaging arrays of spectrometers.

We present a miniature spectrometer, based on the 1-D standing-wave transform spectrometer architecture [1], with an integrated electrostatically-actuated parallel-plate MEMS mirror [2] and a partially transmitting thin-film photodetector. Spectral resolution of 32 nm at λ = 665 nm is demonstrated. Composed of just three separate components stacked and bonded, this design offers mirror stability and permanent relative alignment of optical and electronic components. The spectrometer is made with bulk micromachining and standard silicon device processes, offering potentially simple fabrication of imaging arrays of spectrometers and inexpensive high-volume production. A range of applications exists in which the compact size and simple operation of a MEMS transform spectrometer can outweigh its coarse spectral resolution. Such applications include biochemical analysis, mobile sensing systems, manufacturing line inspection, and vision systems [3-5].

The standing-wave spectrometer creates and samples an optical standing wave as a MEMS mirror scans along the beam axis. The Fourier transform of the resulting time-varying photocurrent yields the optical spectrum. This spectrometer architecture offers the same advantages as other Fourier transform spectrometers, such as throughput and multiplexing, but in an optically 1-D system. The partially transmitting photodetector removes the need for a beamsplitter and second optical arm, minimizing the number of required optical components. The 17 × 13 × 2 mm miniature spectrometer, which is four wafers thick and fabricated as three separate planar components preceding integration, is shown schematically in Fig. 1.

Spectrometer resolution improves with total mirror scan length, so the parallel-plate silicon MEMS mirror is designed for large displacement when driven at its resonance frequency. Instead of bending like a linear flexure, the four mirror support structures buckle, thus achieving large displacement. The basic mirror front plane fabrication has been described previously [2]. Slight modifications were made to the mirror front plane mask. In this new design, the material thickness of the rectangular mirror supports is 29 µm. The reflective surface of the mirror is aluminum to accommodate visible light applications.

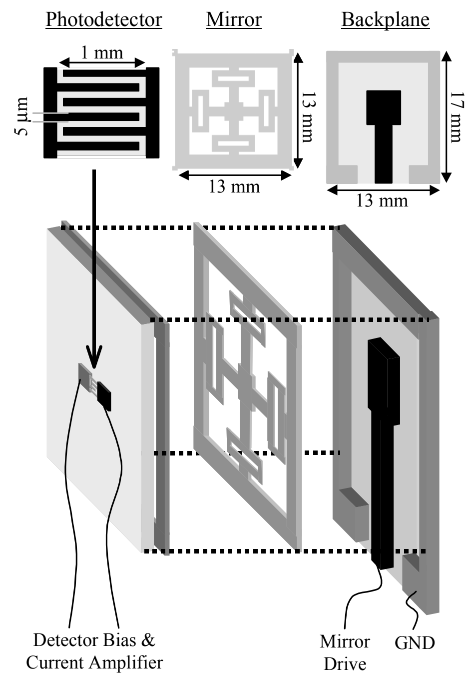

Fig. 1: Integrated standing-wave spectrometer.

The mirror back plane was fabricated from an insulating quartz substrate. 100 Å of chrome and 2000 Å of gold were first deposited on the wafer. The wafer was patterned, leaving a frame of gold to support the mirror front plane. The exposed quartz was then etched 60 µm with 6:1 buffered oxide etch, leaving space for mirror displacement. Finally a center metal electrode was patterned to electrostatically attract the center pillar on the back of the mirror front plane.

The thin-film photodetector, mounted in front of the mirror front plane, must transmit a significant fraction of the input light to allow a standing wave of sufficient intensity. The detector was fabricated by low pressure chemical vapor deposition of 2200 Å polysilicon on a quartz wafer at 620 °C. The wafer was patterned with alternating fingers with a 5 µm spacing, and then 100 Å of titanium, 300 Å of nickel, and 2000 Å of gold were lifted off the wafer. A 13 × 13 mm wafer-thick frame was attached to the back of the detector to provide clearance for mirror motion.

The polysilicon is the optically absorbing material. Ohmic metal-semiconductor contacts are used to extract photocurrent from the 1 × 1 mm active area. The thin-film detector has a f_{3dB} of 5 kHz, which diminishes the amplitude of the interference fringes at high frequencies. This places an upper bound on the useful mirror scan length and, therefore, an upper bound on the spectral resolution of the device. For measurement of an interferogram with 40 kHz frequency components, the responsivity is ~ 5 μA/W with 35 V applied bias. In principle any material can be used for the detector, allowing for different wavelength operation regimes and potentially better frequency response.

The wafer planes were integrated by electroplating 5 μm of indium on both the mirror back plane and the detector frame. The three components were then aligned with the mirror back plane on the bottom, the moving mirror in the middle, and the detector plane on the top. The wafer stack was heated to 190 °C to melt the indium, and pressure was applied. Epoxy was applied around the edges of the frame to add mechanical strength. Electrical leads were soldered onto the two detector electrodes, the moving mirror electrode, and the back plane electrode. Finally, the integrated package was bonded with epoxy to a one-inch aluminum round, for easy mounting in a standard optics mount.

The integrated mirror is actuated by applying a voltage between the back plane electrode and the gold-coated back of the mirror center square, while the 13 × 13 mm front plane frame is held fixed. The capacitance of this parallel-plate system is 2.6 pF, which keeps power consumption low. Driven with a 70.7 V_{pp} DC-offset sinusoid on-resonance at 593 Hz, the mirror moves almost perfectly harmonically with a total scan length of 13.7 μm. The high scan rate enables fast, continuous spectral analysis. The packaging helps dampen external vibrations that could couple to the moving mirror, and helps suppress the effect of air fluctuations. The packaging of all three planar components also guarantees alignment of the back plane electrode with the moving mirror center square, and more importantly, positional and angular alignment of the photodetector absorbing area with the moving mirror reflective surface.

The detector photocurrent is measured via a high-pass filter with f_{3dB} at 10 kHz, to filter DC dark current and parasitic mirror drive noise. A low-noise current amplifier provides gain of 5×10^7 V/A, which is large enough to accommodate the signal attenuation due to interferogram frequencies well beyond the detector f_{3dB}. The interferogram is sampled by a digital oscilloscope and transferred to a computer, where the 'current vs. time' curve is mapped to a 'current vs. mirror displacement' curve, accounting for the nonlinear mirror motion. Finally, a discrete Fourier transform yields the optical spectrum. Figure 2 is the spectrum calculated from an interferogram recorded for an input mixture of a laser diode beam (665 nm at 390 μW) and a HeNe beam (633 nm at 200 μW). Significant power was wasted due to the diode laser's elliptical beam shape. The unequal peak heights in Fig. 2 correspond to different absorbed power levels. Using the 633 nm source to calibrate the spectrometer, the 665 nm source is correctly identified and well discriminated, yielding a spectral resolution of 32 nm, or 724 cm^{-1}.

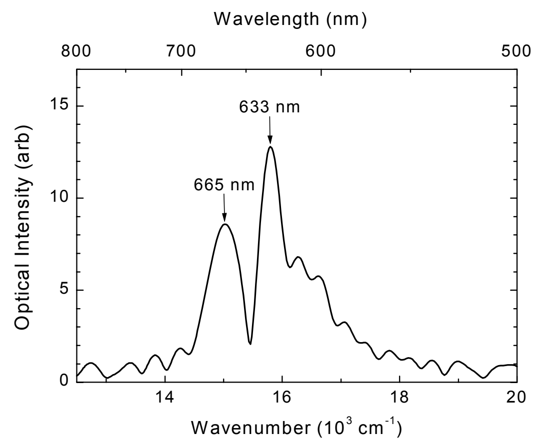

Fig. 2: Optical spectrum of 633 nm, 665 nm mixed input.

In conclusion, we have demonstrated an integrated standing-wave spectrometer with 32 nm resolution at λ = 665 nm. This compact, stable design is composed of three planar components that can be separately fabricated with different materials, in principle accommodating any wavelength range of interest. Each component can be easily produced in arrays, allowing the possibility of an imaging array of spectrometers.

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