IMAGING GIGAHERTZ DYNAMICS IN MICROMECHANICAL RESONATORS USING ULTRAFAST PULSED LASER INTERFEROMETRY

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ABSTRACT

Optical measurements of resonant MEMS can provide direct insight into their dynamics and guide improvements in device performance. This paper presents an optical method based on pulsed laser interferometry that can measure vibrations of MEMS resonators under coherent RF excitation with sub-picometer resolution and at arbitrary frequencies potentially well beyond 10 GHz. Vibration amplitude and phase can be measured across the entire resonator, thereby enabling experimental modal analysis and the imaging of complex dynamics, including mode mixing.

INTRODUCTION

Resonant MEMS operating at frequencies above 1 GHz [1,2] are of great interest for efficient filtering and signal processing in wireless communications and advanced computing. However, the performance of these resonators is still not well understood, including their nonlinear dynamics, dissipation mechanisms, and vibrational modes. This is largely due to limitations in the measurement tools that are available. For example, electrical RF test equipment, although widely used, cannot provide information on mode shapes or the causes of acoustic loss. This paper presents a new interferometric approach that can measure vibrations beyond 10 GHz with sub-picometer resolution, which provides direct insight into the dynamics of resonators operating above 1 GHz.

Conventional optical methods, including interferometric [3], photoelastic [4], and knife-edge techniques [4], use a continuous-wave (CW) laser whose frequency, phase, or intensity is modulated by resonator vibrations. For these methods, a photodetector with bandwidth greater than the vibration frequencies of interest must be used to measure the optical signal. However, resonator vibrations typically become progressively smaller with increasing frequency. Furthermore, the noise in photodetectors and amplifiers, parasitic capacitance and coupling in cables, and electromagnetic interference all increase with increasing frequency. The combination of these issues makes the use of conventional CW optical methods above 1 GHz extremely challenging.

INTERFEROMETRIC METHOD

Due to the above limitations, we have developed a new approach using ultrafast pulsed laser interferometry (PLI) (Fig. 1(a)) that addresses these issues. The laser pulse train forms an electrical frequency comb with individual teeth equally spaced by the repetition rate (f_p), as measured using a fast photodetector (Fig. 1(b)). By tuning f_p , one of the comb frequencies ($n*f_p$) can be placed close to the resonator excitation frequency (f_{ex}), with a measurable offset ($f_b = |f_{ex} - n*f_p|$). Thus, the laser pulse acts like a strobe that mixes down high-frequency vibrations to a beat signal, f_b . A low-bandwidth photodetector is used to measure f_b , which is processed with a lock-in amplifier. While stroboscopic interferometric techniques have been previously reported, they have been limited to operation either below 1 GHz [5] or at discrete, widely separated frequencies [6]. Our approach works at any frequency above 0.95 GHz and has a noise floor comparable to a CW interferometer operating below 1 MHz (≈ 30 fm/ $\sqrt{\text{Hz}}$, which is shot noise limited).

RESULTS AND DISCUSSION

Vibration results for two MEMS resonators are presented here. The first is a silicon width-extensional bulk acoustic resonator (BAR) [4] with a third-order in-plane mode around 0.983 GHz (Fig. 2(a)). The out-of-plane displacement is measured, which results due to the Poisson effect. The excitation was swept by 1 MHz around resonance, beating with the 19th tooth (981.35 MHz) of the comb ($f_p = 51.65$ MHz). The frequency response found with PLI is compared to that obtained by conventional CW laser interferometry in Fig. 3. The signal-to-noise ratio (SNR) is already 4 dB better for PLI while only just approaching 1 GHz. Figure 4 shows surface maps of the vibration amplitude (≈ 3 pm) and phase for the third-order mode.

Figure 1: (a) Schematic of the ultrafast pulsed laser interferometer (PLI) (BS: beam splitter, PBS: polarizing beam splitter, PD: photodetector, M: mirror, $\lambda/4$ WP: quarter wave plate, OL: objective lens). (b) Power spectrum of the laser pulse train measured with a 12.5 GHz fast photodetector, showing a frequency comb with individual teeth spaced by the pulse repetition rate (50.00 MHz). The maximum operational frequency of the PLI is set by the bandwidth of the fast PD, the splitter, and the mixer.

Figure 2: (a) Optical micrograph of a silicon width-extensional bulk acoustic resonator (BAR) with a width of 11.5 μm . Its measured third width-extensional mode is approximately 0.983 GHz. (b) Optical micrograph of an AlN bulk acoustic wave (BAW) transducer with a measured resonance frequency of approximately 2.35 GHz. The transducer size is 75 $\mu\text{m} \times 75 \mu\text{m}$.

Figure 3: Frequency response of the BAR obtained by (a) pulsed laser interferometry and (b) CW laser interferometry. The resonator was operated in air with +10 dBm RF power and 21 V DC bias. The center frequencies differ slightly due to thermal drift and internal frequency inaccuracies in the different RF instruments used.

Figure 4: Mapping the BAR vibrations at 0.9827 GHz using pulsed laser interferometry: (a) vertical vibration amplitude and (b) phase. Drive conditions: 21 V DC bias and +10 dBm RF power. The dashed lines represent the outer dimensions of the BAR, $11.5 \mu\text{m} \times 65 \mu\text{m}$. The amplitude map clearly shows the expected third-order width-extensional mode. The phase transition along the width of the resonant body is nearly 180° , as expected.

Figure 5: Frequency response of the AlN BAW obtained by pulsed laser interferometry, while operated in air with +10 dBm RF power: (a) mechanical resonance at 2.35 GHz and (b) up to 8 GHz.

Figure 6: Mapping the BAW vibrations at 2.351 GHz: (a) vibration amplitude and (b) phase. The dashed lines represent the perimeter of the BAW. The mode shape shows the superposition of the main thickness mode with other lateral resonance modes.

The second device is an AlN bulk acoustic wave transducer (Fig. 2(b)) [7]. Its fundamental mode at 2.35 GHz is extremely difficult to measure using CW laser techniques. Since the resonance linewidth spans multiple comb teeth, the measurement is performed here by using a series of teeth ($f_p = 50.0$ MHz) while f_b is kept constant. The frequency response of the first thickness mode is shown to have an SNR of nearly 30 dB (Fig. 5(a)) and the BAW can be measured out to 8 GHz (Fig. 5(b)). The vibration amplitude and phase maps (Fig. 6) show the superposition of multiple modes, demonstrating that PLI can reveal complex dynamics. Since both displacement and phase are obtained, animations of modes can be generated, making PLI an invaluable tool for investigating the dynamics of gigahertz resonators.

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