Probing the Intrinsic Thermal Noise of Optical Fibers at Infrasonic Frequencies

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Abstract: A Mach-Zehnder-Fabry-Perot-hybrid sensing scheme is proposed for probing the fundamental thermal noise of optical fiber in the infrasonic region. A feasibility analysis is presented and experimental realization is discussed.

OCIS codes: (060.2370) Fiber optics sensors; (120.5050) Phase measurement; (120.2230) Fabry-Perot

1. Introduction

Recently, there has been a lot of interest in the pursuit of highly sensitive, miniature fiber-optic sensors operating at their fundamental limit of performance [1,2]. It is generally believed that such a limit is set by the intrinsic thermal noise of optical fibers, which refers to the spontaneous fluctuations of fiber properties, such as length and refractive index, under the equilibrium condition [3]. Whereas the behaviors of the fiber thermal noise at high frequencies (typically > 1 kHz) have been well understood [4], the exact mechanism that leads to the low-frequency thermal noise, which has a strong 1/*f* dependence, is still up for debate [5,6]. In recent years, several reports have shown that the 1/*f* behavior of thermal phase noise can be attributed to the thermomechanical fluctuation of fiber length [3,5,7]. In particular, Bartolo *et al.* showed that the thermomechanical model led to an excellent agreement between theory and experiment within 20–800 Hz [7]. Below 20 Hz, however, their measurement was dominated by residual intensity noise of the laser. A more definitive experimental verification would require extending the thermal noise probing further toward lower frequencies, i.e. into the infrasonic region.

Reaching the thermal-noise limit at infrasonic frequencies is practically challenging because the minuscule noise can be easily masked by the large low-frequency noises of the laser as well as the system fluctuations caused by external perturbations. Despite some exciting recent progress in thermal noise-limited fiber-optic sensing [1,7], a convincing measurement of the thermomechanical noise spectrum remains unattained. Here I present a new sensing scheme that has the potential to *enhance* the thermomechanical noise by orders of magnitude and hence allow it to stay above the laser noises and ambient noise even in the infrasonic region.

2. Operation principle

Let us begin by first establishing an expected scale of the thermomechanical noise in typical fibers. Following the formulation in [5] and using the typical parameters for single-mode fibers, $T = 298\ \mathrm{K}$, $n = 1.457$, $\lambda = 1.55\ \mu\mathrm{m}$, $E_0 = 19\ \mathrm{GPa}$, $\varphi_0 = 0.01$ and 250-μm fiber diameter, the thermomechanical phase noise amplitude after a single pass through the fiber can be written as $\sqrt{S_\varphi(f)} = 0.571\sqrt{L/f}$ μrad/√Hz, where *L* is fiber length and *f* is frequency.

In principle, such a phase fluctuation can be measured by using a fiber Mach-Zehnder interferometer (MZI) [8]. However, since the noise amplitude scales by $L^{1/2}$, in order for the thermomechanical noise to dominate over other noises, the arms of the MZI have to be made very long (~100 km), which renders the scheme unpractical. On the other hand, it has been shown that a fiber Fabry-Perot (FP) cavity can enhance the single-pass phase noise by a factor of n_g / n when the laser is on resonance with the cavity and the noise frequency is much smaller than the cavity free spectral range [2]. Here *n* is the refractive index of the fiber and n_g refers to the group index of the FP cavity, which is related to the cavity finesse F through the relation $n_g \approx (2/\pi)nF$ when $F \gg 1$. This offers a much more effective way to enhance the thermal phase noise, i.e. using FP cavities as optical path folders in a MZI phase sensor. Fig. 1(a) inset shows a conceptual layout of the proposed MZI-FP hybrid phase sensor. If the laser frequency remains on resonance with both cavities and the two cavities are matched in length and finesse, the phase sensitivity of the MZI is a factor of n_g / n greater than a MZI of the same dimensions but without the FP cavities. For example, if the FP cavities are 1 m long with $F = 1000$, the expected thermomechanical phase noise at the output of the MZI is $515/\sqrt{f}$ μrad/√Hz, a factor of 638 greater than the noise expected from a 1-m fiber MZI without the FP cavities.

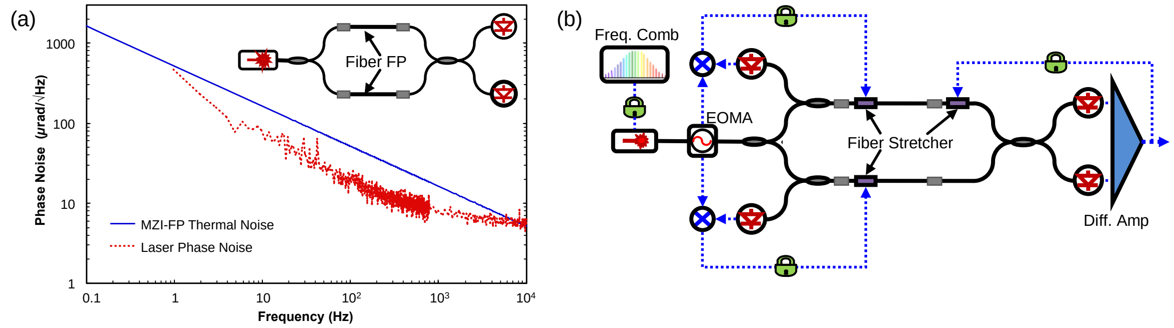

Fig. 1: (a) The thermomechanical phase noise spectrum expected from a MZI-FP hybrid phase sensor (inset) is compared with a typical laser phase noise spectrum. (b) A *proposed* system layout for the MZI-FP hybrid phase sensor. EOMA: electro-optic modulator assembly.

Meanwhile, any mismatch between the lengths and the finesses of the two FP cavities would allow the laser phase noise to leak through the MZI. For a 1-m fiber FP cavity, it should be easy to control its length to well within 1 mm [8]. The mismatch of cavity finesse is somewhat harder to gauge. The new fiber-end coating technology offers a reliable route toward high-finesse (>1000) fiber FP cavities, and a 1% system error is considered feasible within same coating runs. When both FP cavities in Fig. 1(a) inset are in resonance with the laser, the worst-case path length mismatch between the two MZI arms is about 7 m. The corresponding laser phase noise present at the MZI output is shown in Fig. 1(a), which is converted from a typical frequency noise spectrum measured with a commercial low-noise diode laser (RIO Orion Grade 5 by Redfern Integrated Optics). This noise is compared with the expected total thermomechanical phase noise at the output of the MZI, and it is clear that the fiber thermal noise prevails over the laser phase noise at frequencies above 1 Hz even when the laser is in free-run. A long-term laser frequency stabilization referenced to a frequency comb can further suppress the laser phase noise at low frequencies [1], making possible thermal noise-limited detection at sub-Hz frequencies.

Laser intensity noise is also a crucial limiting factor. Its potential impact in an MZI phase measurement scheme can be evaluated following the analysis outlined in [8]. The variation of the differential photo current can be written as $\delta i_d = \varepsilon \alpha I_0 \left(d\phi + \delta k_1 \delta k_2 dx + \phi_q dx \right)$, where $d\phi$ is phase noise, dx is relative intensity noise, δk_1 and δk_2 are the power-splitting errors (from 50%) of the two fiber couplers, and ϕ_q is a possible small phase offset from quadrature. Clearly, the intensity noise comes into the differential photo current as a result of imbalanced power splitting and an imperfect quadrature condition. For example, taking $d\phi$ to be 515 μrad/√Hz at 1 Hz, if $\delta k_1 = \delta k_2 = 0.1$, dx needs to be less than about -26 dB/√Hz at 1 Hz in order for the phase noise to stay above the intensity noise. On the other hand, if we take ϕ_q to be 1 degree, then dx must be below -31 dB/√Hz at 1 Hz to make the phase noise dominate.

3. Experimental realization and conclusion

The experimental realization of the above MZI-FP hybrid scheme requires the two FP cavities be kept on resonance with the laser. This can be done by actively locking the laser frequency with one of the transmission peaks of each cavity. A complete system layout is shown in Fig. 1(b). An electro-optic phase modulator is inserted at the input of the MZI to add side bands to the incident light. A 2×1 fiber coupler in each arm helps extract the PDH error signal from the FP cavity. This error signal is used to drive a fiber stretcher that controls the FP cavity length. To make sure the locking system does not interfere with the phase noise measurement, the bandwidth of the phase locked loop must be set to below the intended noise band (e.g., < 0.1 Hz). In addition, a quadrature lock may also be needed since maintaining the MZI in quadrature is critical for minimizing the impact of laser intensity noise. This can be done by actively controlling the length of one MZI arm (outside the FP cavity) as shown in Fig. 1(b). In conclusion, the MZI-FP hybrid scheme appears to be feasible to achieve thermal noise-limited sensing at infrasonic frequencies.

4. References

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