Synchronization of Coupled Optomechanical Oscillators

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Abstract: We demonstrate experimentally the synchronization of two micromechanical oscillators actuated by the optical radiation field. The mutual coupling is purely optical and fully tunable. Upon synchronization, the phase noise drops in agreement with the prediction.

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Synchronization occurs widely in physical and biological systems. On the nanoscale, it has a broad range of applications ranging from timing, navigation, signal processing, microwave communication and novel computing and memory concepts. Existing coupled micromechanical oscillators suffer from limited range, neighborhood restriction and non-configurable coupling which limit the control, physical size and possible topologies of complex oscillator networks [1, 2]. Here, we demonstrate the synchronization of two dissimilar micromechanical oscillators using the concept of optomechanics [3]. We show that the two micromechanical oscillators can achieve both individual and synchronized oscillation dynamics, harnessing the tuneability of the optical coupling.

We synchronize two optomechanical oscillators (OMOs) [4, 5] spaced apart by 400 nm using solely the coupling through the evanescent optical field (in contrast to a traditional mechanical coupling). Each of the OMOs consists of a pair of double disks (see Fig. 1a,b). As result of the near field coupling the optical modes split into a lower frequency symmetric (S) and a higher frequency antisymmetric (AS) mode (Fig. 1c,d). Light coupled to either one of these modes travels through both cavities. When a continuous wave laser is coupled to the right (R) OMO blue detuned from the optical resonance, it actuates coherent oscillations of the R OMO at its mechanical frequency f_R, which causes light modulation at f_R. When this modulated light travels through the left (L) OMO, it forces the L OMO, with resonant frequency f_L oscillates closer to f_R. The reciprocal occurs when the light goes back into the R OMO. The evanescent optical coupling mutually injects the modulated light from the two OMOs. This mutual injection and the nonlinear nature of optomechanical dynamics form the basis for the onset of synchronized oscillation [6, 7].

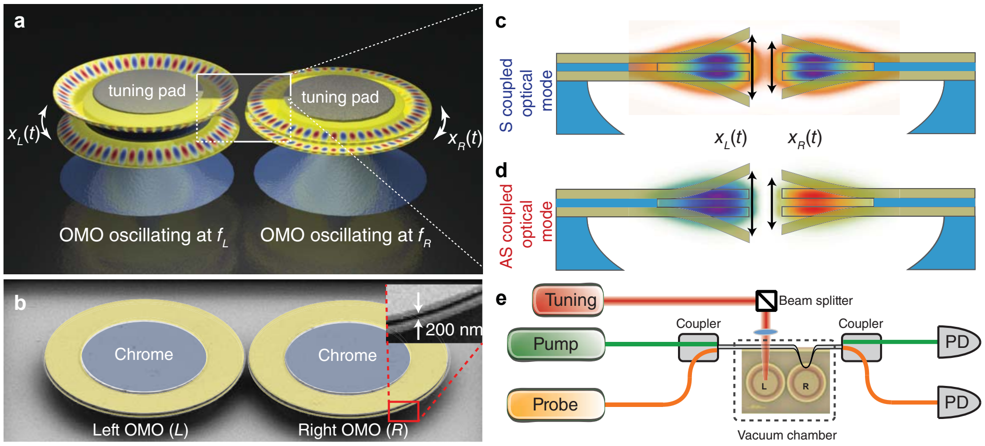

Fig. 1. (a) A schematic of the device. (b) Scanning electron micrograph of the fabricated device. The inset shows the double-disk structure. (c,d) Cross section view of the symmetric (S) and antisymmetric (AS) coupled optical supermodes of the two cavities. The mechanical deformation corresponds to the mechanical mode that the light excites. (e) A schematic of the experimental setup.

In order to control the degree of optical coupling between the oscillators we tune the optical resonant frequency of one of the two cavities. When the resonant frequencies of the two-coupled cavities are degenerate, the split S and AS modes distribute the same power in both OMOs; when their frequencies are different, the coupled optical modes profile become asymmetric. When the cavities' optical frequency difference is large, the coupling is very weak. We achieved the thermo-optic resonant frequency tuning by heating the cavities with an out-of-plane laser. Fig. 1a,b show the deposited chrome metal pads on top of the resonators that are used to enhance the optical absorption of the tuning laser (Fig. 1e).

We characterize the individual behavior of each OMO by switching the optical coupling off. The light is evanescently coupled to each OMO with a tapered optical fiber. Fig. 2a,b shows the characteristic frequency response of the *L* and *R* OMO. As the laser moves from the blue detuned side (bottom-up in Fig. 2a,b) into the cavity resonance, we observe the optical spring effect and the birth of coherent oscillation (white dashed line) that is found in typical optomechanical oscillators [3,5].

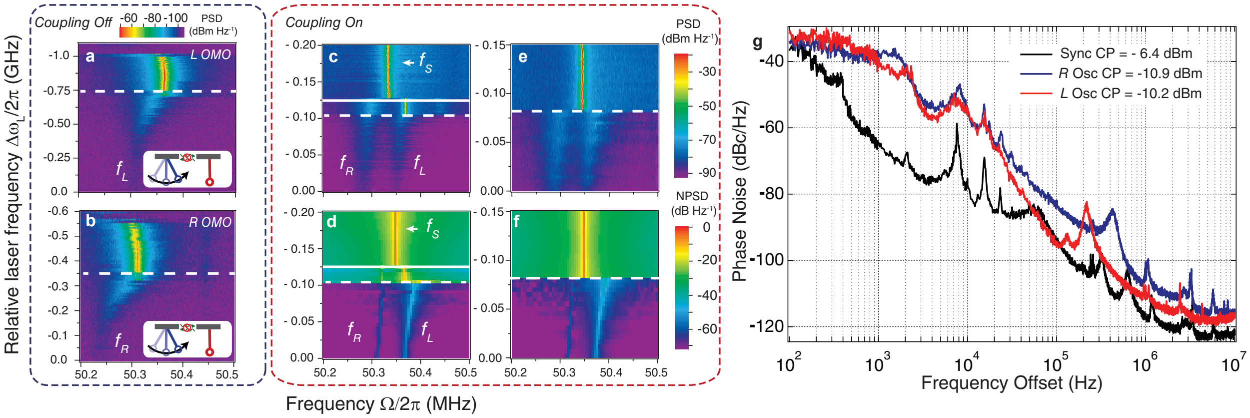

Fig. 2. (a) Radio frequency (RF) spectra of the uncoupled *L* OMO. (b) RF spectra of the uncoupled *R* OMO. The white dashed line represents the onset of self-sustaining oscillation. (c) The dynamics of coupled OMOs with $P_{in} = (11 \pm 1)$ μW. The *L* and *R* OMOs show peaks close to their natural frequencies before synchronization occurs at the horizontal solid white line. The synchronized frequency appears between the two cavities frequencies. (d) Numerical simulation for the condition in Fig. 2c. (e) At $P_{in} = (14 \pm 1)$ μW, the system oscillates directly in synchrony. (f) Numerical simulation for the condition in Fig. 2e. The frequency is relative to the starting laser frequency $\omega_L/2\pi \approx 192,431$GHz. f_S is the synchronized frequency. (g) Phase noise spectrum of the synchronized and individual oscillation states. CP: carrier power.

We demonstrate the onset of synchronization by switching the optical coupling on. In the coupled condition, as the input laser is scanned across the optical resonance, both mechanical frequencies are observed on the radio frequency (RF) spectrum (Fig. 2c,e). For input power of $P_{in} = (11 \pm 1)$ μW, we observe a unison oscillation frequency that appears between the natural frequencies of two cavities (Fig. 2c solid white line) following a short spectral region of asynchronous oscillation (Fig. 2c dashed white line). At higher input power $P_{in} = (14 \pm 1)$ μW, the OMOs directly synchronize when relative laser frequency of -0.16 GHz is reached as shown in Fig. 2e. Fig. 2d,f show numerically generated spectra based on a lumped oscillator model [6,7] with thermal noise taken into account. The simulations exhibit all the essential features of the measured spectra.

Mutually synchronized oscillators can output oscillation signals that have lower phase noise than the output of individual oscillators. Such better noise performance is due to the suppression of low frequency fluctuations [1,8] and the reduction of fundamental noise in correlated oscillators [9]. We increased the optical input power to $P_{in} = (35 \pm 3)$ μW to have sufficient carrier signal strength for the phase noise measurements. Fig. 2g shows the phase noise curve for the individual oscillation states (red curve for *L* OMO, blue curve for *R* OMO) and the synchronized states (black curve). Indeed, we observe that the phase noise is lower in the synchronized state, particularly at < 30 kHz frequency offset from the carrier. The drop in phase noise at low frequency offset may be due to a reduction in slow varying noise mechanisms in agreement with the previous observation in an injection-locked OMO [8].

Monolithic integration and the ability to control the coupling strength in optically coupled micromechanical oscillators are promising for realizing large oscillator networks. Optically coupled mechanical oscillators should enable oscillator networks spread over large areas only limited by optical waveguide or fiber losses. Furthermore, in OMO networks, synchronization phenomena may pave a route for on-chip low phase noise OMO RF sources, enabling a new class of devices in sensing, signal processing and meso-scale quantum optomechanics.

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