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Miniaturized time-scanning Fourier transform spectrometer based on silicon technology

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We present a miniaturized Fourier transform spectrometer (FTS) based on optical microelectromechanical system technology. The FTS is a Michelson interferometer with one scanning mirror. A new type of electrostatic comb drive actuator moves the mirror. We have measured a nonlinearity of the driving system of ± 0.5 μm for a displacement of 38.5 μm. A method is presented to correct the spectrum to get rid of the nonlinearity. The driving reproducibility is ± 25 nm. The measured resolution of the spectrometer after the phase correction is 6 nm at a wavelength of 633 nm.

Fourier transform (FT) spectroscopy is a well-known technique to measure the spectra of weak extended sources. It offers distinct throughput and multiplex advantages, which provide higher signal-to-noise ratio performance than other methods.[1] However, commonly used FT spectrometers require a mirror-scanning mechanism with very high precision, resulting in large size and high cost. Low-cost, miniature spectrometers are key components that permit the realization of small-size, portable sensor solutions for applications such as color measurement and industrial process control. Therefore, recent investigations have dealt with low-cost, miniature spectrometers.[2,3] A spatially modulated FT spectrometer (e.g., a Michelson interferometer with a tilted mirror and a photodiode array) is compact and has no moving parts.[4] However, stationary FT spectrometers have poor resolution and do not benefit entirely from the throughput advantage. We report here on a FT spectrometer with a moving mirror that is extremely compact (5 mm $\times$ 4 mm) and has a scanning system that allows precise motion of the mirror. Low-cost fabrication is possible thanks to the use of silicon technology.[5]

A schematic of the actuator and the basic concept of FT spectroscopy are shown in Fig. 1. In FT spectroscopy we measure the intensity variation $I_R(\delta)$ as a function of the optical path difference δ when a partially coherent plane wave is introduced into a Michelson interferometer. The relation between I_R and δ is known as an interferogram. The power spectrum $B(\sigma)$ and the recorded intensity modulation $I_R(\delta)$ are related by a Fourier transform:

$$B(\sigma) = \int_{-\infty}^{\infty} I_R(\delta)\exp(-i2\pi\sigma\delta)\,\mathrm{d}\delta\,, \tag{1}$$

where σ is the wave number ($\sigma = 1/\lambda$). The theoretical resolution of a FT spectrometer is given by

$$\Delta\sigma = 1/\delta_{\max}\,, \tag{2}$$

where $\delta_{\max} = 2\Delta x_{\max}$ and $\Delta x_{\max}$ is the maximum displacement of the mirror.

Electrostatic comb drive actuators are widely used in microelectromechanical systems because of their simple construction and reliable operation. These actuators permit a considerable displacement of as much as 100 μm,[6] but they cannot drive large loads. Therefore applications are mainly found in the area of optics in which no output force is needed.[6] Nevertheless, in many optical applications, such as Michelson interferometers and linear shutters, one would like to have a displacement that is linear to the applied voltage. Since a conventional comb drive actuator has a voltage-displacement response that is quadratic, other actuator principles, such as piezoelectric or electrodynamic principles, are used. However, these principles can hardly be implemented on silicon. The new design of the actuator that drives the movable mirror in our FT spectrometer permits a linear voltage-displacement response. To obtain linear motion of the mirror we place two identical comb drive actuators (A and B in Fig. 1) opposite each other. When the voltage on comb A is kept constant and is exactly the opposite of V_B, i.e.,

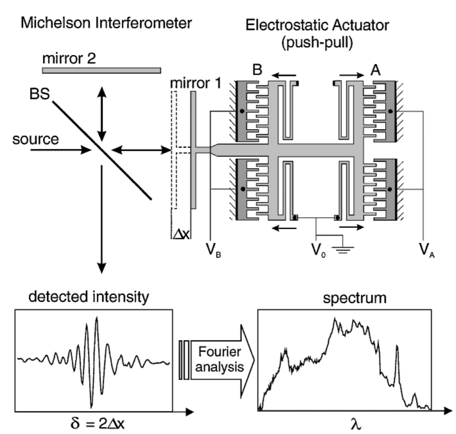

Fig. 1. Schematic of the actuator used for FT spectroscopy: Right, arrangement of the comb electrodes that provide a linear displacement–voltage response that is used for driving the mobile mirror (mirror 1); left, Michelson interferometer. The detected intensity I_R is recorded as a function of the optical path difference δ. $I_R(\delta)$ is Fourier transformed to yield the power spectrum. BS, beam splitter.

$V_A = -V_B$, the displacement Δx is

$$\Delta x = \frac{1}{k}\,\varepsilon_0 n\,\frac{h}{g}\,2V_A V_0\,, \tag{3}$$

where k is the spring constant of the suspension springs, h is the height of the comb fingers, g is the gap between the comb fingers, n is the number of comb fingers on the mobile comb, and ε_0 is the electric permittivity. The maximum displacement of the electrostatic comb drive actuators is limited by the lateral stability of the combs.[7] With proper design, a maximum displacement $\Delta x_{\max}$ of 80 μm can be achieved, which gives a maximum optical path difference $\delta_{\max}$ of 160 μm. For such a displacement the spectroscopic resolution at 633 nm is estimated to be $\Delta\lambda = \lambda^2/\delta_{\max} \approx 2.5$ nm. With our device we obtained $\delta_{\max}$ of 77 μm, yielding a spectroscopic resolution of 5.2 nm at 633 nm. The applied voltage V_0 was ± 10 V. The actuator and mirrors 1 and 2 in Fig. 1 are fabricated in one etch step by deep dry etching of silicon on insulating wafers. To enhance the reflectivity of the plasma-etched mirrors we coat them with a thin layer of aluminum. The chip has a hole through the wafer to accommodate a beam splitter or a beam-splitting plate. The mirrors have a height of 75 μm and a length of 500 μm (see Fig. 2).

To characterize the performance of our device we recorded the interference signal $I_R(\delta)$ produced by focusing a He–Ne laser on the two mirrors. The scan frequency of the mobile mirror is 1 Hz, and the number of sampling points is 1400. We carred out experiments to study an eventual hysteresis effect (the difference between the two directions of the motion) as well as the linearity of the mobile mirror at full performance ($V_0 = \pm 10$ V). No significant hysteresis was observed for V_0 of ± 5 V, corresponding to an optical path difference of 40 μm. The hysteresis in the power spectrum (He–Ne line) is better than 1 nm (Fig. 3). At full performance ($V_0 = \pm 10$ V and $\delta_{\max} = 77$ μm), we observed a drive nonlinearity $\Delta\delta(\delta)$ as great as ± 1 μm as well as a hysteresis effect (Fig. 4). These effects come mainly from the change of the capacitance between the two combs when the displacement Δx becomes large.[8] To get rid of the drive nonlinearity we make a phase correction. We then correct the Fourier transform [Eq. (1)] by taking into account the interferometric measurements of $\Delta\delta(\delta)$:

$$B(\sigma) = \int_{-\infty}^{\infty} I_R(\delta)\exp\{-i2\pi\sigma[\delta + \Delta\delta(\delta)]\}\mathrm{d}\delta\,. \tag{4}$$

Figure 5 shows the spectrum of a He–Ne laser before and after the phase correction. After the correction, the resolution is 6 nm (at 633 nm), which is close to the theoretical limit. The correction applied to one scan is applied to other scans in the same direction, resulting in a resolution that is always better than 10 nm. The reproducibility of the mirror position from the optical path difference is ± 25 nm.

A low-cost miniaturized (5 mm $\times$ 4 mm) time-scanning FT spectrometer with a moving mirror activated by a new electrostatic actuator design has been realized. The feasibility of the device has been

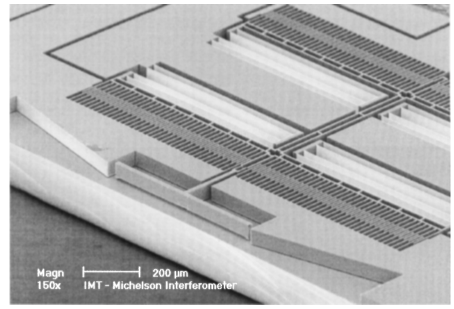

Fig. 2. Scanning electron microscopy photograph of the electrostatic actuator, showing the 75 μm $\times$ 500 μm movable mirror, the combs, and the springs.

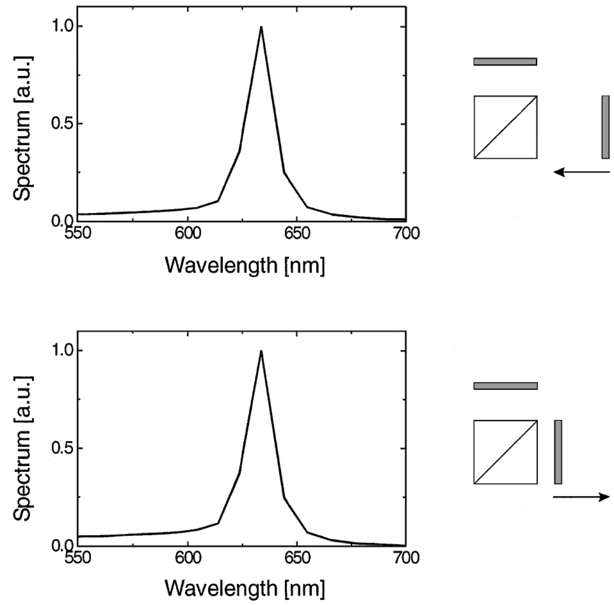

Fig. 3. Two spectra of a He–Ne laser measured for both (backward and forward) directions of the mobile mirror ($V_0 \pm 5$ V and $\delta = 40\mu$m). The wavelength hysteresis is better than 1 nm.

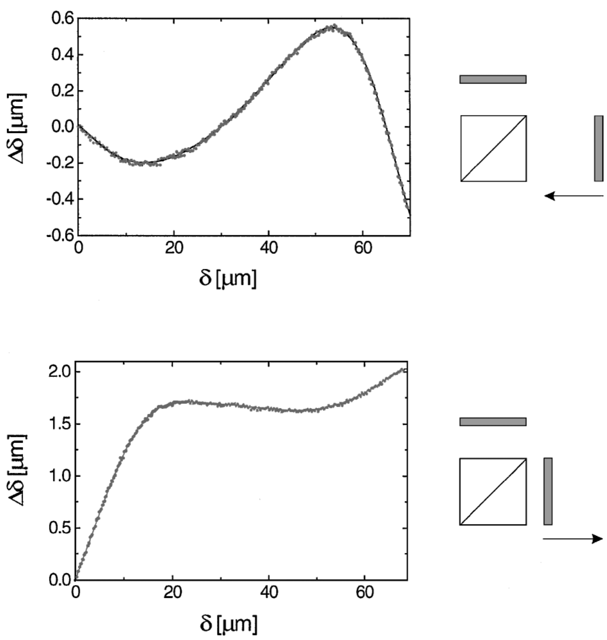

Fig. 4. Nonlinearity $\Delta\delta(\delta)$ of the mobile mirror. Results of the interferometric measurements for both directions of the motion.

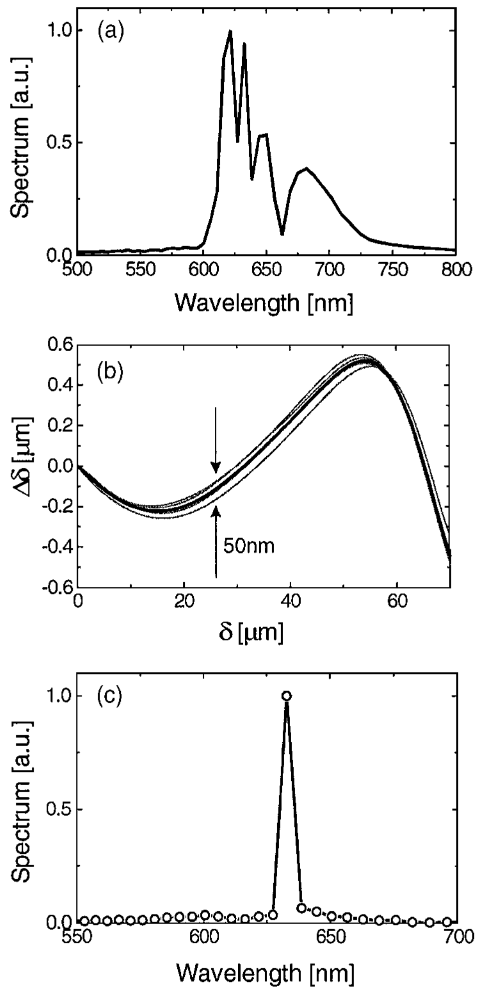

Fig. 5. Spectrum of a He−Ne laser ($V_0 = \pm 10$ V and $\delta_{\max} = 77\ \mu$m) (a) before and (c) after phase correction. (b) Deviation of the nonlinearity $\Delta\delta(\delta)$ for several scans in the same direction. The reproducibility of the mirror motion is better than ±25 nm.

demonstrated by preliminary measurements with a He−Ne laser. From the recorded interferograms it appears that the movable mirror has a drive nonlinearity of ∼1.3%. This inhomogeneity is not present at tensions $|V_0|$ smaller than 5 V. For larger tensions (as great as 10 V) we have applied a phase correction calculated from interferometric measurements of the nonlinearity $\Delta\delta(\delta)$ of the mobile mirror. The correction gives a spectrum of the He−Ne line with a resolution of 6 nm. The same correction has been applied to other scans, yielding a resolution better than 10 nm. The repeatability of the motion of the mirror is better than ±25 nm. The resolution is good enough for applications such as industrial color sensors. In addition, the elongated geometry of the mirror allows us to benefit from the Connes advantage[9] by using a reference wavelength simultaneously.

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