Slow-Light Fiber-Bragg-Grating Strain Sensor With a 280-femtostrain/$\sqrt{\text{Hz}}$ Resolution

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***Abstract*—We report a fiber strain sensor based on a single fiber Bragg grating (FBG) with a minimum detectable strain of 280 femtostrain/$\sqrt{\text{Hz}}$ in the 20-kHz range. This breakthrough was made possible by operating the FBG on one of its slow-light peaks, and utilizing a FBG with a particularly low loss, fabricated using ultrafast pulses, to maximize the sensitivity. A theoretical and experimental noise analysis shows that the sensor noise is limited by laser frequency noise and not fiber phase noise, which suggests that even greater performance can be expected with a more stable laser frequency. © 2012 Optical Society of America**

***Index Terms*—Fiber Bragg gratings, fiber optics sensors.**

I. Introduction

STRAIN sensors utilizing a fiber Bragg grating (FBG) have found practical applications in numerous areas, particularly in structural monitoring of civil structures, robotics, and aerospace. Most FBG strain sensors detect the shift in Bragg wavelength resulting from the application of a strain. This shift is typically detected either with an optical spectrum analyzer or an imbalanced Mach-Zehnder interferometer (MZI). The latter scheme produced a minimum detectable strain (MDS) of 0.6 n$\varepsilon/\sqrt{\text{Hz}}$ [1]. The sensitivity is limited by the linewidth of the signal reflected by the FBG, which imposes a maximum value on the path mismatch in the MZI [2]. Since then, this MDS has been exceeded in a number of other configurations. In [3], the edge of the reflection peak of an FBG was interrogated with a narrow-linewidth laser; a strain-induced shift in the FBG power-reflection spectrum was detected as a change in the power reflected by the grating. An MDS of 45 p$\varepsilon/\sqrt{\text{Hz}}$ was reported. In [5], an MDS of 5 p$\varepsilon/\sqrt{\text{Hz}}$ was measured by recording the power variation on the steep edge of the transmission peak that exists inside the bandgap of a π-shifted grating. Recently, we pushed this limit still further by recognizing that in an FBG with a large index modulation, strong slow-light transmission peaks exist just outside the bandgap[2]. When the FBG is probed at a wavelength that coincides with one of these slow-light peaks, the phase of the transmitted signal varies very rapidly in response to an applied strain, in proportion to the (high) group index at the signal wavelength. This enhanced phase change is converted into a power change by placing the FBG in an MZI. This scheme produced an MDS of 880 f$\varepsilon/\sqrt{\text{Hz}}$ [2]. Since then, we demonstrated an alternative scheme in which the FBG is probed at the steepest slope of one of its slow-light peaks [4]. As in [3], [5], this scheme directly converts the strain-induced shift in the transmission spectrum into a power change, without the need for an MZI. When evaluated with the same FBG as in [2], this approach led to a comparable MDS of 820 f$\varepsilon/\sqrt{\text{Hz}}$. A significant advantage of this scheme is that the sensor's temperature stability is far superior because it does not use an MZI [4]. It is also simpler than the scheme of [5], which requires a complex Pound-Drever-Hall scheme. Because the edges of an FBG's reflection peak may support slow, normal, or fast light, depending on the exact wavelength on these edges and details of the FBG's index profile [6], it is not possible to determine the group velocity of the scheme in [3], a point somewhat academic.

For reference, it should also be mentioned that other fiber strain sensors with extremely low MDSs have been reported that utilize a fiber Fabry-Perot (FP) interferometer made with two FBGs spaced by a length of fiber. In [8], an MDS of 120 f$\varepsilon/\sqrt{\text{Hz}}$ around 2 Hz was reported in a 13-cm FP cavity. In [9], the FP was 2.6 cm long and the MDS was 300 f$\varepsilon/\sqrt{\text{Hz}}$ around 300 Hz. Although these sensors have impressive sensitivities, and they are exploiting a similar principle as in [4] (probing the steepest side of a slow-light resonance), they utilize two FBGs instead of one, and they are longer than single-FBG sensors.

We make a point in this review to distinguish between passive sensors, such as the ones reviewed so far, and active sensors, in particular laser-based strain sensors, which can produce even lower MDSs but require an energy input. A prominent example of active strain sensor can be found in [7], which utilized an FBG incorporated in a fiber laser, and produced an MDS of 56 f$\varepsilon/\sqrt{\text{Hz}}$, in the high acoustic frequency range. Although its implementation is more difficult than a passive sensor, and it requires a large path mismatch that also leads to temperature instability, to our knowledge this reference holds the world record for a fiber strain at higher frequencies.

To narrow the gap between the lowest MDS reported for active and passive sensors, we have improved on our earlier work by implementing the slow-light scheme of [4] with a strong FBG that was fabricated with ultrafast pulses instead of UV light, and exhibited a considerably lower propagation loss. This loss reduction has enabled us to achieve a much larger sensitivity and to demonstrate a new record for a passive FBG strain sensor of 280 f$\varepsilon/\sqrt{\text{Hz}}$, compared to the previous record of 880

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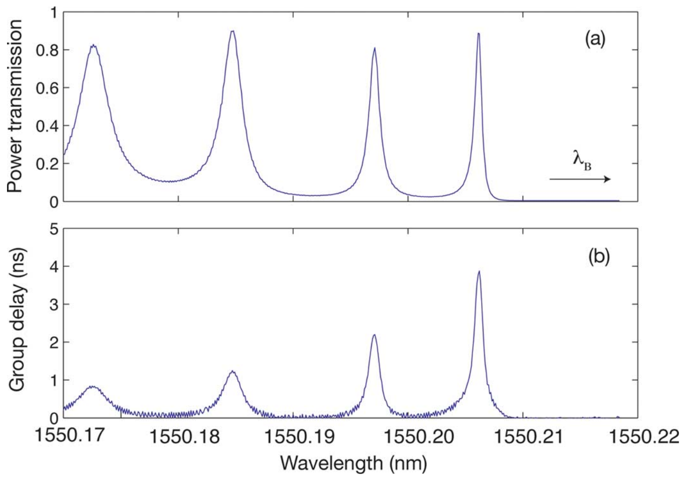

Fig. 1. (a) Measured power transmission spectrum, and (b) measured group delay spectrum of an apodized FBG.

$\mathrm{f}\varepsilon/\sqrt{\mathrm{Hz}}$. [4] This new sensor has essentially the same MDS as the FBG-based FP sensor of [8], but it utilizes a single FBG instead of two, and it is therefore inherently simpler, more compact, and more thermally stable. Compared to the FP sensor of [9], it has a larger MDS, but it benefits from the same advantages cited above. Compared to both FP sensors of [8] and [9], it utilizes a much simpler interrogation scheme and yet it is found to be stable for several hours.

II. Slow Light and Sensitivity

The principle of this FBG strain sensor was described in detail in [4]. In brief, the main contrasting feature of the FBG itself is that it is designed specifically to support strong slow-light transmission peaks. This is accomplished by a combination of (1) large index modulation (greater than ~ 0.001), (2) low propagation loss, (3) suitable apodization, and (4) optimizing the length for this loss[2]. To illustrate the sensor principle, Fig. 1 shows the measured power transmission and group delay spectra of the specific FBG used in this work. Only the portions of the spectra on the short-wavelength side of the bandgap are shown; because the FBG is apodized, the long-wavelength portion does not exhibit slow-light resonances, because both the ac and the dc components of the FBG's index profile are apodized. This grating was fabricated at Université Laval using ultrafast pulses at 403 nm [10]. Fitting these spectra to a model described elsewhere[2] indicates that this grating has an index contrast $\Delta n = 0.99 \times 10^{-3}$ and a length $L = 2.0$ cm, in agreement with the target values during fabrication, and a Gaussian apodization with a normalized full width at half maximum (FWHM) W/L of ~ 2. The measured transmission peak closest to the band edge has a power transmission of 89% and a group delay of 3.88 ns, or a group index of 58.2.

This FBG was evaluated as a strain sensor in the test bed of Fig. 2. Light from a single-frequency tunable laser (Agilent 81682A, $\text{linewidth} \approx 8$ kHz, maximum power 8 dBm) around 1.55 μm was launched into the FBG through a polarization controller. The FBG was wound under a slight tension on a cylindrical piezoelectric transducer (PZT), which applied to it a calibrated strain at a frequency $f_s = 23$ kHz. The laser wavelength

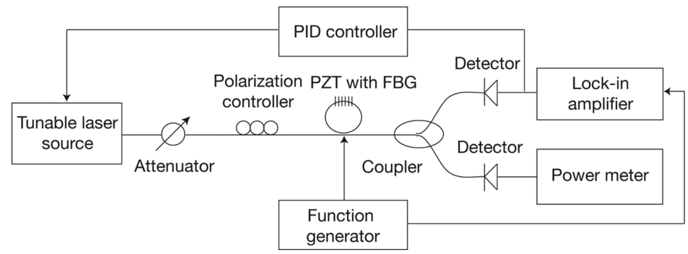

Fig. 2. Schematic of the slow-light strain sensor.

was tuned to the steepest slope of one of the slow-light peaks. When a dynamic strain is applied, the resulting modulation of the dimensions and refractive index of the FBG results in a modulation of the FBG's transmission and slow-light spectra, which oscillate in phase at f_s. This results, in turn, in a modulation of the power transmitted by the FBG. The amplitude of this modulation was measured with a photo-detector (New Focus Model 1811) followed by a lock-in amplifier (SRS 830) (see Fig. 2).

The sensitivity of this device can be exceedingly high because the slope of the transmission resonance is very steep as a result of the low group velocity of the light. The sensor's normalized power sensitivity is defined as

$$S_n(\lambda) = \frac{1}{P_{in}}\frac{dP_{out}(\lambda)}{d\varepsilon} = \frac{dT(\lambda)}{d\varepsilon} = \frac{dT(\lambda)}{d\lambda}\frac{d\lambda}{d\varepsilon} \quad (1)$$

where $d\lambda$ is the spectral shift resulting from a small applied strain $d\varepsilon$. For a silica fiber, $d\lambda/d\varepsilon = 0.79\lambda_B$, where λ_B is the Bragg wavelength [13]. It can be shown easily that for a Lorentzian slow-light resonance, $dT(\lambda)/d\lambda$ is maximum (i.e., the slope is steepest) at $\lambda = \lambda_0 \pm \Delta\lambda\sqrt{3}/6$ and equal to $3\sqrt{3}T_0/(4\Delta\lambda)$, where T_0, λ_0, and $\Delta\lambda$ are the peak transmission, center wavelength, and FWHM of the Lorentzian[4]. By expressing $\Delta\lambda$ as a function of the group delay τ_g in the grating with $\Delta\lambda = \lambda_0^2/(\pi c\tau_g)$, where c is the speed of light in vacuum, we can rewrite the maximum sensitivity from (1) as

$$S_{\max} = \left(\frac{dT(\lambda)}{d\lambda}\right)_{\max}\left(\frac{d\lambda}{d\varepsilon}\right) = \frac{3.22cT_0\tau_g}{\lambda} \quad (2)$$

The conclusion is that the maximum strain sensitivity is proportional to $\tau_g T_0$, or equivalently to the product $n_g T_0 L$, where n_g is the group index at the resonance wavelength λ_0. It depends not only on the group index, but also on the peak transmission of the resonance. Since not all resonances have the same peak transmission and group index (see Fig. 1), for maximum sensitivity one must choose the resonance that has the highest $n_g T_0$ product. The resonance closest to the bandgap is not necessarily the one that does, because even though it has the highest group index, its power transmission is also generally the lowest. The factor of 3.22 in (2) applies for a Lorentzian lineshape. In practice, the lineshape depends on the FBG parameters and may depart from a Lorentzian. When it does this factor needs to be re-evaluated, although it is not generally very different, and the basic dependence in $\tau_g T_0$ still holds. Comparison between the prediction of (2) and the measured maximum sensitivity establishes that this factor gives the correct answer within $\sim 10\%$ for the FBGs that we characterized. Equation (2) therefore provides a convenient tool for quickly assessing the sensitivity of our slow-light sensor. The exact sensitivity spectrum can always be obtained by calculating the derivative of the transmission spectrum (see (2)).

The most critical feature in designing an ultra-sensitive slow-light strain sensor is to achieve a large index modulation Δn while maintaining the loss as low as possible. This is generally challenging because as Δn is increased by exposing the fiber to a higher dosage of laser radiation during fabrication, the loss generally increases. A compromise must therefore be made between Δn and loss so as to maximize the $\tau_g T_0$ product. We met this goal by utilizing FBGs fabricated at Université Laval using femtosecond pulses, a technique that yields a much lower loss coefficient than in UV-written FBGs with a comparable Δn. Several ultrafast FBGs with different index modulations and lengths were characterized to obtain their transmission spectrum and infer their approximate loss coefficient. For the FBG that yielded the best predicted maximum sensitivity (its spectra are the ones shown in Fig. 1), the inferred loss coefficient is $\sim 0.1\ \mathrm{m}^{-1}$. In comparison, the loss coefficients estimated by the same process in a number of UV-written FBGs with a similar Δn purchased from O/E Land, Inc. range from 1.1 to 1.5 m^{-1}. This range is in general agreement with literature values [14]. This significant loss reduction is readily apparent in the large increase in the transmission of the first slow-light peak (89%, see Fig. 1(a)) over the previous UV-written FBG we reported[4], which had a comparable Δn ($\sim 1.0\ 10^{-3}$) but a transmission of only 0.8% for the first peak and 13% for the second peak [4]. As a result of this greatly increased transmission, the expected maximum sensitivity of this new grating, calculated from (2), was significantly higher ($2.15 \times 10^6\ \varepsilon^{-1}$) than previously reported with this UV-written FBG ($1.7 \times 10^5\ \varepsilon^{-1}$ at the second peak [4]). This sensitivity is the highest that we measured among many gratings fabricated with ultrafast lasers or acquired from various commercial sources. On all counts, UV-written FBGs exhibited a significantly lower sensitivity, because of their higher intrinsic loss.

III. Sensor Performance

To validate these predictions, we tested the FBG in the setup of Fig. 2. A 10-mV peak-to-peak voltage at 23 kHz from a function generator was applied to the PZT, which produced a calibrated strain of 2.86 $\mathrm{n}\varepsilon$. At a discrete number of wavelengths over the range shown in Fig. 1, the amplitude of the strain-induced output power modulation was measured with the lock-in amplifier. To thermally stabilize the system against slow drifts in the FBG spectra due to temperature variations, a proportional-integral-derivative (PID) controller was used to lock the laser to a pre-set value of the transmission. The power input to the FBG was $P_{in} \approx 34\ \mu\mathrm{W}$, and the power at the detector was $P_d \approx 23\ \mu\mathrm{W}$. The latter was limited by the saturation level of our low-noise detector.

The measured strain-sensitivity spectrum is shown in Fig. 3. As expected, each slow-light peak gives rise to two narrow sensitivity peaks (compare to Fig. 1(a), one for each slope. The highest sensitivity occurs at the first slow-light peak and is equal to $S_{\max} \approx 2.1 \times 10^6\ \varepsilon^{-1}$. The sensitivity spectrum of this FBG was also predicted theoretically by calculating numerically the derivative with respect to wavelength of the FBG's measured transmission spectrum (Fig. 1(a)) and inserting it in (1). This calculated spectrum is shown in Fig. 3. There is clearly an excellent match between the theoretical and measured spectra. In particular, the predicted maximum sensitivity at the first slow-light resonance is equal to $\sim 2.16 \times 10^6\ \varepsilon^{-1}$ based on (2), which is within 3% of the measured value.

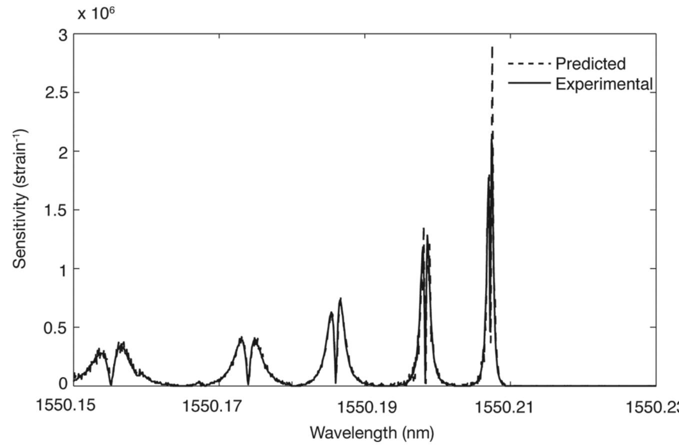

Fig. 3. Measured and predicted sensitivity of the slow-light FBG strain sensor. The FWHM linewidth of the slow-light peak closest to the band edge is approximately 0.1 pm.

The transmission and group delay spectra of an FBG also shift as a result of temperature fluctuations. The temperature-induced spectral shift for a silica fiber is $d\lambda/dT \approx 13\ \mathrm{pm}^\circ\mathrm{C}$ at 1.55 $\mu\mathrm{m}$ [15]. At the wavelength of highest strain sensitivity, the change in transmitted power resulting from this spectral shift is also enhanced by the slow-light resonance in the FBG. Following the same argument as presented in [4], this change in transmission, or normalized temperature sensitivity, can be written as:

$$S_T = \left(\frac{dT(\lambda)}{d\lambda}\right)_{\max} \left(\frac{d\lambda}{dT}\right) = 3.4 \times 10^{-5} \frac{cT_0\tau_g}{\lambda} \quad (3)$$

Clearly, as in most sensors, the same parameter that increases the strain sensitivity ($n_g T_0$ in this case) also increases the temperature sensitivity in a commensurate manner.

At the wavelength of highest strain sensitivity, as discussed above in relation to Fig. 1 $T_0 = 89\%$ and $\tau_g = 3.88$ ns, and (3) gives a temperature sensitivity $S_T = 22.1^\circ\mathrm{C}^{-1}$, which is fairly high. During measurements, the PBF and PZT were placed in a small enclosure to reduce air currents and reduce temperature variations of the FBG. The PID controller was very effective at stabilizing the residual temperature variations of the grating: the strain sensor was able to function for hours without resetting the controller.

The MDS for this strain sensor at the most sensitive slow-light wavelength can be found from

$$\varepsilon_{\min} = \frac{P_{noise}}{P_{in} S_n} \quad (4)$$

where P_{noise} is the total noise equivalent power (in $\mathrm{nW}/\sqrt{\mathrm{Hz}}$) at the detector. Fig. 4 shows the calculated dependence on detected power, at 23 kHz, of the main contributions to the noise in our sensor, which were laser frequency noise, detector noise, optical and electrical shot noise, and laser intensity noise. The latter was calculated as the RIN of our laser, specified by the

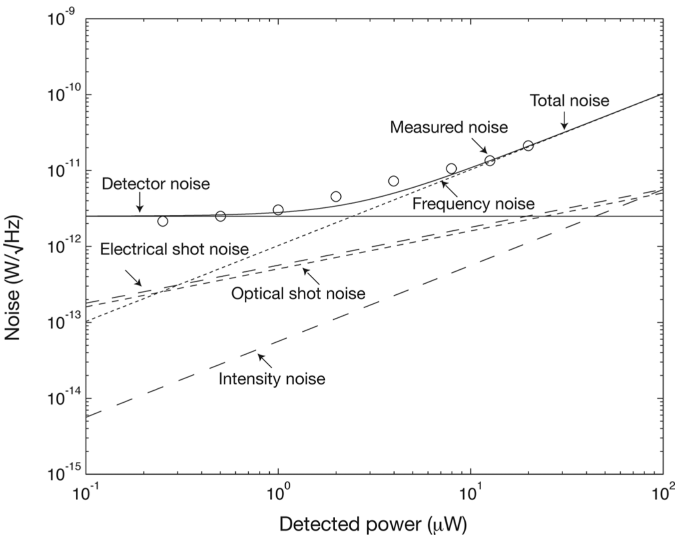

Fig. 4. Predicted noise contributions and measured total noise in our sensor at 23 kHz.

manufacturer, times the detected power. The detector noise was obtained from the manufacturer's stated noise equivalent power (2.5 $\mathrm{pW}/\sqrt{\mathrm{Hz}}$). A semiconductor laser with a linewidth Δv has frequency noise with a power spectral density of $S_f = \Delta v/\pi$ [3]. The laser linewidth is ~ 8 kHz, which yields to a noise of $2.5 \times 10^3\ \mathrm{Hz}^2/\mathrm{Hz}$. The frequency noise of the laser induces a strain-equivalent noise[3]:

$$\varepsilon_{noise} = \sqrt{S_f}\frac{d\lambda}{dv}\frac{d\varepsilon}{d\lambda} = \sqrt{\frac{\Delta v}{\pi}}\frac{\lambda^2}{c}\frac{1}{0.79\lambda} = \sqrt{\frac{\Delta v}{\pi}}\frac{\lambda}{0.79c} \quad (5)$$

where v is the laser frequency. Therefore, the noise induced in the sensor's output power by the laser frequency noise can be calculated from (1) as:

$$\sigma_p = \varepsilon_{noise}\frac{dP_{out}}{d\varepsilon} = \varepsilon_{noise}S_n P_{in} = \sqrt{\frac{\Delta v}{\pi}}\frac{\lambda}{0.79c}S_n\frac{P_d}{0.75T_o} \quad (6)$$

Fig. 4 shows that this contribution (evaluated for the laser linewidth of 8 kHz) is dominant when the detected power exceeds a few μW. The total noise, calculated as the square root of the sum of the square of these contributions, is shown as the solid curve.

The total noise dependence on detected power was also measured by attenuating the power on the detector and recording for each power the noise in the signal as observed on the lock-in amplifier. The experimental data points, plotted in Fig. 4, agree well with the theoretical prediction of the total noise, which give credence to our understanding of the dominant sources of noise in our sensor.

From this analysis, the measured total noise at the detected power of $P_d \approx 23\ \mu$W used to measure the maximum strain sensitivity was $P_{noise} = 20\ \mathrm{pW}/\sqrt{\mathrm{Hz}}$ (see Fig. 4). Entering this noise value, $P_{in} \approx 34\ \mu$W, and $S_{\max} \approx 2.1 \times 10^6\ \varepsilon^{-1}$ in (4) gives a measured MDS of 280 $f\varepsilon\sqrt{\mathrm{Hz}}$ at 23 kHz. The noise and the MDS were measured also at various frequencies down to 3 kHz, and found to increase closely to linearly between 23 kHz and 3 kHz. At 3 kHz both quantities were only about twice as large as at 23 kHz. This value of 280 $\mathrm{f}\varepsilon/\sqrt{\mathrm{Hz}}$ is, to our knowledge, the highest strain sensitivity reported for a passive FBG sensor, and a factor of ~ 18 lower than the previous record [5]. Since the noise is limited by the frequency noise of the laser, even if we further increased the sensitivity of our sensor the MDS would remain the same, since the noise would increase by the same amount as the sensitivity. Further reduction in the MDS will therefore require reducing the laser frequency noise.

Recent investigations of another kind of passive strain sensors utilizing a Fabry-Perot interferometer made with FBGs [8] has raised some controversy [11], [12] by claiming that its MDS was limited by the phase noise of the fiber. This debate was concerned in particular with how to apply the well-accepted expression of the phase noise picked up by light traveling along a length of fiber [16] to the more complicated case of light traveling multiple times in a resonator. The power spectral density of the thermal phase noise S_ϕ of a silica fiber of length L can be calculated using Wanser's formula[16]. The salient finding is that in a high-Q resonator, the phase-noise power spectral density is enhanced by a factor of $(n_g/n_o)^2$. In our case, this factor is 1611. The total phase-noise equivalent power is proportional to $S_\phi^{1/2}$, and therefore it is proportional to n_g. The physical reason for this proportionality is that photons near a slow-light resonance travel through the FBG approximately n_g times. Hence the phase noise they accumulate also scales linearly with n_g. A detailed derivation of this result will be published elsewhere. If we use Wanser's formula and include in it this enhancement factor to estimate the thermal phase fluctuations in our 2-cm FBG at room temperature and at 23 kHz, we find $S_\phi^{1/2} = 9.1 \times 10^{-8}\ \mathrm{rad}/\sqrt{\mathrm{Hz}}$. This thermal phase noise can be converted into a minimum detectable strain by using:

$$\varepsilon_{\min} = \frac{{S_\phi}^{1/2}}{2\pi n_g L}\frac{\lambda}{0.79} \quad (7)$$

In the numerator of (7), $S_\phi^{1/2}$ is proportional to n_g, and $\varepsilon_{\min}$ is independent of n_g. Equation (7) gives an expected strain-equivalent phase noise of 24 $\mathrm{f}\varepsilon/\sqrt{\mathrm{Hz}}$. This value is negligible compared to the other main noise contributions in our sensor (see Fig. 4). Although this result does not resolve the debate concerning the magnitude of thermal phase noise in the sensor of [8], this assessment shows that the resolution of our current sensor is not limited by phase noise. We therefore expect that in spite of the ultra-low MDS this scheme has enabled us to demonstrate, it has not yet reached its full potential.

IV. Conclusions

In conclusion, slow light in a low-loss FBG was utilized to improve the sensitivity in strain sensing to a new world record. A strain sensitivity of $2.1 \times 10^6 \varepsilon^{-1}$ and an MDS of 280 $\mathrm{f}\varepsilon/\sqrt{\mathrm{Hz}}$ at 23 kHz was experimentally demonstrated. This accomplishment was made possible by the use of slow light in a relatively long FBG (2 cm) with a remarkably low loss coefficient of $\sim 0.1\ \mathrm{m}^{-1}$, fabricated using ultrafast pulses instead of UV-laser exposure. An accurate prediction of the measured strain sensitivity was observed with a simple analytical model. Noise analysis suggests that this device was limited by frequency noise of the laser, and that thermal phase noise in the fiber sensor was negligible. By reducing the linewidth laser to reduce the laser frequency noise, and by using an FBG with an even lower loss and an optimized length, we expect to demonstrate even lower strain resolutions.

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