Supplemental Document

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Massively distributed fiber strain sensing using Brillouin lasing: supplement

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1. Amplitude-frequency cross sensitivity

In our initial testing, we found that the sensor exhibited higher noise at very low frequency (<1 Hz). For the data shown in figures 3a,b this low frequency noise resulted in ~1 MHz RMS noise in the mean Brillouin frequency recorded over a 10s of minutes. The entire FUT with the exception of the last ~50 m, was wound on the same spool, but this noise was not correlated from mode to mode, as we might have expected due to environmental drift in the SBS frequency (e.g. due to temperature fluctuations in the lab). However, we found that this noise was closely correlated with the amplitude of the individual lasing modes. We suspect that the longer lengths involved introduced larger environmental drift in the frequency dependent transmission through the system, likely mediated by polarization drift, which resulted in variations in the lasing amplitudes. By taking a linear regression of the lasing frequency versus amplitude the portion of the noise responsible for frequency variation could be removed. However, this procedure adds noise at higher frequencies and could distort the measured signals if there is a physical correlation between frequency and amplitude (e.g. due to frequency dependent detector response). To avoid adding additional noise or degrading signals, this procedure was only performed in cases where the amplitude-frequency cross-correlation was greater than 50%. Figures A1a-d show the frequency and temperature sweeps from the main text with and without this correction.

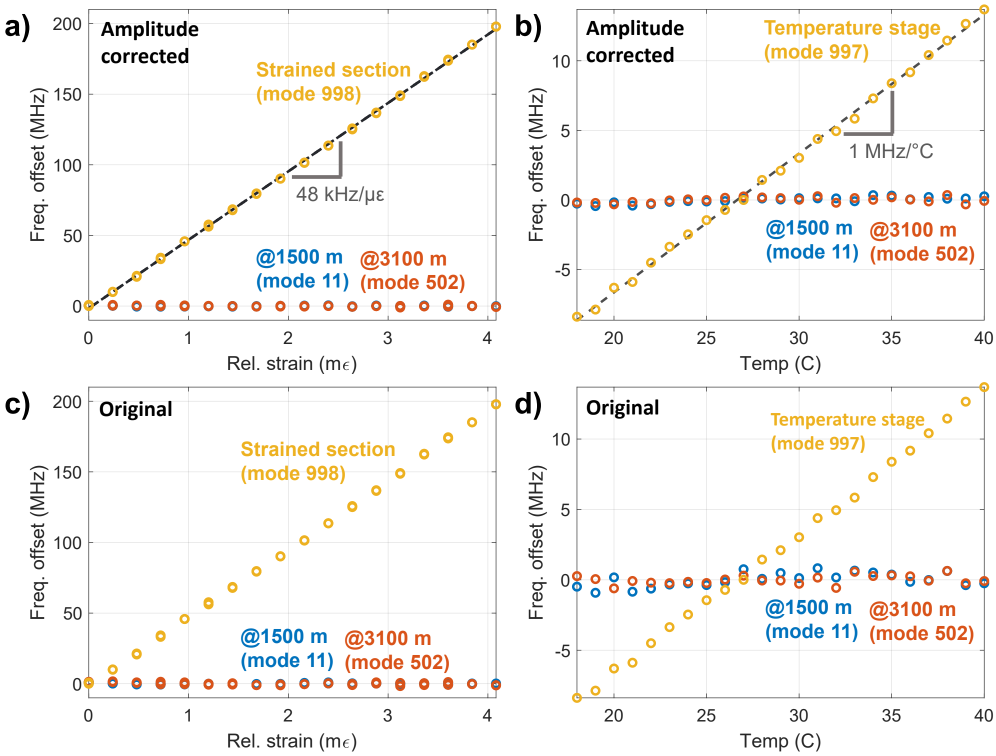

Figure A1. A comparison of the temperature and strain sweeps before and after correcting for the amplitude to frequency cross-sensitivity. (a,b) The data shown in the main text. (c,d) The original data before correction.

2. Pump depletion vs. Modulation instability

Figure A2a shows the power spectral density (PSD) of the transmitted pump for various initial pump powers as measured on an optical spectrum analyzer. At low pump powers the spectrum is a monochromatic peak (with a width limited by the ~0.01 nm resolution of the spectrum analyzer) riding on a 100 GHz ASE pedestal originating from the pump EDFA/WDM combination. However at high pump powers modulation instability becomes dominant, preventing substantial SBS gain at the end of the FUT. Figure A2b shows the power of the peak of the pump spectrum vs. initial pump power. Above 1000 mW, the peak power at the original laser frequency actually decreases due to modulation instability. This is consistent with the increase in noise at very high pump powers shown in Fig. 4(a).

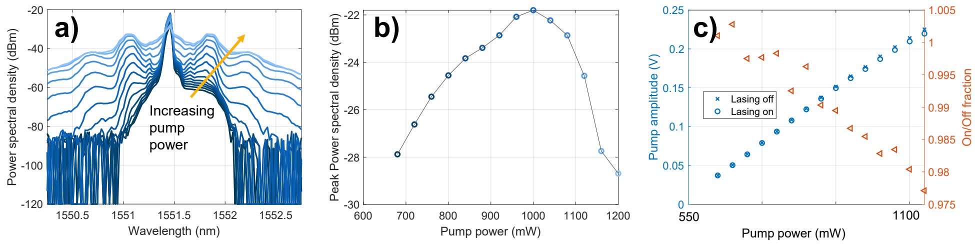

Figure A2. (a) Spectral density of the transmitted pump for incident powers from 680 mW to 1200 mW. At low powers, the pump consist of a single monochromatic peak. At high pump power, modulation instability reduces the power available to lasing modes near the end of the FUT. (b) Peak spectral density from (a) versus pump power. (c) Measured pump pulse amplitude versus pump power with and with lasing (controlled by toggling the fiber ring EDFA). This demonstrates minimal pump depletion even at high powers.

We also investigated pump depletion by measuring the peak power of the transmitted pump as a function of pump power when the SBS lasing was either on (loop EDFA activated) or off (loop EDFA deactivated). Figure A2c shows the peak measured voltage on the photodiode recording the pump pulses vs. pump power and the corresponding ratio of received power in the lasing on vs. lasing off conditions. This indicates that, at maximum, the pump depletion was ~2%.

3. Spatial resolution

The spatial resolution of the Brillouin fiber laser sensor is given by the pump pulse duration and the length of the pulses generated by EOM_2 (which are matched in this work). While the resolution of a BOTDA or BOTDR is also dictated by the pump pulse duration, there are a few important distinctions. In the traditional Brillouin time domain approaches (BOTDA, BOTDR), the gain spectrum measured at a particular position is roughly given by the average gain spectrum of all points within the sensor region (neglecting effects due to the phonon lifetime). However, in this work, each pulse lases at the peak of the average gain spectrum. Note that this is analogous to finding the peak of the spectrum as done in the post-processing of a Brillouin gain spectrum recorded using BOTDA/BOTDR. For small levels of non-uniformity in the SBS resonance frequency across a sensor region, such that there is still a single broadened peak, this tends to approach the average Brillouin frequency shift. However, when there is substantial non-uniformity (e.g. two sections of the sensing region having widely differing Brillouin frequencies), this can lead to multiple distinct peaks in the gain spectrum. In this case, lasing will occur at the largest peak, resulting in a measurement which more closely resembles the mode of the frequency shift distribution. In contrast, a BOTDA or BOTDR system could measure the entire spectrum, revealing the presence of multiple gain peaks. This distinction limits the applicability of techniques such as differential pump pulse measurements to the Brillouin laser sensor presented here [1].

The ultimate spatial resolution of the sensor was not investigated here. However, as the interaction length (pump/mode pulse length) decreases, the gain is diminished due to the limited interaction as well as the finite lifetime of the acoustic phonon. Reducing the Brillouin gain will increase the sensor noise, as shown in Fig. 4 of the main text. At very low gain levels, fluctuations in EDFA gain and losses in the cavity may result in sporadic lasing and mode competition with potential EDFA lasing modes may prevent Brillouin lasing altogether.

References:

1. S. M. Foaleng, M. Tur, J. Beugnot, and L. Thevenaz, "High Spatial and Spectral Resolution Long-Range Sensing Using Brillouin Echoes," J. Light. Technol. **28**, 2993–3003 (2010).