Nanomechanical resonant structures as tunable passive modulators of light

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We report on the optical parametric excitation of silicon nanomechanical resonant structures. The threshold laser power needed to set these structures into self-oscillation was estimated to be around 70 μW. We measured resonant frequencies of up to 38 MHz by optical excitation; this method should extend to much higher frequencies. Under optical amplification of motion, the spectral response at resonance narrowed to the equivalent of a mechanical quality factor >20 000 at room temperature. These structures act as frequency tunable passive modulators of light, requiring no additional drive. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1479209]

Nanomechanical resonant structures, created using advanced lithography, have been of interest for a variety of reasons and measurements of them yield insight into physics that was previously inaccessible in fabricated structures.[1–4] Potential applications are similar to those of microelectromechanical structures (MEMS) and include sensitive mass detectors,[5] scanning probes,[6] reference oscillators and filters in wireless communications,[7] and optical network crossconnects.[8] Many of these applications rely on the devices' oscillation at their resonant frequencies. One advantage of using nanomechanical structures over MEMS is a decrease in the size of the mechanical structures accompanied by an increase in the resonant frequency (high rf and microwave range). Previously published driving schemes for nanomechanical resonant structures include electrostatic force,[3,4] Lorentz force,[1,2] and inertial excitation using a piezo crystal.[9] This is the first report in which structures with dimensions below a micrometer have been actuated by light. This driving method utilizes the thermal effects induced by low-power unmodulated laser light coupled to the mechanical motion. Recently we reported on the optical drive and parametric amplification[10,11] of the motion of ~10 times larger MEMS structures with ~40 times lower resonant frequency, using a similar effect. Some of the advantages to the all-optical drive and detection scheme include the absence of any other electric or magnetic fields and operation over a wide range of temperatures. Parametric amplification of the mechanical vibration with light[10] (which causes self-oscillation) is induced by the interferometric pattern created by the light reflected from the mechanical structure and the substrate underneath (the two create a Fabry–Pérot cavity).[3] The modulation of the spring constant is achieved by the laser light heating (and its temperature gradient) which induces the compressive stress pushing the structure up/down. Energy pumping at twice the resonant frequency occurs as the structure moves away from the equilibrium position through a peak absorption (hotter) region of the light pattern in one part of the cycle. Both amplification and damping of the motion were observed by studying identical structures fabricated on different substrates, thereby shifting the location of the light intensity extrema.

One set of structures was fabricated on commercially available silicon-on-insulator (SOI) substrates having a 205 nm film of single-crystal silicon on 400 nm of buried silicon dioxide (205/400 nm substrate). The other batch was fabricated on a 250/1000 nm substrate. The fabrication process has been described elsewhere.[4] The doubly clamped paddles (inset of Fig. 1) had resonant frequencies from 4 to 25 MHz. We also measured doubly clamped silicon beams, 7 μm long and 200 nm wide, each with a resonant frequency of 38 MHz.

The devices were driven in a vacuum of about 10^{-6} Torr. A 17 mW HeNe laser at 632.8 nm was used for optical drive and detection.[3,4] The reflected light modulated by the movement of the structure was detected by a photodetector and sent to a spectrum analyzer. The laser spot had

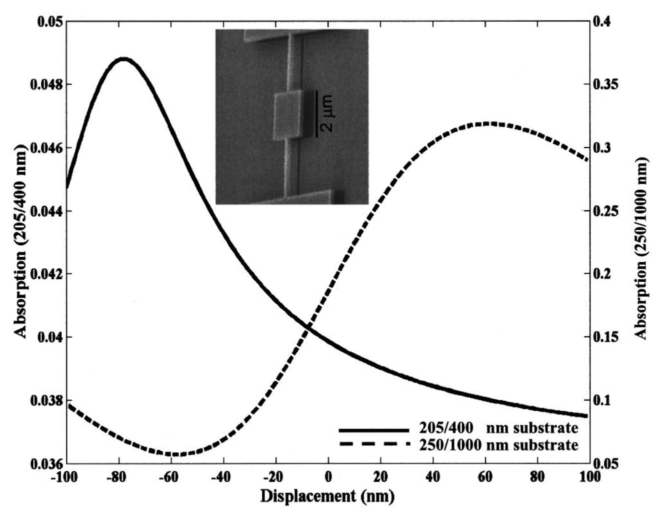

FIG. 1. Calculated absorption of 632.8 nm light in the device on a 205/400 nm (solid line) and 250/1000 nm (dashed line) silicon/vacuum-gap substrate plotted against the displacement of the device, a doubly clamped silicon paddle (shown in the micrograph inset) over the given displacement range. As the laser power is increased, the energy added to the device causes the range of motion to include the absorption peak (for 205/400 nm) and absorption minimum (for 250/1000 nm).

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a diameter of about 5 μm, completely covering the 2×2 μm paddle. The paddle geometry was chosen because it can absorb large amounts of light and the much smaller arms provide a pathway for diffusing heat on the time scale needed. Figure 1 shows the calculated absorption of light[12] as a function of the device motion for the two different substrates.

The heating of the structures in this study can be approximately described as that of a uniform beam where the heating in the middle will cause compressive stress, σ, given by[13]

$$\sigma = E \alpha \Delta T$$

where E is Young's modulus, α is the thermal coefficient of expansion, and ΔT is the temperature increase due to heating. For the flexural mode,[4] ΔT modulates the spring constant of the structure, thus affecting its resonant frequency, f_0, according to[14]

$$\frac{1}{f_0}\frac{df_0}{dT} = -\frac{6\alpha L^2}{\pi^2 h^2},$$

where L and h are the length and thickness of the beam, respectively. The frequency of the structure determines the rate at which the modulation is achieved. There are two reasons why this driving scheme works for small structures and will work at much higher frequencies; the mechanical quality factor (Q) before the self-oscillation starts is sufficiently high, 5000–7000, the importance of which will be discussed below, and the heat diffusion time constant for the structures is similar to their period of oscillation. Because of the matched time scales, the structures can cool and heat sufficiently fast in one cycle of oscillation thus allowing the spring constant to be efficiently modulated within one cycle of oscillation. For example, the oscillation period observed for a structure with 4.5-μm-long arms was 2.2×10^{-7} s. We calculate the heat diffusion time constant, t, using

$$t = \frac{l^2}{D},$$

where D is the thermal diffusivity of single crystal silicon and l is the characteristic length scale. The time constant thus obtained is 8×10^{-7} s, on the same order of magnitude as the oscillation period. For a uniform beam, the oscillation period and the heat diffusion time constant both scale as l^2. Thus, the viability of this technique can be extended to the size (and thus frequency) range of as small a structure as can be fabricated.

As expected, we observe a linear decrease in the resonant frequency with regard to the laser power on both substrates when the structures are driven with a piezo element below the light-induced self-oscillation threshold. For the 4.5 μm long arm, a change in the measured laser power of about 50 μW corresponds to an estimated temperature change of about 0.5 K. The actual power absorbed can be estimated by the change in the frequency; this analysis gives us an absorption coefficient of about 0.036. The frequency of the structure was observed to change by as much as 15% when the laser power was varied by 1.2 mW.

From the measured Q factor before self-oscillation, and from the fractional decrease in the resonant frequency

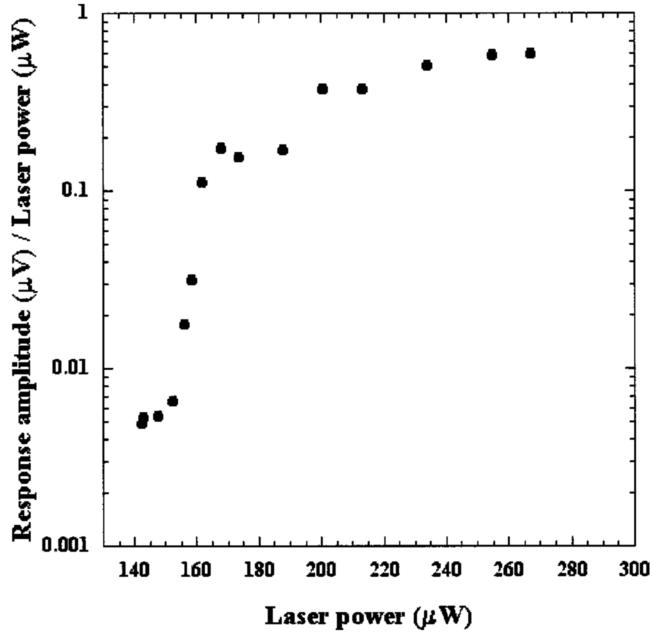

FIG. 2. Onset of self-oscillation in a paddle (normalized by the laser power) vs the estimated laser power illuminating the device (not adjusted for the actual power absorbed in top layer silicon). The amplitude refers to the optical amplitude as detected by a photodetector. The device is fabricated on a 205/400 nm substrate.

($\Delta f_0/f_0$) versus the laser power we calculate the threshold power needed for the self-excitation according to[15]

$$\frac{1}{Q} = \frac{\Delta f_0}{f_0}.$$

The calculated threshold laser power needed for the self-oscillation of a 4.5-μm-long support structures was found to be about 70 μW whereas the measured threshold power was about 140 μW (Fig. 2). The calculated and the measured value are within the experimental error due to the defocusing of the laser beam.

Whereas the vibration of a structure on the 205/400 nm substrate is amplified as the laser power is increased (Fig. 2), the motion of the 250/1000 nm substrate structure is damped. We expect this to happen if an absorption maximum (for 205/400) as opposed to an absorption minimum (for 250/1000), as in Fig. 1, is closer to the equilibrium position of the structures. Due to the slight sagging of the structures (which we observe) the respective absorption extrema are indeed closer to the equilibrium point. We also expect to see a narrowing in frequency of the resonant response for the amplified motion of the (205/400) structures due to the deviations from the Lorentzian line shape caused by the nonlinear nature of the parametric amplification. This narrowing of the resonant response can be expressed as a quality factor, Q^*, given by the ratio of the resonant frequency to the half-width of the power spectral response. The enhanced Q^* values measured for these structures were up to 30 000, compared to 5000–7000 before self-oscillation and the amplitude increased by 3 orders of magnitude (Fig. 2).

We have also observed laser light modulation by the resonant structures. Figure 3 shows a longitudinal laser mode beat frequency at 1.024 GHz modulated by the structure's resonant frequency. If the incoming laser light is at ω_L, the

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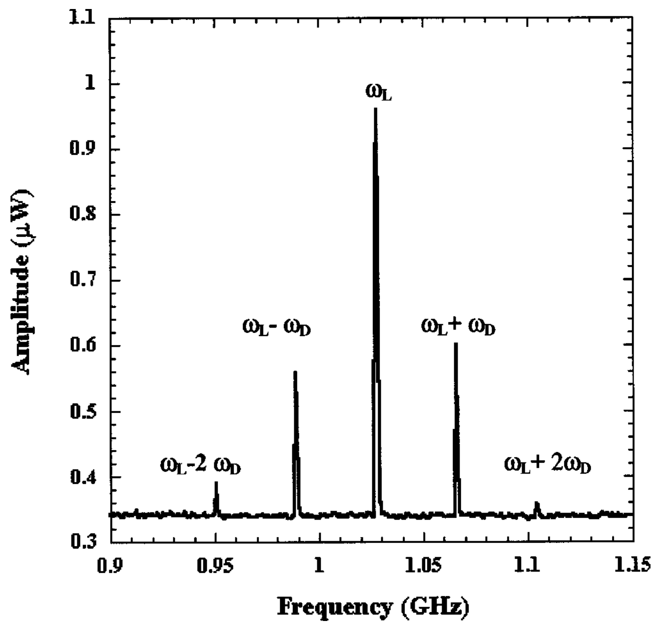

FIG. 3. Multiple of a laser cavity longitudinal mode beat (caused by the mode spacing at 256 MHz) at 1.024 GHz (ω_L) modulated by the motion of an 7-μm-long resonating silicon wire at its resonant frequency, 38 MHz (ω_D). First-harmonic modulation can also be seen.

laser mode frequency, and the device modulates the light at its resonant frequency, ω_D, then the reflected light has components at not only ω_L and ω_D but also $\omega_L \pm \omega_D$. Hence the devices act as passive modulators of the laser light at their resonant frequencies requiring no external drive (unlike other optomechanical modulators[16]). This particular scheme can be used for modulation of light at the rates determined by the resonant frequency of the devices and a tunable laser can work over a range of device/gap thicknesses to achieve the desired modulation conditions.

Signal processing at high frequencies, such as frequency conversion, is easily achieved with these nanomechanical structures. In the above example, the laser mode acts as the reference (local) oscillator and the mechanical oscillation as the low frequency signal to be shifted in frequency. As with rf mixers, the two signals are multiplied, producing signals at new frequencies as described above. Furthermore, the resonant frequency of the mechanical device is easily tuned by the laser power and thus the carrier (mechanical oscillation) signal can be tuned. The detection and actuation method used here are so sensitive that even silicon beams as narrow as 200 nm produce enough signal to modulate the light. For even higher frequency applications one could consider small-cavity lasers such as many solid-state lasers which have a high-frequency mode spacing (~50 GHz) and very narrow spectral response. The instability of the mechanical oscillator frequency mainly comes from the fluctuations in our laser power. The frequency of the structure can be stabilized by a feedback loop to adjust the power of the laser which extends the applicability of these devices as laser power meters and feedback stabilizers.

In summary, we demonstrate an optical driving scheme for nanomechanical resonant structures with resonant frequencies up to 38 MHz and with a possibility of extending it to much higher frequencies. The devices act as very efficient tunable light modulators at their resonant frequency; a property that can be used for optical signal-processing applications.

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