DOI 10.5162/SMSI2025/P52

Modelling Membrane-Based Compact Fiber-Interferometric Gas Pressure Sensors in Cryogenic Environments

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Summary: Ultra-thin nanomechanical membrane oscillators are used in various technological applications. Recently, the ability to sense gas pressures across a ten-decade measurement range was demonstrated by interrogating the motion of a silicon-nitride trampoline membrane with a free-space interferometer. To increase the flexibility and compactness of this sensing solution, the use of optical fibers is a promising pathway toward broad applicability. Here, we model the interface between an optical fiber and a silicon-nitride membrane, and verify pressure readings from a prototype sensor inside a cryogenic vacuum system using a rarefied gas simulation. We find the fiber-based sensor to have a comparable readout sensitivity to a free-space setup while delivering predictable and precise pressure readings even in cryogenic environments.

Keywords: interferometry, MEMS, vacuum, cryogenics, gas pressure sensing, silicon-nitride membranes, finite-difference time-domain method, rarefied gas simulation

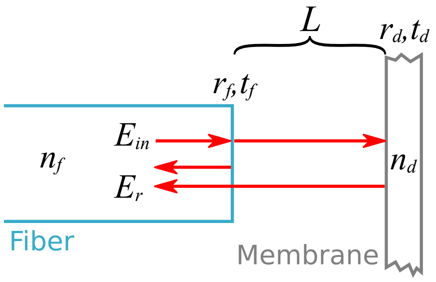

Fig. 1: Schematic of the fiber-membrane interferometer. A part of the incoming light wave E_{in} is reflected at the fiber tip while another part propagates in free space to the membrane, which itself reflects a part of this light. Back at the fiber tip, the two components recombine and interfere, forming the reflected wave E_{r}. Adapted from [2].

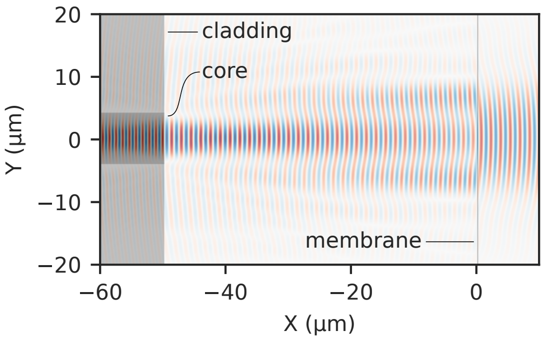

Fig. 2: Simulated electrical field pattern for the fiber-membrane interferometer. A continuous wave is emitted from the fiber core (dark gray) on the left of the image. The membrane (thin line at $X = 0$) reflects a part of the light back into the fiber, while some light is lost by transmission through the membrane or reflection into the fiber cladding.

Pressure Sensing Principle

A 50-nm-thick silicon nitride membrane is immersed in the gas to be analyzed. Through its high internal stress and frame design, the membrane with a sidelength of approx. 1 mm is able to oscillate in its drum mode with very low internal friction. Any presence of residual gas particles increases the damping of the membrane oscillation, reducing its mechanical ringdown time. By measuring this ringdown time interferometrically, the pressure of the surrounding gas is reconstructed as demonstrated before with up to a ten-decade measurement range [1].

Modelling the Fiber-Membrane Interface

The interferometer for detecting the membrane motion is formed right in the space of approx. 100 µm between the fiber tip and membrane surface, see fig. 1. As the membrane oscillates, it modulates the distance between the fiber tip and the membrane surface and, consequently, the phase of the light reflected by the membrane. This light then interferes inside the fiber with the light that was internally reflected at the fiber tip, modulating the total reflected optical power.

As the membrane oscillation is converted to a modulation of the light power reflected by the interferometer, the modulation amplitude and the photonic shot noise of the power measurement fundamentally determine the smallest detectable membrane displacement. To estimate the displacement signal and shot noise of the fiber-

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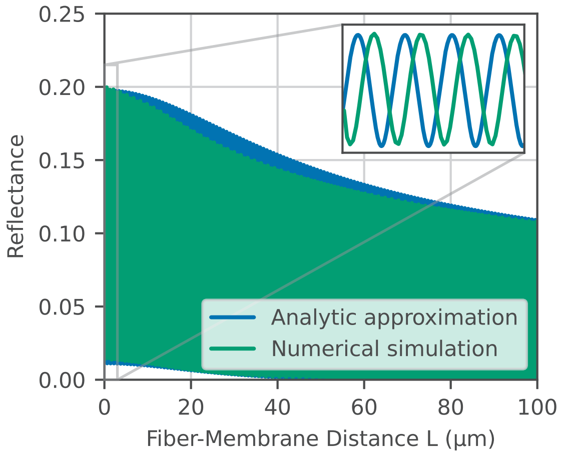

Fig. 3: Modelled reflectance of the fiber-membrane interferometer as the distance between fiber tip and membrane is varied. The analytic approximation assumes a gaussian mode profile of the light exiting the fiber, while the numerical simulation is the result of a finite-difference time-domain (FDTD) optics simulation [3] implementing the actual fiber eigenmode.

membrane interferometer, the interferometer reflectivity as a function of distance L between the fiber tip and the membrane was estimated using both a numerical simulation (fig. 2) and an analytic method, which differ by 7 % at most.

Fig. 3 shows the predictions of the interferometer reflectance. The highest signal-to-noise ratio is achieved at small gaps L, where the interference signal has the highest amplitude. In this case, no reflected light is lost due to mode mismatch between the reflected beam and the fiber eigenmode, which corresponds to the performance of a free-space interferometer. At a distance of 100 µm, more than half of the maximum signal is still conserved. In a shot-noise-limited scenario, this equates to losing less than 30 % in signal-to-noise ratio.

Modelling Pressure Gradients in Cryogenic Environments

To demonstrate the pressure sensing ability of a fiber-based prototype sensor at cryogenic temperatures, it was placed in a vacuum chamber immersed in liquid nitrogen (fig. 4(a)). Nearby, a controlled stream of gas entered the chamber to control the gas pressure. The pressure reading from the membrane sensor was compared to a commercial pressure gauge placed in the room-temperature top part of the system [4]. However, due to pressures being in the free molecular flow regime, the pressures inside the vacuum system varied substantially by location inside the system, leading to differences between the pressure reading in the two locations. To verify the measured pressure differences between the top and bottom of the vacuum system, a finite-elements simulation [5] was conducted, see fig. 4(b). It verified the pressure differences to within 15 % of the observed values.

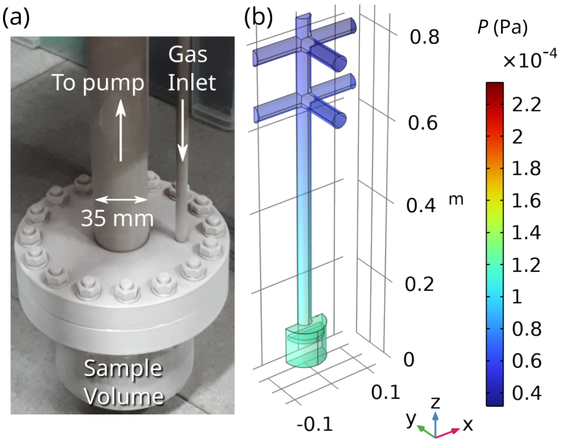

Fig. 4: (a) Photograph of sample volume in cryostat. (b) Model geometry and simulated pressure distribution in cryostat vacuum system. Gas is injected in the bottom chamber at cryogenic temperature and pumped out of the system near the top at room temperature.

Conclusion

By modelling the fiber-membrane interface, we estimated the shot-noise-limited readout sensitivity of portable cm-scale fiber-interferometric pressure sensors to reach at least 70 % of a free-space table-top Michelson interferometer. Further, molecular flow simulations of the pressure gradients inside a cryogenic test setup match the measurements within 15 %. Overall, the presented simulations support the development of our novel, broadly applicable gas pressure sensor combining a nanomechanical resonator with a compact and flexible fiber-based readout, especially for applications in cryogenic environments.

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