Super-sensor based on fast light Brillouin fiber laser

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A theoretical analysis shows that a sensor based on a white light cavity resonator implemented with a Brillouin fiber ring laser achieves ultra-high sensitivity.

Optical interferometers (which extract information from the superposition pattern of two waves) and resonators (optical cavities where light circulates in a closed path) are among the most precise physical measurement approaches, which makes them key components in many diverse research fields, from gravitational wave detection to rotation sensing. Such devices work by accurately detecting and measuring the phase shifts induced by small changes in the optical path of light as it interacts with the quantity being measured. Though the physical causes of such changes in optical path ‘length’ can vary, the detection mechanisms are similar. A resonator-based sensor uses the disturbance-induced shift of its resonance frequency to quantify the disturbance.

Thus, all optical sensors essentially detect changes in optical path length. Enhancing their sensitivity and accuracy requires increasing the slope of the measured signal as a function of the measured quantity, so that even tiny changes produce a larger and more easily quantified output. In a resonant cavity-based sensor, the basic parameter determining the sensitivity ($S$) is the amount by which the resonance frequency shifts in response to a change in the cavity length (i.e., the optical path length of the cavity).

Recent studies have shown that there is tremendous potential for enhancing the accuracy and sensitivity of these types of sensors by devising devices that exhibit a nonlinear response to the measured quantity. In our work, we focused on the ‘white light cavity’ (WLC) effect (an arrangement for making the cavity resonate over a wider range of frequencies) as a way to substantially augment the sensitivity of an optical resonator. More specifically, we proposed and analyzed a theoretical implementation of an ultra-sensitive WLC sensor based on a Brillouin fiber laser (a laser that uses Brillouin scattering to achieve optical gain).

Conventional optical cavities are characterized by resonance frequencies, that is, generally discrete frequencies for which constructive interference occurs in the cavity. A WLC structure introduces into the cavity an anomalous dispersive element that modifies this property. When set correctly, the phase shift of this element compensates the phase shift of conventional propagation, making the cavity resonant for a wide range of frequencies.

The sensitivity of a cavity-based sensor is inversely proportional to the cavity group delay (a measure of the time delay of a pulse propagating in the cavity). For an ideal WLC, the group delay is essentially zero (the round-trip phase is frequency independent), thereby yielding an extremely large sensitivity. This can be understood intuitively by considering that, in a WLC, a wide range of frequencies satisfy the resonance condition for a given cavity length $L$. When $L$ is changed to $L'$, however, none of the frequencies in that band will any longer satisfy the resonance condition. Consequently, the resonance frequency must shift significantly from its original value to re-satisfy the resonance condition for the new length. The outcome is that even very small changes in $L$ produce a considerable shift in the resonance frequency, resulting in a large sensitivity $S$.

However, the enhanced sensitivity of WLCs does not, by itself, directly yield a corresponding improvement in the minimum measurable perturbation, due to the mitigating effect of the associated broadening of the cavity resonance linewidth. It is thus also necessary to use an active cavity (i.e., a laser),

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which has a substantially narrower linewidth than a passive cavity even under the WLC condition.

The scheme we investigated consists of a Brillouin fiber ring laser incorporating an intra-cavity resonator that acts as the negative phase component for achieving the WLC condition (see Figure 1). The advantages of the fiber implementation are simplicity, compact size, and robustness. The ultra-narrow bandwidth Brillouin gain ensures single-mode operation of the laser.

The ring-resonator implementation of the phase component provides three parameters for controlling phase response: the ring circumference and the two coupling coefficients. The WLC condition can be satisfied by many combinations of these parameters. However, the solutions differ in the sensitivity enhancements they produce, and in the induced round-trip losses. As a general trend, higher sensitivity is accompanied by larger cavity loss (see Figure 2).

The ultimate test of a sensor’s efficacy is the minimum detectable change in the optical path ($\delta L_{\text{min}}$). This quantity, which in a laser sensor is determined by fluctuations of the lasing frequency, is limited by noise. The most fundamental noise source, which cannot be compensated, is the quantum detection or shot noise. The frequency fluctuations due to shot noise are inversely proportional to the cavity quality (Q) factor, while the resonance shift is determined by $S$. Since the Q factor and $S$ are inversely related (Q decreases for larger $S$), there is a design tradeoff and it is not obvious whether it is more advantageous to increase the sensitivity or the Q factor.

Figure 3 shows the dependence of $\delta L_{\text{min}}$ on the coupling coefficient of the resonator $k_1$, where smaller values of $k_1$ correspond to a higher Q and smaller $S$. Although it is beneficial to increase Q (at the expense of $S$), the differences are minor and any choice of $k_1$ is essentially acceptable. The important parameter is $\delta L_{\text{min}}$, which for our arrangement is in the order of $10^{-25}$ m. This compares well with the $\delta L_{\text{min}}$ for a conventional sensor of this type, which is $\sim 4 \times 10^{-17}$. In other words, the WLC design enhances $\delta L_{\text{min}}$ by eight orders of magnitude.

In summary, WLC lasers are a promising new approach for constructing ultra-sensitive sensors. The proposed fiber-optic-based implementation makes the concept readily applicable in practice. In future work, we intend to follow up this analysis with an experimental demonstration of the scheme, and to address the noise source compensation issues needed to exploit the concept to its full capacity.

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