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Invited Paper

Miniature fiber acoustic sensors using a photonic-crystal membrane

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ABSTRACT

This paper discusses recent developments in fiber acoustic sensors utilizing a miniature Fabry–Perot (FP) interferometer fabricated at the tip of a fiber. The FP is made of a high-reflectivity photonic-crystal membrane placed ~30 μm from the reflective end of a single-mode fiber. When exposed to an acoustic wave the compliant membrane vibrates, and this vibration is detected as a modulation of the optical power reflected by the FP. The interferometer is enclosed in a sensor head designed, with the assistance of an electro-mechanical model, to minimize squeezed-film damping of the thin air gap between the reflectors and obtain a good acoustic response. The sensor head is fabricated out of silica elements and assembled with silicate bonding to minimize thermal expansion and ensure thermal stability. In the first sensor of this type the reflector at the fiber tip is a gold coating. It exhibits an average minimum detectable pressure (MDP) of 33 $\mu Pa/\sqrt{Hz}$ (1–30 kHz), a high thermal stability, and a weak polarization dependence. The second sensor incorporates several improvements, including a larger membrane for increased vibration amplitude, and higher reflectivity mirrors (PC and fiber tip) for increased displacement sensitivity. Its measured response is flat between ~600 Hz and 20 kHz, with a normalized sensitivity as high as ~0.17 Pa^{-1}. Between 1 kHz and 30 kHz its average MDP is ~2.6 $\mu Pa/\sqrt{Hz}$, the lowest reported value for a fiber acoustic sensor this small. These results demonstrate the promising potential of this class of stable and compact optical sensors for highly sensitive detection in the audible range.

1. Introduction

Acoustic sensors are used for applications in multiple disciplines, including the energy sector (oil and gas extraction), medical devices (magnetic resonance and acoustic/ultrasonic imaging), underwater communications, seismic research (underwater survey), nondestructive testing (monitoring large structures), and military applications (aerial, ground, and underwater surveillance). Performance requirements vary greatly, but in general the sensors are expected to have a fairly low minimum detectable pressure (MDP), as low as 10 $\mu Pa/\sqrt{Hz}$ in some cases, a wide bandwidth (hundreds of Hz to a few kHz is typical), and a high dynamic range (60 dB in pressure is common). For some applications, in particular oil exploration, it is often necessary to multiplex many sensors to achieve a high spatial resolution.

Most high-end commercial microphones use capacitive sensing, which provides a higher sensitivity and a lower noise than other types, such as electret and piezoelectric microphones. For example, a state-of-the-art condenser microphone (Brüel & Kjær 4179) can detect a pressure as low as 0.1–1 $\mu Pa/\sqrt{Hz}$ over the 10 Hz–10 kHz range [1]. However, these microphones are assembled manually at high cost, they require a high polarization voltage (200 V) and an expensive low-noise amplifier, and they are bulky (~10 × 1 × 1 cm). To overcome some of these issues, acoustic sensors based on micro-electro-mechanical-system (MEMS) structures have been developed. Most of them use capacitive sensing too: a thin compliant membrane forms one of the plates of a capacitor, and a change in voltage across the capacitor is detected when the membrane vibrates due to an acoustic wave. Many membrane materials (silicon nitride [2], poly-silicon [3], silicon oxide/nitride [4], and aluminum [5]) were implemented to increase the compliance and thus the sensitivity, as well as several designs to lower the noise, flatten the frequency response, and/or reduce manufacturing cost and complexity [2]. Among these, microphones with a silicon–nitride membrane achieved an MDP of ~3 $\mu Pa/\sqrt{Hz}$ at 1 kHz and a flat response between 1 and 20 kHz [2].

The use of photons and optical fibers to detect acoustic waves is an attractive alternative because fiber sensors can be extremely sensitive and, unlike established technologies, they are immune to electromagnetic interference. In addition, they can be very compact, a key feature in applications such as oil-well monitoring where space is limited. Fiber acoustic sensors also operate well in harsh environments (at sea, at elevated temperature, or in oil wells). Multiple sensors can also be multiplexed on a single or a pair of long fibers to form sensor arrays for distributed sensing and/or to probe remote regions.

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Table 1
Performance of selected acoustic sensors.

Authors (Year)	Flat band	Average MDP (μPa/√Hz)	Minimum MDP (μPa/√Hz)	Sensing scheme/ Medium	Ref.
B&K 4179 (1984)	10 Hz–10 kHz	0.16	0.1	Capacitive/ Air	[1]
Scheeper (2003)	20 Hz–20 kHz	~2.8	~1.4	Capacitive/ Air	[2]
Akkaya (2012)	~700 Hz–~8.6 kHz	~65	5.6[a]	Fabry–Perot/Air	[18]
Kilic (2011)	~400 Hz–~10 kHz	~173	12[a]	Fabry–Perot/Water	[17]
Foster (2011)	~30 Hz–~7 kHz	~72	~46	DFB fiber laser/Air	[21]
Zhang (2008)	100 Hz–1 kHz	~215	140	Fiber laser/ Water	[20]
Løvseth (1999)	N/A	~20,000	283	DFB fiber laser/Air	[19]
Dandridge (1991)	N/A	~76	~50	MZ/Water	[12]
Bucaro (2005)	0.01 Hz–20 kHz	~680	~400	Fiber bundle/Air	[23]
Kurmer (1992)	N/A	N/A	1,000	Sagnac interfer./Air	[11]
Moccia (2012)	4 Hz–35 kHz	N/A	10,000[a]	FBG/Water	[9]

N/A = data not available.
[a] At a resonance.

The first fiber-optic acoustic sensors, reported in 1977 by Bucaro [6] and Cole [7], were based on the phase modulation of an optical mode induced by pressure on the refractive index of a fiber. Since then, a wide range of principles have been explored, including many types of fiber interferometers (fiber Bragg grating [8,9], Sagnac [10,11], Mach–Zehnder (MZ) [12–14], and Fabry–Perot [15–18]), fiber lasers [19–21], and vertical silicon nanowire arrays [22]. Table 1 summarizes the measured properties of the subset of these publications that provide either a measured MDP value or sufficient measured data to calculate it. It lists the frequency range of the flat band, the average MDP over the flat band, and the minimum MDP (which may occur at some mechanical resonance outside of the flat band). Unfortunately, several of the cited references mention only an absolute sensitivity in V/Pa, which has limited value because a voltage can always be amplified to arbitrarily large values if one is not concerned with noise. The first two sensors in the table are electrical, and they have both a very large bandwidth and a very low average MDP over this bandwidth (0.16 and 2.8 μPa/√Hz). The rest of the sensors are optical. Other than the fiber bundle sensor [23], they are all interferometric. Fiber-laser-based sensors [19–21] have produced excellent MDPs, in the range of ~50–300 μPa/√Hz, over fairly limited ranges (30 Hz to 7 kHz). The FBG-based sensor [9] has a poor MDP (~10 mPa/√Hz) but a broad bandwidth (up to 35 kHz). MZ-based sensors can be highly sensitive [12–14], but then they require very long lengths of fiber and are consequently fairly bulky and have limited response at low frequencies [13,14]. Sagnac-based sensor also tend to suffer from the same limitations [10,11]. In some cases, for example in MZ-based sensors, the sensitivity to input polarization requires implementing complicated polarization diversity and demodulation schemes to combat polarization-induced signal fading [13,14]. Sensitivity to temperature is also a common issue [8,16,17,19].

In recent years, our research group has been studying an acoustic fiber sensor that utilizes a miniature FP interferometer placed at the tip of a fiber (see Fig. 1a), a device first proposed and implemented with a very low finesse FP in [15]. The FP consists of a deformable photonic-crystal (PC) membrane placed within a few tens of microns of the mirrored tip of a single-mode fiber [18]. The PC membrane acts as the FP's second reflector. When an acoustic wave is incident on it, it vibrates, which modulates the FP cavity length at the acoustic frequency. This modulation causes the FP reflection spectrum to be modulated in frequency, at this frequency. This spectrum modulation is detected by launching a single-frequency laser signal into the FP via the fiber at a wavelength λ_0 tuned to a steep portion of a FP resonance (see Fig. 1b). These hybrid devices combining fiber and MEMS technologies rank among the most promising for high-sensitivity applications. They exhibit a high sensitivity arising from the large flexibility of the very thin membrane, high thermal stability, and great compactness (typical volume of ~cm^3). As shown in Table 1, they have been demonstrated to have a low average MDP (~65 μPa/√Hz) over a fairly broad flat band (~700 Hz to ~8.6 kHz) [18].

In this paper, we first present an overview of the concept, design, and fabrication of these devices, as well as the principle of the model used to predict their sensitivity, noise, and MDP. We then report the performance of two specific sensors. The first one, previously reported in [18], utilizes a gold-coated reflector at the end of the fiber. It exhibits an average MDP of 33 μPa/√Hz over the 1–30 kHz range, a very good thermal stability, and a weak polarization dependence. The second sensor incorporates a 25% larger membrane, which increased the displacement per unit pressure 2.3-fold; a fiber reflector (dielectric mirror) and a PC with higher reflectivities, which increased the displacement sensitivity; and optimized laser power to reduce the optoelectronic noise. This sensor exhibits a remarkably low MDP averaging ~2.6 μPa/√Hz between 1 and 30 kHz, the lowest reported value for a fiber acoustic sensor of this size.

2. High-sensitivity thermally stable acoustic fiber sensor

2.1. PC membrane design and fabrication

The PC membrane performs two functions. First, being compliant it acts as a transducer that converts the incident acoustic energy into a physical vibration. Second, it is a high reflector and part of an FP interferometer that converts this vibration into a modulation of the optical power reflected by the FP. The PC consists of a square pattern of circular holes on a 450-nm-thick film of silicon. A square membrane was selected because for equal area a square shape deflects more than a circular shape, and hence produces a higher sensitivity. When the PC has the correct hole size and period, light in a certain range of frequencies incident on the PC at normal angle cannot propagate through the PC and is reflected. A commercial simulator based on finite-difference time-domain analysis was used to predict the period and hole diameter that yield maximum reflectivity around the target wavelength of operation (~1550 nm). For the predicted optimum period (900 nm) and diameter (800 nm), the predicted reflectivity spectrum of the PC has a maximum greater than 99% at 1550 nm, with a 10% full width of ~48 nm [24]. This broad bandwidth relaxes the constraint on the sensor's operating wavelength.

The PC membranes were fabricated using photolithography at the Stanford Nanofabrication Facility on a 4-in. silicon-on-insulator wafer (450-nm thick device layer, 1-μm buried oxide, and 450-μm handle layer). The arrays of holes were first patterned using reactive ion etching. The etched structures were then covered with an oxide film for protection during fabrication, then with a nitride film to prevent bulging of the membranes (the tensile stress of the nitride film compensates for the compressive stress of the oxide film). Third, the handle layer was etched in tetramethylammonium hydroxide to open the back side of the PC membranes. The wafer was then diced into 5 × 5 mm pieces, each containing one PC membrane. Finally the PC membranes were released individually