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Phase noise measurement of external cavity diode lasers and implications for optomechanical sideband cooling of GHz mechanical modes

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New Journal of Physics **15** (2013) 015019 (11pp)

Received 30 June 2012

Published 25 January 2013

Online at <http://www.njp.org/>

doi:10.1088/1367-2630/15/1/015019

Abstract. Cavity-optomechanical cooling via radiation pressure dynamical backaction enables ground-state cooling of mechanical oscillators, provided the laser exhibits sufficiently low phase noise. In this paper, we investigate and measure the excess phase noise of widely tunable external cavity diode lasers, which have been used in a range of recent nano-optomechanical experiments, including ground-state cooling. We report significant excess frequency noise, with peak values of the order of $10^7 \text{ rad}^2 \text{ Hz}$ near 3.5 GHz, attributed to the diode lasers' relaxation oscillations. The measurements reveal that even at GHz frequencies diode lasers do not exhibit quantum-limited performance. The associated excess backaction can preclude ground-state cooling even in state-of-the-art nano-optomechanical systems and can, moreover, lead to noise-induced sideband asymmetries.

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1. Introduction

In recent years, the mutual coupling of optical and mechanical degrees of freedom has been observed in a plethora of systems and it gives rise to a variety of phenomena (Kippenberg and Vahala 2008, Favero and Karrai 2009, Marquardt and Girvin 2009, Aspelmeyer *et al* 2010). This parametric radiation pressure coupling (Braginsky and Manukin 1977) enables sensitive measurements of the mechanical oscillator's position with an imprecision at (Anetsberger *et al* 2009) and below (Teufel *et al* 2009, Anetsberger *et al* 2010) the standard quantum limit, amplification (Carmon *et al* 2005, Kippenberg *et al* 2005, Rokhsari *et al* 2005, Teufel *et al* 2008) and cooling (Arcizet *et al* 2006, Gigan *et al* 2006, Schliesser *et al* 2006) of mechanical motion via dynamical backaction, optomechanical normal mode splitting (Dobrindt *et al* 2008) and strong coupling (Groblacher *et al* 2009), optomechanically induced transparency (Weis *et al* 2010, Safavi-Naeini *et al* 2011) and quantum coherent coupling (Teufel *et al* 2011, Verhagen *et al* 2012) of optical and mechanical degrees of freedom, mechanically mediated quantum state transfer (Wang and Clerk 2012) of optical and microwave fields, and optomechanical entanglement. Of particular interest has been the objective to achieve ground-state cooling of a macroscopic mechanical oscillator using the technique of optomechanical resolved-sideband cooling (Marquardt *et al* 2007, Wilson-Rae *et al* 2007, Schliesser *et al* (2008)).

Previous experiments and theoretical analysis (Diósi 2008, Schliesser *et al* 2008, Rabl *et al* 2009, Yin 2009, Abdi *et al* 2011, Ghobadi *et al* 2011, Phelps and Meystre 2011) have shown, however, that optomechanical experiments in general, and sideband cooling in particular, are sensitive to excess phase noise of the employed laser. In atomic laser cooling, the limit of cooling arises from the stochastic nature of the spontaneous emission process of the atom and can be insensitive to phase noise of the cooling laser. In cavity optomechanical cooling, the quantum limit (Marquardt *et al* 2007, Wilson-Rae *et al* 2007) arises from the quantum fluctuations of the intracavity field, i.e. the driving laser itself. This makes optomechanical cooling very sensitive to phase noise, as pointed out early in Diósi (2008) and Schliesser *et al* (2008). A laser that exhibits excess (classical) phase noise will lead to an additional contribution to the final occupancy. Excess phase noise not only impacts optomechanical sideband cooling, but can also lead to noise-induced sideband asymmetries (Harlow *et al* 2012, Khalili 2012) when performing noise thermometry (Safavi-Naeini *et al* 2012).

For this reason, optomechanical experiments necessitate the use of filtering cavities (Arcizet *et al* 2006) or low-noise solid-state lasers (Schliesser *et al* 2008) such as Ti:Sa and Nd:YAG lasers, which offer quantum-limited performance for sufficiently high Fourier frequencies (typically >10 MHz). Diode lasers, in contrast, exhibit significant excess phase

noise in this frequency range (Zhang *et al* 1995) and its impact has been observed in optomechanical cooling experiments of a 75 MHz radial breathing mode (Schliesser *et al* 2008). Moreover, there exists an additional, well-known contribution (Wieman and Hollberg 1991) to the excess phase and amplitude noise at high Fourier frequencies (>1 GHz), which is fundamentally linked to damped relaxation oscillations caused by the carrier population dynamics (Piazzolla *et al* 1982, Vahala *et al* 1983, Vahala and Yariv 1983, Yamamoto *et al* 1983). These relaxation oscillations cause primarily excess phase noise, whose magnitude is in close agreement with theoretical modeling (Ritter and Haug 1993, Ahmed and Yamada 2004). Interestingly, optical feedback (such as provided by an external cavity)—while reducing noise at low frequency—can even lead to an enhancement of this relaxation oscillation noise (Chen 1984).

Quantitative measurements of the high-frequency excess phase noise (at GHz frequencies) for modern widely tunable external cavity diode lasers, however, are scarce. Measurements of the high-frequency phase noise have, however, become increasingly important, as diode lasers have been used in optomechanical experiments that involve nano-optomechanical systems such as one-dimensional nanobeams (Eichenfield *et al* 2009) and two-dimensional photonic crystals (Gavartin *et al* 2011, Sun *et al* 2012) as well as microdisc cavities (Ding *et al* 2010, 2011, Xiong *et al* 2012) with GHz mechanical modes. Here diode lasers provide an advantage due to their frequency agility and large piezo-scan range, compared to, e.g., low-noise fiber lasers in the 1550 nm range.

As such, a quantitative characterization of extended cavity diode laser phase noise in the GHz domain and evaluation of its impact on quantum optomechanical experiments is highly desirable. Here we present such a characterization of several commonly employed widely tunable external cavity diode lasers, which are identical in geometry and manufacturer to the model used in recent optomechanical ground-state cooling experiments (Chan *et al* 2011). Our results indicate that, as expected, significant excess phase noise is indeed present in such lasers at GHz frequencies whose magnitude can impact optomechanical sideband cooling of nano-optomechanical systems.

2. Theory

Radiation pressure optomechanical sideband cooling allows cooling of a mechanical oscillator to a minimum occupation (Marquardt *et al* 2007, Wilson-Rae *et al* 2007) of $\bar{n}_f = \kappa^2/16\Omega_m^2 \ll 1$, where Ω_m is the mechanical frequency and κ is the optical energy decay rate. This limit arises from the quantum fluctuation of the cooling laser field. Excess classical phase or amplitude noise causes a fluctuating radiation pressure force noise that increases this residual occupancy. Of particular relevance is phase noise, whose heating effect has been observed in experiments employing toroidal optomechanical resonators (Schliesser *et al* 2008).

To quantitatively analyze the effect of phase noise on a cavity-optomechanical system, we consider the influence of a phase modulated pump laser interacting with an optical cavity, which exhibits a mechanical mode with resonance frequency Ω_m . It is instructive to first consider (in complex notation) a coherent phase modulation at a frequency Ω_m (coinciding with the mechanical oscillator frequency) of the laser's input field,

$$s_{\text{in}}(t) \approx \exp(-i(\omega t + \delta\phi \sin(\Omega_m t)))s_{\text{in}}. \quad (1)$$

For weak phase modulation, the input field is well approximated by two sidebands, i.e.

$$s_{\text{in}}(t) \approx \left(1 + \frac{\delta\phi}{2} e^{-i\Omega_m t} - \frac{\delta\phi}{2} e^{+i\Omega_m t} \right) s_{\text{in}} e^{-i\omega t}. \quad (2)$$

Using standard input–output coupling theory (Haus 1984, Gardiner and Collett 1985, Gorodetsky and Ilchenko 1998, Kippenberg and Vahala 2007), the intracavity field amplitude $a(t)$ is determined by the equation of motion

$$\frac{d}{dt} a(t) = (-\kappa/2 - i\omega_c) a(t) + \sqrt{\eta\kappa} s(t), \quad (3)$$

where ω_c denotes the cavity resonance frequency, κ denotes the total cavity decay rate and $\eta = \kappa_{\text{ex}}/\kappa$ denotes the ratio of cavity coupling κ_{ex} to its feeding mode compared to total cavity losses κ . Pumping the cavity with this phase modulated input field (which is assumed to exhibit a linewidth that is much smaller than the modulation frequency, i.e. satisfying the resolved sideband condition $\Omega_m \gg \kappa$) on the lower sideband, i.e. with the laser detuning $\Delta = \omega - \omega_c = -\Omega_m$, yields therefore an intracavity field of

$$a(t) \approx \left(\frac{1}{i\Omega_m} + \frac{\delta\phi}{2} \frac{1}{\kappa/2} e^{-i\Omega_m t} \right) \sqrt{\eta\kappa} s_{\text{in}} e^{-i\omega t}. \quad (4)$$

Thus, the intracavity field contains the off-resonant pump field and the resonantly coupled upper phase modulation sideband. The lower phase modulation sideband can be neglected, due to the resolved sideband regime.

Thus, the modulation sideband is resonantly *enhanced* by the cavity instead of being suppressed by a putative cavity filtering effect. The simultaneous presence of carrier and modulation sideband leads consequently to a radiation-pressure force (cf Kippenberg and Vahala 2007),

$$F(t) = \hbar G |a(t)|^2 = \frac{GP}{\omega} \frac{2\eta\delta\phi}{\Omega_m} \sin(\Omega_m t) + \bar{F},$$

where \bar{F} is a (for the present analysis irrelevant) static force, $P = \hbar\omega |s_{\text{in}}|^2$ is the launched input power and $G = \partial\omega_c/\partial x$ is the frequency pull parameter of the optomechanical system. The variance of the force fluctuations at the mechanical resonance frequency is correspondingly

$$\langle \delta F^2 \rangle = \langle F^2 \rangle - \bar{F}^2 = \frac{4\eta^2 G^2 P^2}{\omega^2 \Omega_m^2} \frac{1}{2} \delta\phi^2. \quad (5)$$

These considerations carry over directly to phase fluctuations of the cooling laser field described by a (symmetrized, double-sided) phase noise spectral density $\bar{S}_{\phi\phi}(\Omega)$ (expressed in $\text{rad}^2 \text{Hz}^{-1}$), which denotes the random phase fluctuations per unit bandwidth, that is, $\bar{S}_{\phi\phi}$ corresponds to $\langle \delta\phi^2 \rangle$. Analogously, \bar{S}_{FF} corresponds to $\langle \delta F^2 \rangle$. Alternatively, such fluctuations may be described in terms of laser frequency noise with the corresponding frequency noise spectral density $\bar{S}_{\omega\omega}(\Omega) = \bar{S}_{\phi\phi}(\Omega) = \bar{S}_{\phi\phi}(\Omega) \Omega^2$ (expressed in $\text{rad}^2 \text{s}^{-2} \text{Hz}^{-1}$), and we use both descriptions interchangeably (Riehle 2004). The resulting force fluctuations in this case are given by the expression (Schliesser *et al* 2008, Schliesser 2009)

$$\bar{S}_{\text{FF}}^{\text{L}}(\Omega) \approx \frac{4\eta^2 G^2 P^2}{\omega^2 \Omega^2} \frac{\bar{S}_{\omega\omega}(\Omega)}{\Omega^2} \quad (6)$$

in the resolved-sideband regime. To derive from this excess force noise the residual occupation of the mechanical oscillator, one can consider the laser as providing an additional bath with

a temperature $k_B T_{\text{Laser}} \approx \hbar \Omega_m \bar{n}_L$ with an equivalent force noise spectral density $\bar{S}_{\text{FF}}^L(\Omega) = 2m_{\text{eff}}\Gamma_m \bar{n}_L \hbar \Omega_m$. The effective occupancy \bar{n}_L of the cold bath that the laser field is providing is consequently given by $\bar{n}_L \approx \bar{S}_{\text{FF}}^L(\Omega_m)/2m_{\text{eff}}\Gamma_m \hbar \Omega_m$, where the laser force spectral density is given by equation (6). This additional residual occupancy can be derived by comparing it with the Langevin force fluctuations of the thermal bath $\bar{S}_{\text{FF}}^{\text{th}}(\Omega) = 2m_{\text{eff}}\Gamma_m \bar{n}_{\text{th}} \hbar \Omega_m$ with $\bar{n}_{\text{th}} \approx k_B T/\hbar \Omega_m$. The final occupancy of the oscillator in the presence of sideband cooling is then given by $n_f \approx (\bar{n}_L + \bar{n}_{\text{th}}) \Gamma_m/\Gamma_{\text{cool}}$, with $\Gamma_{\text{cool}} \approx 2\eta G^2 P/m_{\text{eff}}\Omega_m^3 \omega$ in the resolved-sideband regime (Schliesser *et al* 2008). This yields an excess occupancy due to frequency noise of (Schliesser *et al* 2008, Rabl *et al* 2009)

$$\bar{n}_f^{\text{excess}} \approx \frac{\bar{n}_p}{\kappa} \bar{S}_{\omega\omega}(\Omega_m), \quad (7)$$

where $\bar{n}_p \approx \eta \kappa P/\hbar \omega \Omega_m^2$ is the intracavity photon number in the resolved-sideband regime. For an optimized cooling power, the lowest occupancy that can be reached in the presence of frequency noise is given by

$$\bar{n}_f^{\text{min}} \approx \sqrt{\frac{\bar{n}_{\text{th}}\Gamma_m}{g_0^2} \bar{S}_{\omega\omega}(\Omega_m)}, \quad (8)$$

where we have used the vacuum optomechanical coupling rate (Gorodetsky *et al* 2010) $g_0 = G\sqrt{\hbar/2m_{\text{eff}}\Omega_m}$ and neglected quantum backaction⁵.

3. Measurement of the diode laser phase noise

Laser phase noise is frequently modeled by a (Gaussian) random phase $\phi(t)$ which obeys the simple noise model $\langle \dot{\phi}(t)\dot{\phi}(s) \rangle = \gamma_c \Gamma_L e^{-\gamma_c |t-s|}$, where Γ_L is the laser linewidth, and γ_c^{-1} is a correlation time, leading to a low-pass-type frequency noise spectrum

$$\bar{S}_{\omega\omega}(\Omega) = \frac{2\Gamma_L \gamma_c^2}{\Omega^2 + \gamma_c^2} \quad (9)$$

with a white noise model in the limit $\gamma_c \rightarrow \infty$ (Diósi 2008, Rabl *et al* 2009, Ghobadi *et al* 2011, Phelps and Meystre 2011). In practice, the relation between the laser linewidth and the frequency noise spectrum does not follow this simple model, as there are several contributions of different physical origin to the phase noise of a diode laser: the laser's linewidth is mostly dominated by acoustic fluctuations occurring at low Fourier frequencies, leading to a typical short-term linewidth of ~ 300 kHz for unstabilized external-cavity diode lasers. In addition, relaxation oscillations⁶ occur in diode lasers (due to the fast cavity decay rate and short carrier lifetime) at high (> 1 GHz) Fourier frequencies, which are not described by the above model. Therefore, it is important to measure the frequency-dependent phase noise spectrum $\bar{S}_{\phi\phi}(\Omega)$.

To this end, an optical cavity is employed for quadrature rotation (Zhang *et al* 1995, Riehle 2004), converting phase to amplitude fluctuations which are measured with a photodetector (cf figure 1). In principle, a high-resolution spectrum of the optical field can

⁵ For comparison with Rabl *et al* (2009) note that we use energy decay rates κ instead of field decay rates $\kappa' \equiv \kappa/2$, and we denote with Γ_m the mechanical energy dissipation rate instead of the mechanical decoherence rate $\Gamma'_m \equiv (k_B T/\hbar \Omega_m)\Gamma_m$, which we refer to as γ here.

⁶ Relaxation oscillations are fundamental to any laser and result from the nonlinear nature of the coupled photon and population rate equation (Siegman 1986).

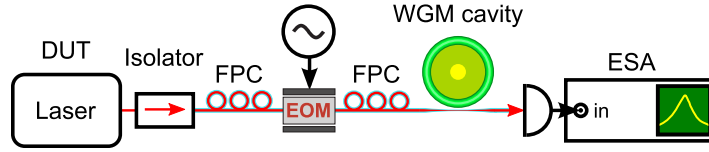


Figure 1. The setup to measure diode laser phase noise at GHz frequencies. DUT: device under test; FPC: fiber polarization controller; EOM: electro-optic modulator; WGM: whispering gallery mode of a low- Q disc microcavity; ESA: electronic spectrum analyzer.

also be used for phase noise measurement, in which case the relaxation oscillations appear as sidebands around the carrier (cf e.g. Ritter and Haug 1993, Riehle 2004).

The devices under test are three 1550 nm extended cavity diode lasers in Littman–Metcalf configuration of the most commonly used models⁷. Care is taken to introduce proper optical isolation of the laser diode to avoid optical feedback. The quadrature rotating cavity is a fiber coupled silica microcavity (a disc featuring purposely a broad linewidth of $\kappa/2\pi \approx 2$ GHz, facilitating cavity locking) and the transmission is detected by a fast photodetector (New Focus) whose photocurrent is fed into a spectrum analyzer (ESA). Similar to the approach presented in Zhang *et al* (1995) the transduction of frequency noise $\bar{S}_{\omega\omega}(\Omega)$ into power fluctuations at the output of the cavity (I denotes photon flux) is calculated to be given by (Schliesser 2009)

$$(\hbar\omega)^2 \bar{S}_{\Pi}^{\text{fn}}(\Omega) = \frac{4(\hbar\omega)^2 |S_{\text{in}}|^4 \eta^2 \Delta^2 \kappa^2 \left((1-\eta)^2 \kappa^2 + \Omega^2 \right) \bar{S}_{\omega\omega}(\Omega)}{\left(\Delta^2 + \left(\frac{\kappa}{2}\right)^2 \right) \left((\Delta - \Omega)^2 + \left(\frac{\kappa}{2}\right)^2 \right) \left((\Delta + \Omega)^2 + \left(\frac{\kappa}{2}\right)^2 \right)}. \quad (10)$$

Here, Δ is the laser detuning from the cavity resonance and Ω is the analysis frequency. We note that the optomechanical response of the microdisc cavity is neglected in the above analysis. This is absolutely justified as the well-coupled, fundamental mechanical modes of the microdisc (exhibiting frequencies < 100 MHz) are far below the frequency range in which we are interested to measure the diode laser (> 1 GHz).

The noise equivalent power of the employed photodetector is ~ 24 pW Hz^{-1/2} and therefore not sufficient for detecting the quantum phase/amplitude noise for the power levels used in this work (< 1 mW), but does allow the detection of excess noise. (To detect the quantum noise at GHz frequencies using this detector would require an average power exceeding $P_{\text{min}} \approx \text{NEP}^2/\hbar\omega > 5$ mW, where NEP denotes the noise equivalent power of the employed photodiode.) Indeed, as shown in figure 2, we observe a peak at about 3.5 GHz in the detected photocurrent fluctuations when the laser is detuned from the cavity resonance. This noise has been reported previously (Piazzolla *et al* 1982, Vahala *et al* 1983, Vahala and Yariv 1983, Yamamoto *et al* 1983, Ritter and Haug 1993, Ahmed and Yamada 2004) and is attributed to relaxation oscillations, which because of the short carrier lifetime exhibit high frequencies well into the GHz range. We confirmed that the noise is indeed predominantly phase noise, by scanning the laser across the cavity resonance while keeping the analysis frequency fixed (figure 3). The pronounced double-peak structure follows equation (10) and reveals that the noise is predominantly in the phase quadrature.

To calibrate the measured noise spectra, we imprint onto the diode laser a known phase modulation using an external (fiber-based) phase modulator following the method of Gorodetsky *et al* (2010). In brief, the V_{π} of the phase modulator (the voltage that needs to be

⁷ New Focus TLB-6328 (serial numbers 008 and 280) and TLB-6330 (serial number 043).

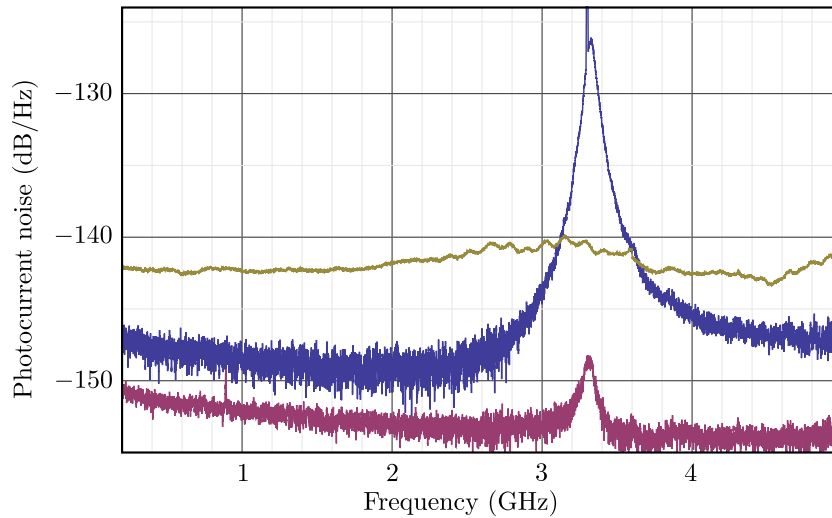


Figure 2. Noise of a semiconductor laser with weak optical feedback from a grating (Littman configuration). Shown is the power spectral density (PSD) of photocurrent fluctuations, normalized to total photocurrent, when laser light is directly detected (red), or tuned to the side-of-the-fringe of an approximately 4 GHz-wide optical cavity (blue). The yellow trace is the background signal in the same normalization, which was subtracted from all traces.

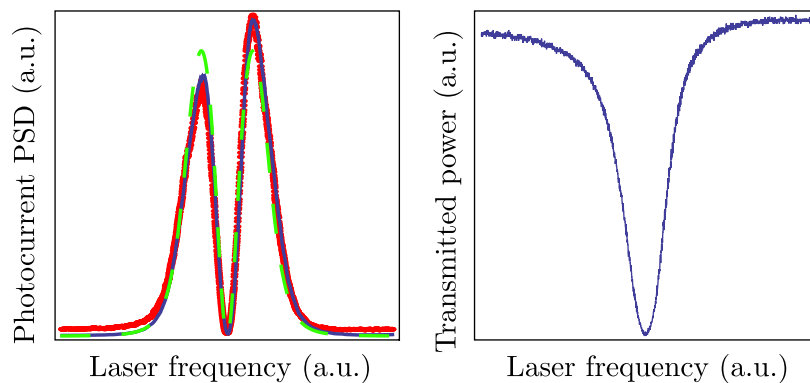


Figure 3. Photocurrent PSD in a 1 MHz bandwidth at a Fourier frequency of 3.5 GHz as a function of laser detuning (left panel). Red dots are measured without any additional modulation, showing only the laser's intrinsic fluctuations; the blue line was measured with a strong external frequency modulation at 3.5 GHz. The blue curve was rescaled by a factor of 44 and corresponds, in this normalization, to a frequency modulation PSD of $\bar{S}_{\omega\omega}(2\pi \cdot 3.5 \text{ GHz}) \approx 1.6 \times 10^7 \text{ rad}^2 \text{ Hz}$. The most striking deviation of these measurements from the model of equation (10) (green dashed line) is the asymmetry of the peaks, which can be explained by the asymmetric lineshape of the employed cavity (right panel).

applied to achieve a π phase shift) is determined in independent measurements by scanning a second diode laser over the phase modulated laser, in order to determine the strength of the modulation sidebands. The measured V_π and the manufacturer's specifications differed by

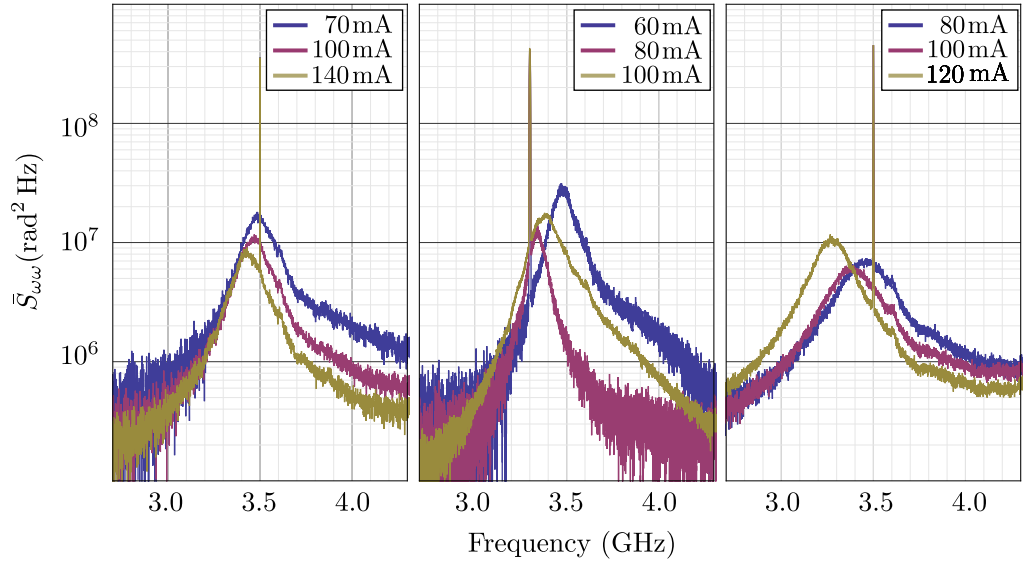


Figure 4. PSD of frequency fluctuations for three different lasers after subtraction of the background signal. The sharp peak is due to external phase modulation, which was used to calibrate the spectra.

typically less than 10%. In a second and independent measurement (to characterize the noise level of a third laser), the phase modulator was characterized by scanning a phase modulated laser over a narrow cavity resonance and recording the transmission spectrum. Calibration via the modulation peak proceeds by using the relation $\bar{S}_{\omega\omega}^{\text{cal}}(\Omega) \equiv \Omega^2 \delta\phi^2 / (4\text{RSB})$, where RSB is the resolution bandwidth of the recording with the electronic spectrum analyzer, $\delta\phi$ is the modulation index and Ω is the modulation frequency. Figure 4 shows this calibration procedure applied to the three lasers. The level of frequency fluctuations was measured for a total of three devices and found to vary only slightly between the lasers (despite their differing by 10 years in manufacturing date). The maximum frequency noise was in the range of $\bar{S}_{\omega\omega}^{\text{max}} \approx \mathcal{O}(10^7)$ $\text{rad}^2 \text{ Hz}$, corresponding to phase fluctuations about 30 dB above the quantum noise limit $\bar{S}_{\phi\phi}(\Omega) = \hbar\omega/4P$ of a $P = 1$ mW beam. This level of phase noise agrees well with theoretical predictions (Ahmed and Yamada 2004).

4. Ground-state cooling limitations

In order to achieve ground-state cooling, only a certain amount of laser phase noise can be tolerated, as the presence of the cooling light in the cavity leads to additional fluctuating forces and an excess phonon number according to equation (6). For an optimum cooling laser power, the residual thermal occupancy and the excess occupancy caused by radiation pressure fluctuations are equal, and their sum can be below unity only if

$$\bar{S}_{\omega\omega}(\Omega_m) < \frac{g_0^2}{\gamma} = \frac{g_0^2}{k_B T / \hbar Q_m}, \quad (11)$$

constituting a necessary condition for ground-state cooling ($n_f^{\text{min}} < 1$) (Rabl *et al* 2009). Evidently, systems that exhibit large optomechanical coupling g_0 and low mechanical decoherence rate $\gamma = k_B T / \hbar Q_m$ (that is, low bath temperature T and high mechanical

quality factor Q_m) can tolerate larger amounts of laser frequency noise. However, even the recently reported nano-optomechanical system (Chan *et al* 2011) with the record-high $g_0/2\pi = 0.91$ MHz as well as $T \approx 30$ K and $Q_m \approx 50\,000$ requires $\bar{S}_{\omega\omega}(2\pi \cdot 3.68 \text{ GHz}) < 4 \times 10^5 \text{ rad}^2 \text{ Hz}$, a value reached by none of the three lasers we have tested. The phase noise at the relaxation oscillation frequency is found to exceed this value by a factor of $\times 10$ –50 for the three lasers tested. Using the above thermal decoherence parameters, the noise at the relaxation oscillation frequency corresponds to a minimum occupancy of $\bar{n}_f^{\min} \approx \sqrt{(\gamma/g_0^2)S_{\omega\omega}(\Omega_m)}$ of $\bar{n}_f^{\min} \approx 20$ –40 quanta (for the lowest and the highest measured noise, respectively).

5. Summary

We conclude that the widely employed frequency-tunable external cavity diode lasers should not be expected to be quantum limited, but exhibit significant excess phase noise up to very high (GHz) Fourier frequencies.

We have observed a peak in this noise at a frequency around 3.5 GHz. This observation implies important limitations to optomechanical sideband cooling also for systems based on microwave-frequency range mechanical oscillators if the laser noise is not suppressed. In addition, this classical excess phase noise can give rise to sideband asymmetries which are entirely *classical* in nature (Harlow *et al* 2012, Khalili 2012) masking the signatures that are expected from a quantum mechanical description (Khalili *et al* 2012, Safavi-Naeini *et al* 2012).

The noise originating from high-frequency relaxation oscillations can be suppressed by external filters with a narrow cavity linewidth (effective suppression, however, requires a free spectral range exceeding the mechanical resonance frequency). Alternatively, the noise may be mitigated by laser systems which exhibit relaxation oscillation frequencies at much lower Fourier frequencies. In the telecommunication range, this can be achieved by fiber lasers, which however lack the frequency agility of diode lasers (Hald and Ruseva 2005).

Acknowledgments

We are grateful to V L Velichansky and P Poizat for stimulating discussions. This work was supported by the NCCR of Quantum Engineering. MLG acknowledges support from the ‘Dynasty’ Foundation and RFBR grant no. 11-02-00383-a. TJK and MLG acknowledge support from an ‘ERAnet’ Russia program.

References

- Abdi M, Barzanjeh S, Tombesi P and Vitali D 2011 Effect of phase noise on the generation of stationary entanglement in cavity optomechanics *Phys. Rev. A* **84** 032325
- Ahmed M and Yamada M 2004 Field fluctuations and spectral line shape in semiconductor lasers subjected to optical feedback *J. Appl. Phys.* **95** 7573–83
- Anetsberger G, Arcizet O, Unterreithmeier Q, Riviere R, Schliesser A, Weig E, Kotthaus J and Kippenberg T 2009 Near-field cavity optomechanics with nanomechanical oscillators *Nature Phys.* **5** 909–14
- Anetsberger G, Gavartin E, Arcizet O, Unterreithmeier Q, Weig E, Gorodetsky M, Kotthaus J and Kippenberg T 2010 Measuring nanomechanical motion with an imprecision below the standard quantum limit *Phys. Rev. A* **82**
- Arcizet O, Cohadon P-F, Briant T, Pinard M and Heidmann A 2006 Radiation-pressure cooling and optomechanical instability of a micromirror *Nature* **444** 71–4

- Aspelmeyer M, Gröblacher S, Hammerer K and Kiesel N 2010 Quantum optomechanics? Throwing a glance *J. Opt. Soc. Am. B* **27** A189–97
- Braginsky V B and Manukin A B 1977 *Measurement of Weak Forces in Physics Experiments* (Chicago, IL: University of Chicago Press)
- Carmon T, Rokhsari H, Yang L, Kippenberg T and Vahala K 2005 Temporal behavior of radiation-pressure-induced vibrations of an optical microcavity phonon mode *Phys. Rev. Lett.* **94** 223902
- Chan J, Mayer Alegre T P, Safavi-Naeini A H, Hill J T T, Krause A, Gröblacher S, Aspelmeyer M and Painter O 2011 Laser cooling of a nanomechanical oscillator into its quantum ground state *Nature* **478** 89–92
- Chen Y C 1984 Phase noise characteristics of single mode semiconductor lasers with optical feedback *Appl. Phys. Lett.* **44** 10–12
- Ding L, Baker C, Senellart P, Lemaitre A, Ducci S, Leo G and Favero I 2010 High frequency GAAS nano-optomechanical disk resonator *Phys. Rev. Lett.* **105** 263903
- Ding L, Baker C, Senellart P, Lemaitre A, Ducci S, Leo G and Favero I 2011 Wavelength-sized GAAS optomechanical resonators with gigahertz frequency *Appl. Phys. Lett.* **98** 113108
- Diósi L 2008 Laser linewidth hazard in optomechanical cooling *Phys. Rev. A* **78** 021801
- Dobrint J, Wilson-Rae I and Kippenberg T 2008 Parametric normal-mode splitting in cavity optomechanics *Phys. Rev. Lett.* **101** 263602
- Eichenfield M, Chan J, Camacho R M, Vahala K J and Painter O 2009 Optomechanical crystals *Nature* **462** 78–82
- Favero I and Karrai K 2009 Optomechanics of deformable optical cavities *Nature Photon.* **3** 201–5
- Gardiner C and Collett M 1985 Input and output in damped quantum systems: quantum stochastic differential equations and the master equation *Phys. Rev. A* **31** 3761–74
- Gavartin E, Braive R, Sagnes I, Arcizet O, Beveratos A, Kippenberg T J and Robert-Philip I 2011 Optomechanical coupling in a two-dimensional photonic crystal defect cavity *Phys. Rev. Lett.* **106** 203902
- Ghobadi R, Bahrapour A R and Simon C 2011 Optomechanical entanglement in the presence of laser phase noise *Phys. Rev. A* **84** 063827
- Gigan S, Bohm H R, Paternostro M, Blaser F, Langer G, Hertzberg J B, Schwab K C, Bauerle D, Aspelmeyer M and Zeilinger A 2006 Self-cooling of a micromirror by radiation pressure *Nature* **444** 67–70
- Gorodetsky M L and Ilchenko V S 1998 Optical microsphere resonators: optimal coupling to high- Q whispering-gallery modes *J. Opt. Soc. Am. B* **16** 147–54
- Gorodetsky M, Schliesser A, Anetsberger G, Deleglise S and Kippenberg T J 2010 Determination of the vacuum optomechanical coupling rate using frequency noise calibration *Opt. Express* **18** 23236–46
- Gröblacher S, Hammerer K, Vanner M R and Aspelmeyer M 2009 Observation of strong coupling between a micromechanical resonator and an optical cavity field *Nature* **460** 724–7
- Hald J and Ruseva V 2005 Efficient suppression of diode-laser phase noise by optical filtering *J. Opt. Soc. Am. B* **22** 2338–44
- Harlow J, Palomaki T, Kerckhoff J, Teufel J, Simmonds R and Lehnert K 2012 Asymmetric absorption and emission of energy by a macroscopic mechanical oscillator in a microwave circuit optomechanical system *APS March Meeting Abstracts* p B4008
- Haus H A 1984 *Waves and Fields in Optoelectronics* (Englewood Cliffs, NJ: Prentice-Hall)
- Khalili F *et al* 2012 in preparation
- Khalili F Y, Miao H, Yang H, Safavi-Naeini A H, Painter O and Chen Y 2012 Quantum back-action in measurements of zero-point mechanical oscillations *Phys. Rev. A* **86** 033840
- Kippenberg T, Rokhsari H, Carmon T, Scherer A and Vahala K 2005 Analysis of radiation-pressure induced mechanical oscillation of an optical microcavity *Phys. Rev. Lett.* **95** 033901
- Kippenberg T and Vahala K 2007 Cavity optomechanics *Opt. Express* **15** 17172–205
- Kippenberg T J and Vahala K J 2008 Cavity optomechanics: back-action at the mesoscale *Science* **321** 1172–6
- Marquardt F, Chen J P, Clerk A A and Girvin S M 2007 Quantum theory of cavity-assisted sideband cooling of mechanical motion *Phys. Rev. Lett.* **99** 093902
- Marquardt F and Girvin S M 2009 Optomechanics *Physics* **2** 40

- Phelps G A and Meystre P 2011 Laser phase noise effects on the dynamics of optomechanical resonators *Phys. Rev. A* **83** 063838
- Piazzolla S, Spano P and Tamburini M 1982 Characterization of phase noise in semiconductor lasers *Appl. Phys. Lett.* **41** 695–6
- Rabl P, Genes C, Hammerer K and Aspelmeyer M 2009 Phase-noise induced limitations in resolved-sideband cavity cooling of mechanical resonators *Phys. Rev. A* **80** 063819
- Riehle F 2004 *Frequency Standards* (New York: Wiley-VCH)
- Ritter A and Haug H 1993 Theory of laser diodes with weak optical feedback: I. Small-signal analysis and side-mode spectra *J. Opt. Soc. Am. B* **10** 130–44
- Rokhsari H, Kippenberg T, Carmon T and Vahala K 2005 Radiation-pressure-driven micro-mechanical oscillator *Opt. Express* **13** 5293–301
- Safavi-Naeini A, Chan J, Hill J, Alegre T, Krause A and Painter O 2012 Observation of quantum motion of a nanomechanical resonator *Phys. Rev. Lett.* **108** 33602
- Safavi-Naeini A H, Mayer Alegre T P, Chan J, Eichenfield M, Winger M, Lin Q, Hill J T, Chang D E and Painter O 2011 Electromagnetically induced transparency and slow light with optomechanics *Nature* **472** 69–73
- Schliesser A 2009 Cavity optomechanics and optical frequency comb generation with silica whispering-gallery-mode microresonators *Dissertation Thesis* LMU Munich
- Schliesser A, Del’Haye P, Nooshi N, Vahala K J and Kippenberg T J 2006 Radiation pressure cooling of a micromechanical oscillator using dynamical backaction *Phys. Rev. Lett.* **97** 243905
- Schliesser A, Rivière R, Anetsberger G, Arcizet O and Kippenberg T 2008 Resolved-sideband cooling of a micromechanical oscillator *Nature Phys.* **4** 415–9
- Siegman A E 1986 *Lasers* (Mill Valley, CA: University Science Books)
- Sun X, Zheng J, Poot M, Wong C W and Tang H X 2012 Femtogram doubly clamped nanomechanical resonators embedded in a high- Q two-dimensional photonic crystal nanocavity *Nano Lett.* **12** 2299–305
- Teufel J D, Donner R, Castellanos-Beltran M A, Harlow J W and Lehnert K W 2009 Nanomechanical motion measured with imprecision below that at the standard quantum limit *Nature Nanotechnol.* **4** 820
- Teufel J D, Donner T, Li D, Harlow J W, Allman M S, Cicak K, Sirois A J, Whittaker J D, Lehnert K W and Simmonds R W 2011 Sideband cooling of micromechanical motion to the quantum ground state *Nature* **475** 359–63
- Teufel J D, Harlow J W, Regal C A and Lehnert K W 2008 Dynamical backaction of microwave fields on a nanomechanical oscillator *Phys. Rev. Lett.* **101** 197203
- Vahala K, Harder C and Yariv A 1983 Observation of relaxation resonance effects in the field spectrum of semiconductor lasers *Appl. Phys. Lett.* **42** 211
- Vahala K and Yariv A 1983 Semiclassical theory of noise in semiconductor lasers—Part II *IEEE J. Quantum Electron.* **19** 1102–9
- Verhagen E, Deleglise S, Weis S, Schliesser A and Kippenberg T J 2012 Quantum-coherent coupling of a mechanical oscillator to an optical cavity mode *Nature* **482** 63–7
- Wang Y-D and Clerk A 2012 Using interference for high fidelity quantum state transfer in optomechanics *Phys. Rev. Lett.* **108** 153603
- Weis S *et al* 2010 Optomechanically induced transparency *Science* **330** 1520–3
- Wieman C E and Hollberg L 1991 Using diode lasers for atomic physics *Rev. Sci. Instrum.* **62** 1–20
- Wilson-Rae I, Nooshi N, Zwerger W and Kippenberg T J 2007 Theory of ground state cooling of a mechanical oscillator using dynamical backaction *Phys. Rev. Lett.* **99** 093901
- Xiong C, Pernice W H P, Sun X, Schuck C, Fong K Y and Tang H X 2012 Aluminum nitride as a new material for chip-scale optomechanics and nonlinear optics *New J. Phys.* **14** 095014
- Yamamoto Y, Saito S and Mukaim T 1983 AM and FM quantum noise in semiconductor lasers—Part II. Comparison of theoretical and experimental results for AlGaAs lasers *IEEE J. Quantum Electron.* **19** 47–58
- Yin Z 2009 Phase noise and laser-cooling limits of optomechanical oscillators *Phys. Rev. A* **80** 033821
- Zhang T C, Poizat J-Ph, Grelu P, Roch J-F, Garngier P, Marin F, Bramati A, Jost V, Levenson M D and Giacobino E 1995 Quantum noise of free-running and externally-stabilized laser diodes *Quantum Semiclass. Opt.* **7** 601–13