

Fabrication and laser control of double-paddle silicon oscillators

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(Received 10 August 2004; accepted 24 January 2005; published online 18 March 2005)

We describe a fabrication technique for double-paddle oscillators based solely on wet etching, resulting in quality factors up to $8 \cdot 10^5$ at room temperature and in vacuum. The quality factor achieved is the highest demonstrated so far at room temperature. The fabrication procedure, not involving any dry etching step, represents a valid and low cost alternative to the other techniques previously presented. Laser excitation and resonance frequency tuning is shown to be applicable to these resonant structures and to be a useful alternative to mechanical and electrical excitation methods used so far, especially for applications in which a remote excitation system is required (e.g., in a high-temperature environment). © 2005 American Institute of Physics.

[DOI: 10.1063/1.1876972]

I. INTRODUCTION

Single-crystal mechanical oscillators have proved to be a powerful tool for different applications like magnetic force microscopy,¹ characterization of thin films at low temperature,² study of metallic films at high temperature,³ torque magnetometry,⁴ and investigation of quantum effects.⁵ The key property is the very small damping (high quality factor) of these oscillators. In 1978 McGuigan and co-workers⁶ measured a quality factor of about $2 \cdot 10^9$ for a longitudinal mode of a single-crystal silicon cylinder of mass 4.9 kg at 3.5 K. This result stimulated further efforts to improve the mechanical performances of microfabricated structures. An important development in this field was the double-paddle oscillator (DPO) by Kleiman and co-workers.⁷ A further improvement in the quality factor of single-crystal oscillators was obtained by Pohl and co-workers at Cornell University, who produced and used DPOs to study elastic properties of thin metal films.² A typical DPO is shown in Fig. 1. Six different eigenmodes of this type of oscillator have been identified in the frequency range between 0.1 and 6 kHz.⁸ One of them, an antisymmetric torsion mode, exhibits its very small losses and insensitivity to thermal cycling. Its quality factor was found to be about $3 \cdot 10^5$ at 300 K and on the order of $8 \cdot 10^7$ at 4 K.⁹ The difference between this result and the values reported by McGuigan and co-workers suggests that there could be still room for further improvements of the DPOs. Moreover, recent studies of the thermoelastic effect in single crystal micromechanical oscillators¹⁰ have

confirmed that the internal friction observed below 60 K cannot be explained in terms of thermoelastic losses.

Inspired by a proposal of Price,¹¹ we set up an experiment in which a DPO is used as a resonant sensor to detect the dynamical gravitational field generated by a mass, which is periodically moved in front of the oscillator. The goal of this experiment is to test the validity of Newton's gravity law at distances smaller than 1 mm.¹² In the present work we report on the fabrication of DPOs produced for this experiment, which differs from the standard procedures used in the previously cited works. We evaluate our fabrication method with respect to the oscillators' performance. We also show actuation of DPOs by means of a laser beam and control of their torsional constant. Optical actuation of resonant microstructures has been previously applied by different groups.¹³ This technique has not yet been reported for DPOs. It does not require the DPOs to be conducting and does not need any electrodes in proximity of the DPOs unlike the electrostatic excitation.⁸

II. THE DOUBLE-PADDLE OSCILLATOR

A. Theoretical considerations

As shown in Fig. 1, a DPO consists of two masses, denoted by head and wings, that are connected by a torsion rod, the neck. The wings are connected to the base, the foot, by another torsion rod, the leg. This system can be modeled as a coupled oscillator consisting of two masses (head and wings) and of two springs (neck and leg). Since each spring can be twisted or bent in different directions, several vibration modes exist. In the present work we will restrict attention to an antisymmetric torsion mode, known in literature as AS2.⁸

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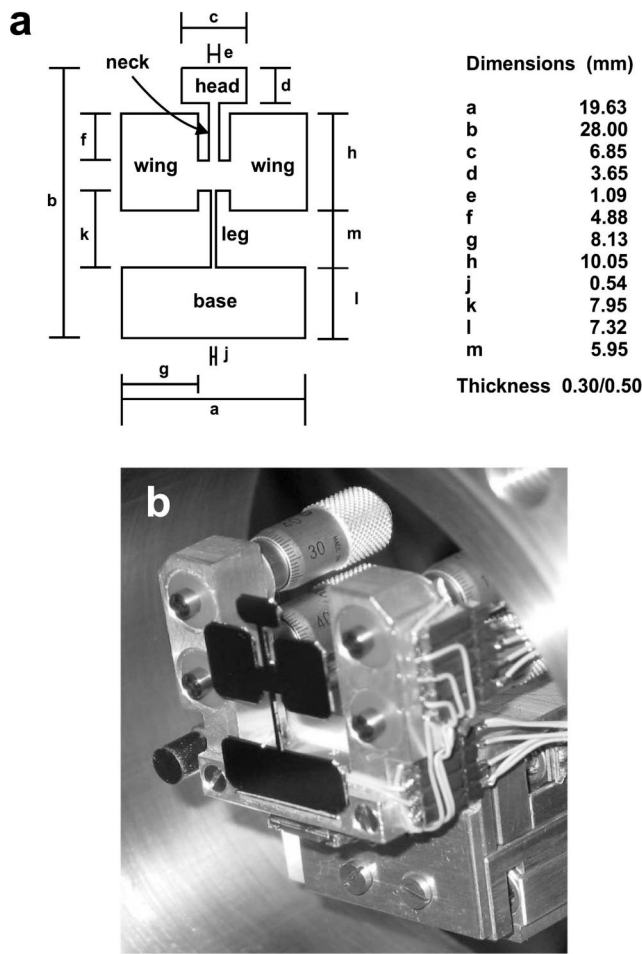


FIG. 1. (a) Dimensions of the double-paddle oscillator. (b) The DPO mounted on an aluminium holder, that is provided with a set of distance sensors used in our experiment to test gravity at small distances (see Ref. 12).

It consists of a twist of the neck around its length and a synchronous oscillation of the wings around an axis orthogonal to the DPO symmetry axis. The oscillations of head and wings are out of phase.¹⁴ This mode is particularly interesting because of its very low internal losses.

The resonance frequency of the mode AS2 is given, to first approximation, by¹⁵

$$\nu_0 = \frac{1}{\pi} \sqrt{3} \sqrt{\frac{1}{c^3 d} g t^2 \frac{\beta}{\rho f' e}}, \quad (1)$$

where c is the full width of the oscillator head, t is the oscillator thickness, f' is the neck length, e is the neck width, d is the height of oscillator head, $g = 61.7$ GPa the shear modulus of silicon about the (100) orientation,¹⁶ and β is a parameter, that depends weakly on the ratio t/e . In our calculations β is equal to 0.25.¹⁷

A parameter, which characterizes the damping losses for each mode, is the quality factor. It can be easily determined by exciting the oscillator at resonance, then turning off the excitation and following the decay of the oscillation amplitude. From this decay the ring-down time τ is determined. The quality factor is then given by the relation $Q = \pi \nu_0 \tau$.

Even in absence of external drive, the oscillation amplitude does not vanish completely. This is due to thermodynamic fluctuations. Internal dissipation in silicon is the coupling mechanism between the microscopic fluctuations and the macroscopic state of motion of the oscillator as stated by the fluctuation-dissipation theorem.¹⁸ This intrinsic noise can be quantitatively described using the theory of Brownian motion, in which a fluctuating thermal force, known as Langevin force, is responsible for the oscillator excitation. For a torsional oscillator, like the DPO, the power spectral density of the Langevin torque is given by

$$S_L = \sqrt{\frac{\pi k_B T m c^2 \nu_0}{3Q}}, \quad (2)$$

where m is the mass of the oscillator head and T is the temperature. The power spectral density of the oscillator angular deviation ϑ at resonance is then given by

$$S_{\vartheta}(\nu_0) = \frac{Q}{k} S_L, \quad (3)$$

where $k = (2\pi\nu_0)^2 I$ is the torsional spring constant of the oscillator and $I = \frac{1}{3} m c^2$ is its momentum of inertia around the vertical axis.

B. Fabrication technique

The DPO design we implemented is similar to the one developed by Pohl and co-workers.⁸ Its dimensions are shown in Fig. 1(a).

The oscillators were fabricated from a 300- μm - (or 500- μm -) thick, float zone refined, double-side polished, $\langle 100 \rangle$ oriented, and p -doped silicon wafer with a room-temperature specific resistance larger than 10 k Ω cm. On each side a 80-nm-thick silicon nitride layer had been thermally grown (Crystec). The wafer was laid on a clean room wipe and a small notch was scratched with a diamond scribe in the direction parallel to the crystal axis $\langle 100 \rangle$. The scribe tip was then put in the notch and pressed firmly. In this way the wafer was split in more samples having an edge parallel to the crystal direction $\langle 100 \rangle$.¹⁹ For cleaning, the sample was then immersed in boiling acetone and afterwards in boiling propanol for a few minutes. After blowing dry with nitrogen, the sample was put on a hot plate at 230 $^{\circ}\text{C}$ and at ambient pressure for 30 min in order to eliminate solvent residuals, that could degrade the quality of the sample surface. Since the most photoresists have bad adhesion on silicon nitride, a primer (Allresist, AR 300-80) was spun on each side of the sample. These thin layers were annealed at 170 $^{\circ}\text{C}$ for 3 min. Next, a positive photoresist (Allresist, AR 4040) was spun on both sides. The thickness of each layer was 1.4 μm . Baking at 95 $^{\circ}\text{C}$ for 3.5 min was required in order to temper the photoresist. To reproduce the oscillator pattern on the photoresist layer, the sample was put in contact with a chrome coated glass mask, on which the shape of the oscillator had been previously printed via scanning laser lithography. In order to minimize the mechanical losses of the DPO, it is important to carefully align the sample, so that the crystal axis $\langle 110 \rangle$ is parallel to the symmetry axis of the DPO.⁸ The sample was then exposed for 12 s to light from a mercury

short-arc lamp, which produced a radiation in the wavelength range between 350 and 550 nm. The intensity required for the exposure of the resist layer was 70 mJ/cm^2 . After developing in a 60% aqueous solution (by weight) of AR 3035 (Allresist) for 4 min, the sample was rinsed, blown dry and annealed at 110°C for 10 min. The bare silicon nitride was then stripped in a H_3PO_4 solution (concentration 85% by weight in water) at 140°C . Under these conditions an etch rate of about 1 nm/min was measured. After the conclusion of this step the nitride layer had been etched except in the area corresponding to the oscillator. In order to eliminate the residual photoresist, the sample was put in boiling N-methylpyrrolidone for about 15 min. The silicon etching was then performed in a KOH solution (30% concentration by weight in water) at 99°C . The measured etch rate was about $3 \mu\text{m/min}$. Next, the silicon nitride layer on the free standing structure was removed by HF solution (concentration 20% by volume in water) for 5 min. The oscillator was then rinsed and blown dry. The total time required to fabricate a DPO was about 5 h.

III. MEASUREMENTS AND RESULTS

A. Oscillator characterization

Since any coupling of the oscillator to the external environment would introduce mechanical losses, fastening it without degrading its mechanical properties is a crucial task. As suggested in Ref. 14, a small displacement during the oscillation takes place in the upper part of the foot. For this reason in our setup only the lower half of the oscillator foot was carefully glued with Stycast 1260 on an aluminium holder, as shown in Fig. 1(b). The oscillator holder was mounted on a piezoelectric transducer resting on a passive vibration isolation system to reduce the influence of seismic noise. This setup was operated in a high vacuum chamber (typical pressure 10^{-6} mbar and room temperature). In order to characterize the mechanical properties of the DPOs, an optical detection system was set up. A He-Ne laser beam was reflected by the DPO onto a split photodiode, which generated a photocurrent proportional to the amplitude of the angular displacement of the oscillator. This setup could detect a displacement of the laser beam of the order of 10^{-11} m in a bandwidth of 1 Hz. An electrical heater, mounted on the DPO support, allowed us to control the oscillator temperature. The temperature could be stabilized using an analog proportional integral differential controller. The measured temperature instability (in vacuum) was smaller than 10 mK over several hours.

The resonance frequency (and consequently the spring constant) is a function of the temperature of the oscillator. The temperature dependence of the resonance frequency has been measured, as shown in Fig. 2. The frequency-temperature coefficient, obtained from a linear fit, was found to be -169 mHz/K for a $300\text{-}\mu\text{m}$ -thick oscillator.

In order to determine the quality factor of the mode AS2, the oscillator was driven at resonance by the piezoelectric transducer. The excitation was then turned off. Using a lock-in amplifier the amplitude decay was measured. The result of a typical measurement is shown in Fig. 3(a). The

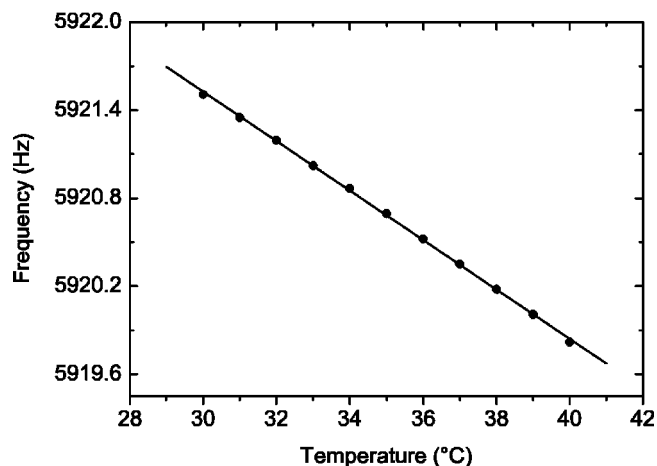


FIG. 2. Dependence of a $300\text{-}\mu\text{m}$ -thick DPO resonance frequency on the temperature.

experimental data were fitted by a single exponential function with a ring-down time $\tau=23 \text{ s}$, which corresponds to $Q=7.7 \cdot 10^5$ (oscillator thickness $500 \mu\text{m}$). This value exceeds any measurement previously reported in literature. Houston *et al.*¹⁰ have developed a model in which the quality factor of the mode AS2 is calculated assuming that the internal friction is due to the thermoelastic losses associated with a vibrational flexural component of this mode. Under this assumption the quality factor is given by

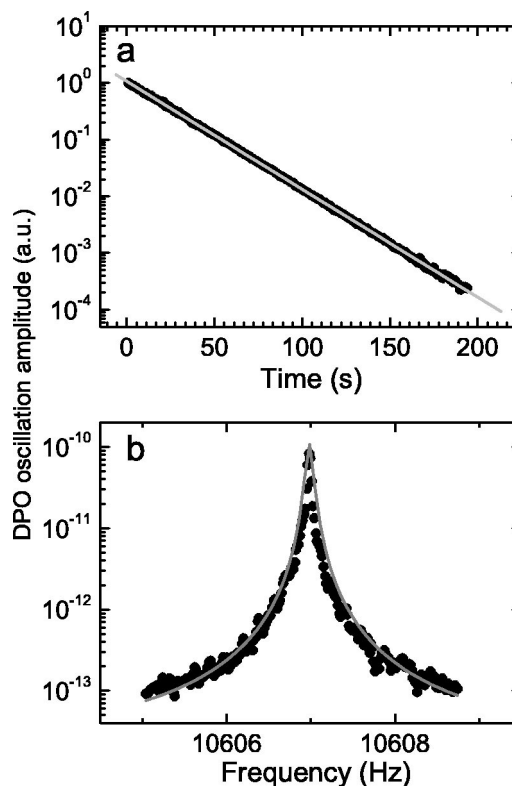


FIG. 3. (a) Ringdown measurement for a $500\text{-}\mu\text{m}$ -thick DPO at room temperature. The resulting decay constant is 23 s, which corresponds to a quality factor of $7.7 \cdot 10^5$. (b) Spectrum of the same oscillator excited by Brownian noise. The solid line represents a Lorentzian fit. The linewidth (FWHM) is 13 mHz.

TABLE I. Experimental characterization of different DPOs. The theoretical resonance frequencies for the mode AS2 are derived from Eq. (1).

Oscillator	1	2	3	4	5
Thickness (μm)	300	300	500	500	500
Measured res. freq. (kHz)	5.9	5.2	8.6	8.9	10.6
Calculated res. freq. (kHz)	5.3	5.3	8.9	8.9	8.9
Q factor at 300 K and 10^{-6} mbar	$2.0 \cdot 10^5$	$1.3 \cdot 10^5$	$2.6 \cdot 10^5$	$3.0 \cdot 10^5$	$7.7 \cdot 10^5$

$$Q = \left[p \frac{E\alpha^2 T}{\gamma} \frac{\omega_0 \delta}{1 + (\omega_0 \delta)^2} \right]^{-1}, \quad (4)$$

where p is the modal participation factor and is equal to the ratio of vibrational flexural energy relative to total modal energy, E is the Young's modulus, α is the thermal expansion coefficient, γ is the specific heat, ω_0 is the angular frequency of the mode AS2, and δ is the thermal relaxation time is given by

$$\delta = \frac{t^2 \gamma}{\pi^2 \kappa} \quad (5)$$

with κ as the thermal conductivity. Substituting the material properties of silicon²⁰ in Eq. (4) and using Eq. (1), it is easy to show that the quality factor of the mode AS2 scales as t^{-3} and is about $2 \cdot 10^5$ for a 300- μm -thick DPO. This value is in good agreement with our results for the thin oscillators. For the thicker oscillators the measured values are significantly higher than expected from Eq. (4). A possible explanation is a strong reduction in the modal participation factor with increasing thickness, a reasonable assumption, which overcompensates the factor t^{-3} .

The use of a passive vibration isolation system allowed to measure the excitation due to thermal noise. As shown in Fig. 3(b) the resonance curve has a Lorentzian form and its width [full width at half maximum (FWHM)] is $\Delta\nu = 0.013$ Hz, which implies a quality factor $Q = \nu_0 / \Delta\nu = 8 \cdot 10^5$ in good agreement with the results obtained from the ring-down measurement. The measured angular displacement due to the thermal noise is $6.2 \cdot 10^{-10}$ rad/Hz^{1/2}. Hereby, the electronic noise level of the detection system was $1.3 \cdot 10^{-11}$ rad/Hz^{1/2}. The expected value from Eq. (3) is $8.8 \cdot 10^{-10}$ rad/Hz^{1/2} at resonance. The difference between these values is due to the uncertainty in the material parameters and to the approximations in Eq. (1).

Table I summarizes the results of the characterization of different oscillators. The discrepancies between the calculated and measured resonance frequency are due to variations in the fabrication process. For example photoresist underetching due to a longer duration of the etching step caused the higher resonance frequency of one of the thicker oscillators. A comparison of our oscillators with others described in the literature^{21–25} is shown in Fig. 4.

B. Optical actuation

In the past, DPOs were mainly excited by electrostatic techniques. These require a metallic coating on the oscillator and the use of an electrode in the vacuum vessel.³ In some applications, e.g., detection of small forces, optical actuation represents a suitable alternative. Although already used for

different kinds of microoscillators,¹³ this approach has not previously been implemented for DPOs. The principle relies on the modulation of the intensity of a laser beam impinging on the oscillator. If the modulation is at the resonance frequency of the DPO, the periodic stress caused by the temperature modulation can couple to the oscillator mode. We have used a He–Ne laser (spot size ~ 1 mm²) to excite the DPO. The beam was positioned on the DPOs wing or neck. An acousto-optical modulator driven at the DPO resonance frequency by a signal generator produced a sinusoidal amplitude modulation of the laser beam output power. The modulation depth was nearly 100%.

In Fig. 5(a) the response of the DPO to a rectangular optical excitation signal with a peak power of 10 μW is shown. Figure 5(b) shows that the angular displacement of the oscillator head is proportional to the average power and to the power modulation amplitude of the laser beam. This measurement was for the laser beam impinging on the DPO wing. However, the efficiency of the excitation depends strongly on which part of the oscillator is illuminated. The strongest effect was measured when the laser beam was put on the bridge connecting neck and wings of the oscillator. This dependence allows, at least in principle, the use of previously calibrated DPOs as position sensitive photodetectors or as power meters. By comparing the signal and noise levels in Fig. 5(a), we can estimate that the minimum detectable power for a 300- μm -thick DPO is 10 nW in a bandwidth of 0.1 Hz. Its sensitivity could be enhanced through a strongly absorbing coating on the DPOs most sensitive area, which, where appropriate, could be also chosen to widen the spectral range of the detector. Figure 5(c) shows the effect of two counter-propagating beams impinging on opposite sides of

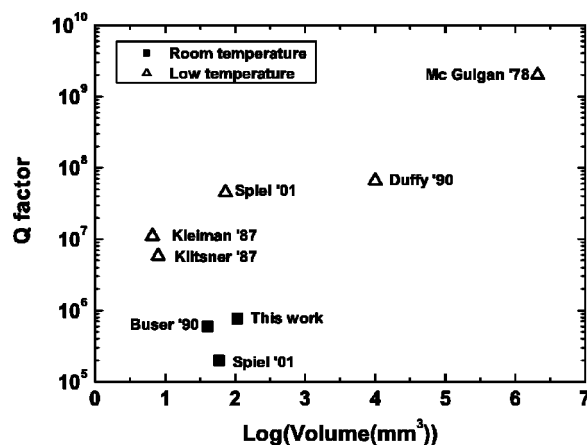


FIG. 4. Comparison of the quality factors of different macroscopic mechanical oscillators. (Picture adapted from Ref. 21.)

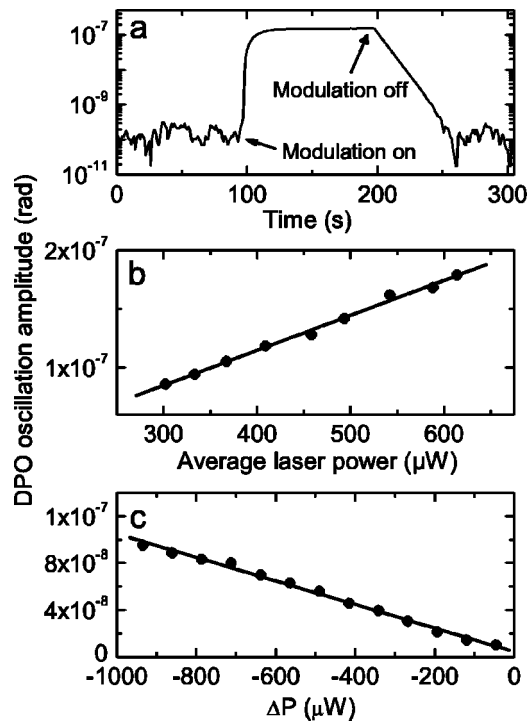


FIG. 5. (a) Response of the oscillator to laser power modulation, that was turned on at $t=93$ s and off at $t=195$ s. The fluctuations in the signal amplitude occurring when the laser is off, are due to Brownian noise of the oscillator. Lock-in time constant was 0.3 s. (b) Optical excitation of a DPO by a laser beam modulated at the oscillator's resonance frequency. (c) Optical excitation of a DPO by two counterpropagating laser beams, that impinge on the oscillator's wing. ΔP is the difference in the optical power of the beams.

the oscillator (see also Ref. 26). The angular oscillation amplitude of the DPO vanishes if the difference of the average power of the laser beams is equal to zero.

A second optical excitation method has also been studied. In this case the laser beam impinging on the oscillator had a constant average power, but its position was modulated. This was obtained by mounting a mirror on a piezoactuator driven at the resonance frequency of the AS2 mode. The laser beam reflected by the oscillating mirror onto the DPO causes a position dependent temperature modulation, which excites the oscillator. The DPO oscillation amplitude as a function of the scan amplitude is shown in Fig. 6(a). The laser optical power in this case was 5 mW. The DPO amplitude was found to be about 500 times larger than the thermal noise at room temperature. Figure 6(b) shows that the DPO amplitude is proportional to the optical power of the laser beam used for the excitation.

The DPO can also be frequency tuned by the laser. This was accomplished by illuminating the neck of the DPO with a laser beam with a constant output power. As shown in Fig. 6(c) the resonance frequency of a 300- μ m-thick DPO is a linear function of the laser beam average power. The measured frequency-power coefficient is -50 Hz/W. The optical power required to shift the DPO resonance frequency of $\Delta\nu = \nu_0/Q = 0.03$ Hz is 0.6 mW.

ACKNOWLEDGMENTS

The authors wish to thank M. Weingran, B. Sanvee (for their experimental help), Professor R. Pohl (for providing

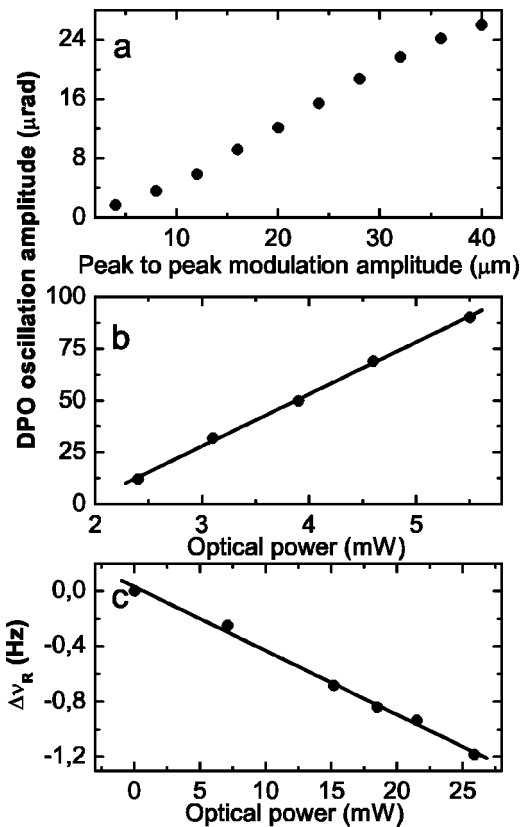


FIG. 6. (a) Excitation of a DPO by a laser beam scanned on the region connecting the wings to the leg. The laser power was 5 mW. (b) DPO excited by a position modulated laser beam. Here the scan amplitude is constant (40 μ m), but the laser power is varied. (c) $\Delta\nu_R$ is the shift of the resonance frequency induced by a continuous wave laser beam illuminating the neck of a 300- μ m-thick DPO.

them with paddles in the initial phase of this work), C. L. Spiel (for helpful discussions), D. Püttjer, M. Schneider, the staff of the Center for Semiconductor and Optoelectronics (ZHO) of the University of Duisburg, P. Dutkiewicz, R. Gusek, H. Hoffmann, W. Kussmaul, and W. Röckrath (for their technical support). One of the authors (L.H.) gratefully acknowledges the DAAD for a fellowship and V. White for proofreading this manuscript.

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