Sensitivity Analysis of a Proposed Novel Opto-Nano-Mechanical Photodetector for Improving the Performance of LIDAR and Local Optical Sensors

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Abstract. We propose a novel approach to the development of a new generation of optical sensors with enhanced detection sensitivity for chemical species. The novelty comes from combining an extremely high Q cantilever sensor with an already well established very sensitive technique, frequency modulation (FM) spectroscopy. In existing implementations, this inherent sensitivity is limited by the inadequacy of current state-of-the-art electronic filters to differentiate the weak amplitude modulated (AM)signal from the inevitable high-frequency laser noise, a consequence of the deterioration in the quality factor with increasing frequency exhibited by these filters. Our approach combines FM techniques with the rapidly advancing technology of nano-mechanical resonator (cantilever) development. Here a cantilever functions as both a sensitive photodetector and a high-quality spectral or temporal filter. These ultra-low mass devices enable detection of the photon momentum rather than conventional detection by photon energy. At least one order of magnitude enhancement appears feasible with existing cantilever technology.

Until recently the most widely used technique for remote sensing was differential absorption Lidar (DIAL). The basic principle of DIAL is based on using two radiation frequencies: one is tuned to an absorption spectral line of the species of interest, and the other is tuned off this spectral line. The attenuation of the backscattered light at these two frequencies is compared and the absorbance of the species is extracted from the difference. The main limitation of this technique is the difficulty of detecting small changes due to absorption on a large fluctuating background. To avoid this limitation, the frequency modulation (FM) technique has been applied by several research groups, including the Pacific Northwest National Laboratory [1], the NASA/Goddard space Flight Center [2], and the Sarnoff Research Institute [3]. FM spectroscopy has proven to be one of the most sensitive absorption-based spectroscopic techniques. The essential idea is that when a frequency modulated laser beam enters an absorbing medium the emerging, the partially absorbed beam is amplitude modulated (AM). If the modulation index of the frequency modulation is sufficiently small, the spectrum of the incident FM beam consists primarily of the peak at the carrier frequency $\omega_c$ and sidebands at $\omega_c \pm \Omega$, where $\Omega$ is the modulation frequency. In addition to the component at the carrier frequency, the intensity of the output beam has a component that oscillates sinusoidally at $\Omega$ and with an amplitude proportional to the modulation index and the difference in the
attenuation coefficients of the absorber at the frequencies $\omega_c + \Omega$ and $\omega_c - \Omega$. It is important for the FM method that there be little spectral overlap between the carrier and the sidebands. If the modulation frequency is not high enough, the spectral wings of the sidebands and the carrier will overlap, making the exact amplitude and phase balance required for full FM beat cancellation impossible. Thus, one of the major limiting factors in FM spectroscopy is laser noise, which requires that the modulation frequency be large compared with the laser bandwidth. However, electronic detection systems, consisting of a photodetector and several amplification cascades, produce an additional noise that increases with increasing modulation frequency, so that the shift to higher modulation frequency could be inefficient.

We suggest the use of nano-mechanical cantilevers as photodetectors and filters with much higher Q factors than are currently possible by conventional electronic methods. In this approach the AM signal reflected by the Earth’s surface or aerosols and molecular backscattering in the atmosphere actuates a cantilever by resonant light pressure or by optical gradient forces (see Fig. 1). Note that reflection from the Earth’s surface is the dominant contribution to the AM signal. In a variant of the local sensor (see Fig. 2), the light emerges from a multi-pass absorption cell and actuates the cantilever. To achieve a high sensitivity we propose to apply a method similar to laser cooling of the nano-cantilever, a technique that was demonstrated recently [4]. It was shown that sub-mK cooling is feasible with this technique. Optical actuation of cantilevers by light has already been demonstrated [5,6]. In our case, the cantilever functions both as a high-frequency detector and as a high-Q filter. By choosing the cantilever resonance frequency appropriately, the proposed sensor can be made to operate in the thermal noise limit. The use of cantilevers in FM-LIDAR and local FM-sensors in this way offers the possibility of detecting low absorption and concentrations with unprecedented sensitivity.

![Figure 1. The schematic setup of the FM-LIDAR system with opto-nano-mechanical photodetector.](image1)

![Figure 2. Left: FM absorption spectroscopy setup. Right: A setup for optical detection of the cantilever vibrations.](image2)

According to a theoretical consideration [7], the signal-to-noise ratio is given by
where $Q$ is the quality factor of the cantilever, $R$ is the reflection coefficient, $k$ is the spring constant of the cantilever, $k_B$ is Boltzmann’s constant, $T$ is the temperature, $P_0$ is the incident laser power, $\omega_0$ is the fundamental frequency of the cantilever, and $P_N(\omega) = \xi(\omega_0)P_0$ is the spectral density of the laser intensity noise, where $\xi(\omega_0)$ is the relative intensity noise (RIN). Let’s consider as an example the following parameter values: $T = 4^\circ K$, $P_0 = 100 \mu W$, and $\omega_0 = 20 MHz$. For these values of the parameters the laser noise dominates if the RIN satisfies the inequality $\xi(\omega_0) > 1.8 \times 10^{-5} Hz^{-1/2}$. This value of the RIN is typical for solid state lasers. Neglecting the shot noise and the thermal noise, we obtain $S \sim (\alpha L)^2 Q(\omega_0/\xi(\omega_0))$. The condition $S = 1$ gives $\alpha L \approx \xi(\omega_0)(\omega_0/Q)^{1/2} = 1.8 \times 10^{-4}$. To compare this estimate of the minimal absorption, we estimate a corresponding value for a conventional electronic detection. Electronic photodetection usually involves at least three electronic stages. The first stage is a photodetector and preamplifier or photomultiplier or avalanche photodiode. The second stage is a lock-in-amplifier, and the third stage is an output amplifier. Each stage produces noise. The noise of the first two stages increases significantly at higher modulation frequencies. Usually it is characterized by the noise figure, $NF = 10 \log(SNR_{out}/SNR_{in})$ (where $SNR_{out}$ and $SNR_{in}$ are the SNR in the output and input signals, respectively). For a modulation frequency greater than 10 MHz, the noise figure for the photodetector and preamplifier is about $NF_1 = -2 \text{ dB}$; for the lock-in-amplifier $NF_2 = - (3 – 5) \text{ dB}$; and for the output amplifier $NF_3 = - 4 \text{ dB}$. Thus the total noise figure is $NF = NF_1 \times NF_2 \times NF_3 = - 10 \text{ dB}$ and the RIN is $\xi_{eff} = \xi \times NF$. The SNR for electronic photodetection can be written as

$$S_{eff} = \frac{g^2 P_0^2 (\alpha L)^2}{\Delta f e(gP_0 + 2k_B T / R) + \Delta f g^2 \xi_{eff}^2 (\omega_0) P_0^2},$$

Where $g = e \eta / h \omega$, $h \omega$ is the photon energy, $e$ is the electric charge, $\eta$ is the quantum efficiency, $\Delta f$ is the bandwidth, and $\xi_{eff} (\omega) = \xi(\omega) \times NF$. The first term in the denominator corresponds to the laser shot noise, the second term to the thermal noise, and the third term to the laser intensity noise. For the parameter values $R = 50 \Omega$, $\eta = 0.8$, $\xi(\omega) = 1.8 \times 10^5 Hz^{-1/2}$, and $NF = -10 \text{ dB}$, the laser intensity noise dominates, and the condition $S_c = 1$ for the minimum detectable absorption gives $\alpha L = \xi(\omega) NF \Delta f^{3/2}$. To avoid additional loss of signal, the effective bandwidth $\Delta f$ should exceed the bandwidth of the modulation. The assumption that the cantilever bandwidth $\omega_0/Q = \Delta f$ implies $0.1(\alpha L)_{electronic} = (\alpha L)_{cantilever}$, i.e. the smallest measurable absorption using the cantilever is less than the corresponding value for electronic detection by an order of magnitude.

In conclusion, we have presented estimates indicating that opto-nano-mechanical sensors based on cantilevers can be employed as high-Q filters to circumvent laser noise limitations on the sensitivity of frequency modulation spectroscopy.

References
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