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Distributed Brillouin Fiber Laser Sensor: Karle Fellowship Final Report

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Distributed fiber sensors are a powerful tool for structural health monitoring and environmental sensing due to their ability to remotely monitor the strain at 1000s of locations using low-cost optical fiber. Sensors based on Brillouin scattering are uniquely suited to these task since they can make completely distributed, absolute measurements of strain, with a long range (>100 km), small sensing size (<1 cm), and a huge absolute dynamic range, all in standard off-the-shelf telecom fiber. These sensors function by measuring the resonance frequency of the non-linear Brillouin interaction in fiber which shifts linearly with strain and temperature. However, existing Brillouin sensors are hampered by fundamentally poor response resulting in small frequency shifts compared to the linewidth of the interaction. To overcome this limitation we introduced a technique known as distributed Brillouin fiber laser sensing (DBFLS) which establishes a series of narrowband lasing modes that experience Brillouin gain at discrete locations. The high intensity and narrow linewidth associated with the lasing transition enables high precision strain and temperature measurements. This work was conducted under my Naval Research Laboratory Karle Fellowship. This memo reviews the operation of the DBFLS and its performance and serves as a final report for the fellowship.

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DISTRIBUTED BRILLOUIN FIBER LASER SENSOR:

Karle Fellowship Final Report

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Abstract:

Distributed fiber sensors are a powerful tool for structural health monitoring and environmental sensing due to their ability to remotely monitor the strain at 1000s of locations using low-cost optical fiber. Sensors based on Brillouin scattering are uniquely suited to these task since they can make completely distributed, absolute measurements of strain, with a long range (>100 km), small sensing size (<1 cm), and a huge absolute dynamic range, all in standard off-the-shelf telecom fiber. These sensors function by measuring the resonance frequency of the non-linear Brillouin interaction in fiber which shifts linearly with strain and temperature. However, existing Brillouin sensors are hampered by fundamentally poor response resulting in small frequency shifts compared to the linewidth of the interaction. To overcome this limitation we introduced a technique known as distributed Brillouin fiber laser sensing (DBFLS) which establishes a series of narrowband lasing modes that experience Brillouin gain at discrete locations. The high intensity and narrow linewidth associated with the lasing transition enables high precision strain and temperature measurements. This work was conducted under my Naval Research Laboratory Karle Fellowship. This memo reviews the operation of the DBFLS and its performance and serves as a final report for the fellowship.

1. Introduction:

Brillouin fiber sensors are able to make fully distributed absolute strain and temperature measurements using standard telecom fiber. Brillouin sensors have been demonstrated with large dynamic range[1–5] and operating at long distances[6,7] with high spatial resolution[8–13]. These aspects have made Brillouin sensors well suited for a number of application, particularly in structural health monitoring. However, these sensors exhibit poor sensitivity when compared to other fiber sensing modalities such as fiber Bragg gratings or Rayleigh scattering. Ultimately this weak sensitivity comes from the inherently low strain and temperature response of the Brillouin frequency shift compared to the linewidth of the interaction (despite the relatively narrow linewidth of the Brillouin resonance, ~30 MHz), resulting in poor signal to noise ratio (SNR).

To overcome this limitation we proposed to use the linewidth narrowing effects associated with the lasing transition to greatly improve the SNR. Brillouin fiber lasers have previously been demonstrated with very narrow linewidths by leveraging the already narrowband nature of the interaction [14–16]. However these fiber cavities, while sensitive to strain and temperature, are sensitive to these changes anywhere in the cavity and could not be used to make distributed measures. Here we use a pulsed pump to excite a series of lasing modes in a fiber cavity. The pump pulse period is carefully tuned to match the round trip time in lasing cavity such that the lasing modes only experience Brillouin gain at distinct locations in the fiber under test (FUT). The frequency of the lasing modes then matches the Brillouin resonance frequency and is responsive to changes in temperature or strain at only one position each.

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My Karle fellowship was proposed to create, demonstrate, and investigate the performance of a distributed Brillouin fiber laser sensor. During the fellowship I produced an initial prototype and presented the basic noise performance, bandwidth and dynamic range (ref. [17]). This was followed up with investigations into noise scaling with sensor spatial resolution (ref. [18]). This work was then extended to practical lengths and numbers of sensors while addressing a weakness in the initial design where the fiber was not contiguously sampled (ref. [19]). Below I detail each of these steps.

2. Overview of DBFLS:

This section overviews the basic operation of the DBFLS. Additional details and figures can be found in ref. [17].

The distributed Brillouin fiber laser sensor is designed to create a series of lasing modes that experience Brillouin amplification at discrete positions in the FUT. The system resembles a standard fiber ring laser with a few important modifications. The ring is split into two halves. The FUT forms one half and a feedback section forms the other. The feedback section is of equal or greater length than the FUT. A pair of directional couplers (fiber circulators) introduce pump pulses into the beginning of the FUT and couple the pulses back out at the distal end. These pump pulses initially produce counter propagating spontaneous Brillouin scattering. The backscattered light is directed into the feedback portion of the ring (by the circulator at the beginning of the FUT) and is introduced back into the fiber under test after a delay in the feedback fiber (by the second circulator). Crucially, the pump pulse repetition period is fine tuned to match the round trip time of flight for the backscattered light. This ensures that the next pump pulse encounters each portion of the series of lasing modes at the same position in the fiber on each round trip, amplifying (via stimulated Brillouin scattering) that lasing mode with a gain spectrum characteristic of the Brillouin resonance at that position. If the round trip gain exceeds the lasing threshold, the modes will lase with a frequency locked to the Brillouin resonance frequency at the position of Brillouin amplification. Importantly, since the feedback fiber is longer than the FUT, the series of lasing modes never overlaps itself, preventing lasing on a cavity mode of the ring. This ensures that the lasing frequency is locked only to the Brillouin resonance frequency. On each round trip a portion of the lasing modes is coupled out of the ring and combined with a local oscillator beam on a photodetector. The beat frequency between these beams vs. time can then be extracted and converted to Brillouin resonance frequency versus sensor position.

There are a few practical difficulties with implementing the scheme described above. First, the polarization overlap of the pump and probe need to be carefully considered since the Brillouin amplification efficiency is dependent on this overlap. To ensure that the lasing modes have a consistent polarization on each round trip, we insert a polarization controller into the feedback section of the fiber ring. This controller is followed by a polarization beam splitter (PBS) and the controller is tuned to maximize transmission through the PBS, preventing polarization procession of the lasing modes. However, this does not ensure that the pump pulses actually overlap with each lasing mode at the sensor position. Using a polarization switch the pump pulses alternate between two orthogonal polarization states such that, averaged across two round trips, all the lasing modes experience some Brillouin amplification. Second, an erbium doped fiber amplifier (EDFA) is included into the feedback section. This provides some gain to the lasing modes, relaxing the gain requirements of the Brillouin amplification. Lastly, we introduce an electro-optic intensity modulator (EOM), biased to zero transmission, within the feedback fiber. This EOM is driven with a series of N pulses, creating N transparency windows. The series is repeated with a period matching the pump pulse period. The pulsing splits the series of lasing modes into N pulses, preventing cross-talk (inter-mode interaction) between neighboring modes. The amplitudes of the pulses are also controlled to prevent gain competition between the modes, by balancing the round trip gain of each mode with an equal amount of loss, without depleting amplifiers.

3. Results of initial prototype:

The initial prototype of the DBFLS is detailed in ref. [17]. Here I review the basic findings presented in that manuscript. As an initial demonstration of the DBFLS, we created a system using 400 m of fiber under test. The system excited 40 lasing modes separated into 40 ns pulses spaced by 100 ns, resulting in 40 sensor positions, with 4 m resolution, spaced by 10 m. In that study, we investigated sensor noise, bandwidth, and dynamic range. We also noted the marked increase in severity of Doppler frequency shift [20] when the system measured dynamic strain and proposed a solution.

The strain noise of the laser sensors was measured with the FUT in a quiescent state. The minimum detectable noise was found to be 3.9 $n\varepsilon/Hz^{½}$, corresponding to a frequency noise of ~100 $Hz/Hz^{½}$. This represented a substantial improvement over the state of the art [3,21–23].

In principle, the dynamic range of the DBFLS strain measurement is limited only by the failure point of the fiber since the lasing frequency of the sensor will continue to shift and that shift can continue to be measured. However, because the frequency was measured by the beat frequency of the lasing modes and a local oscillator, the range was limited by the frequency range of this detection and digitization. In our case this would limit the system to frequency shifts of >350 MHz or 7 mε. In practice, our measurements were limited by the magnitude of strain we could apply to our fiber strain stage. This allowed us to demonstrate strain up to ~5 mε.

Because of the feedback of the lasing modes, their frequency may require several round trips to update and match the local Brillouin resonance frequency at the sensing position. To test this rate, we modulated the pump frequency at various rates from 10 Hz to 50 kHz and measured the response of the lasing modes to this fluctuation. We found that the response dropped by 3 dB at ~10 kHz. This was equivalent to ~20 round trips to fully track the pump frequency.

However, the feedback introduces another issue in dynamic measurements. In the presence of dynamic strain in the FUT, the lasing modes experience a Doppler frequency shift with each round trip as they pass through the dynamically strained section. Since, as noted above, the Brillouin gain cannot immediately correct for this frequency shift, this can cause large errors in the measurement. We observed this phenomenon even at low strain frequencies. We then introduced a scheme to compensate for this error by measuring the response of the modes to a reference Doppler shift and computationally subtracting away the effects of cross-talk (see ref. [17] for full details).

In a follow-up manuscript to this work, we investigated how sensor size impacts the noise of the DBFLS (See ref. [18]). Here, the lasing mode and pump pulses were varied in duration from 10 to 40 ns resulting in minimum strain noise of 45 nε/√Hz for 40 ns pulse and 4 nε/√Hz for 10 ns pulse. We attributed the increased noise for shorter pulses to a broadening of the SBS spectrum when using such short pump pulses and to an increase in the uncertainty present in frequency measurements with shorter measurement times.

4. Fully distributed and practical system:

One question left unanswered from our initial demonstration was whether the scheme could scale to more practical lengths and to greater numbers of sensors. It was unclear whether the mode competition, pump depletion, and attenuation might prevent further scaling. To address this concern, we demonstrated a system with 1000 modes probing the last 3.5 km of a 5 km fiber. However, in the previous work, the pulsed lasing modes only probed 40% of the FUT, leaving gaps between sensors. In this practical demonstration we also introduced a technique to make fully contiguous measurements by creating two sets of circulating lasing modes. We then characterized the temperature and strain response, measured strain noise, and probed the limitations of further improvements in noise. These results are further detailed in ref. [19].

To make fully contiguous measurements, we modified the system to allow for two sets of modes to circulate and to probe different sets of positions. We first increased the length of the feedback fiber such that was greater than three times the length of the FUT making the total ring length more than four times the size of the FUT. This allows two sets of lasing modes to circulate without overlapping. The pump pulse period was then reduced to half of the round trip time of flight for the ring cavity, alternately amplifying each set. Finally, the intensity modulator in the feedback section was driven with two sets of pulses. In both cases, the pulses were 40 ns long separated by 72 ns and were composed of 500 such pulses. The second set of pulses was separated from the first by half of the round trip time of flight for the cavity plus a 36 ns offset. In this way the first set probed the “odd” positions in the FUT while the second set probed the “even” positions, so that all positions in the fiber were measured without gaps.

This configuration was then used to probe a much longer length of fiber than in our previous work: 3.5 km of a 5 km fiber, using 1000 modes. During this work, we observed that the increase in length and number of sensors did lead to manageable mode competition. While there were many more modes to control, changes in the amplitude of one mode had a much smaller impact on the much larger number of other modes. We also measured temperature and strain over a range of 18 to 40 °C and 0 to ~4 mε respectively. In both cases, we measured the expected Brillouin frequency shift and found cross-talk to be below the noise level.

Finally we measured the sensor noise vs. position in the FUT. We measured a minimum strain noise of 34 nε/√Hz (with average noise of 52 nε/√Hz). We also investigated the strain noise as a function of peak pump pulse power. We observed that the noise decreased with increasing pump power until a minimum was reached with ~1 W of pump power. Increasing the pump power beyond that level didn’t improve the noise for modes sensing near the beginning of the FUT but resulted in much greater noise for sensors at the end of the FUT. By measuring the transmitted pump power and spectrum we showed that this phenomenon was due to modulation instability at high power (and not pump depletion), robbing the sensors at the end of the FUT of available pump power. We noted that this is the same limitation on pump power for other Brillouin fiber sensor systems and is amenable to similar solutions.

5. Conclusions

This memo described the work conducted under my NRL Karle Fellowship. The work investigated the operation and performance of the DBFLS. This sensor captured the important qualities of Brillouin sensing (distributed, absolute, strain and temperature measurements using standard unmodified telecom fiber) while addressing the limiting factor of these systems, the poor sensitivity. We produced a first of its kind system with high performance and demonstrated the basic trade-offs and limitations of this approach.

References

1. H. Zheng, D. Feng, J. Zhang, T. Zhu, Y. Bai, D. Qu, X. Huang, and F. Qiu, "Distributed vibration measurement based on a coherent multi-slope-assisted BOTDA with a large dynamic range," Opt. Lett. **44**(5), 1245–1248 (2019).

2. J. Urricelqui, A. Zornoza, M. Sagues, and A. Loayssa, "Dynamic BOTDA measurements based on Brillouin phase-shift and RF demodulation," Opt. Express **20**(24), 26942–26949 (2012).

3. G. Yang, X. Fan, and Z. He, "Strain dynamic range enlargement of slope-assisted BOTDA by using brillouin phase-gain ratio," J. Light. Technol. **35**(20), 4451–4458 (2017).

4. D. Zhou, Y. Dong, B. Wang, T. Jiang, D. Ba, P. Xu, H. Zhang, Z. Lu, and H. Li, "Slope-assisted BOTDA based on vector SBS and frequency-agile technique for wide-strain-range dynamic measurements," Opt. Express **25**(3), 1889–1902 (2017).

5. Z. Yang, M. A. Soto, D. M. Chow, P. Ray, and L. Thevenaz, "Brillouin Distributed Optical Fiber Sensor Based on a Closed-Loop Configuration," J. Light. Technol. **36**(5), 1239–1248 (2018).

6. M. A. Soto, G. Bolognini, and F. Di Pasquale, "Optimization of long-range BOTDA sensors with high resolution using first-order bi-directional Raman amplification," Opt. Express **19**(5), 4444–4457 (2011).

7. M. A. Soto, G. Bolognini, and F. Di Pasquale, "Long-range simplex-coded BOTDA sensor over 120km distance employing optical preamplification," Opt. Lett. **36**(2), 232–234 (2011).

8. K. Y. Song, Z. He, and K. Hotate, "Distributed strain measurement with millimeter-order spatial resolution based on Brillouin optical correlation domain analysis and beat lock-in detection scheme," Opt. Lett. **31**(17), 2526–2528 (2006).

9. A. W. Brown, B. G. Colpitts, and K. Brown, "Dark-Pulse Brillouin Optical Time-Domain Sensor With 20-mm Spatial Resolution," J. Light. Technol. **25**(1), 381–386 (2007).

10. A. Bergman, T. Langer, and M. Tur, "Coding-Enhanced Ultrafast and Distributed Brillouin Dynamic Gratings Sensing Using Coherent Detection," J. Light. Technol. **34**(24), 5593–5600 (2016).

11. Y. Dong, H. Zhang, L. Chen, and X. Bao, "2 cm spatial-resolution and 2 km range Brillouin optical fiber sensor using a transient differential pulse pair," Appl. Opt. **51**(9), 1229–1235 (2012).

12. W. Li, X. Bao, Y. Li, and L. Chen, "Differential pulse-width pair BOTDA for high spatial resolution sensing," Opt. Express **16**(26), 21616–21625 (2008).

13. A. Dominguez-Lopez, M. A. Soto, S. Martin-Lopez, L. Thevenaz, and M. Gonzalez-Herraez, "Resolving 1 million sensing points in an optimized differential time-domain Brillouin sensor," Opt. Lett. **42**(10), 1903–1906 (2017).

14. Y. Liu and M. Zhang, "Multiwavlength Brillouin Erbium fiber laser sensor with high resolution," in *2017 Conference on Lasers and Electro-Optics Pacific Rim (CLEO-PR)* (2017), pp. 1–3.

15. H. Xie, J. Shao, Z. Sun, and J. Sun, "Simultaneous Measurement of Strain and Temperature Based on Radio-Frequency Demodulation," IEEE Photonics Technol. Lett. **29**(7), 623–626 (2017).

16. H. Xie, J. Sun, and D. Feng, "Simultaneous measurement of strain and temperature based on hybrid EDF/Brillouin laser," Opt. Express **24**(11), 11475–11482 (2016).

17. J. Murray, A. Cerjan, and B. Redding, "Distributed Brillouin fiber laser sensor," Optica **9**(1), 80–87 (2021).

18. J. B. Murray, A. Cerjan, and B. Redding, "Distributed Brillouin Fiber Laser Sensor," in *Optical Fiber Sensors* (2022), p. Under review.

19. J. B. Murray, A. Cerjan, and B. Redding, "Massively distributed fiber strain sensing using Brillouin lasing," Opt. Express (Under review), (2022).

20. J. B. Murray and B. Redding, "Suppressing non-local effects due to Doppler frequency shifts in dynamic Brillouin fiber sensors," Opt. Express **28**(8), 10760 (2020).

21. J. B. Murray and B. Redding, "Combining Stokes and anti-Stokes interactions to achieve ultra-low noise dynamic Brillouin strain sensing," APL Photonics **5**(11), 116104 (2020).

22. Y. Peled, A. Motil, and M. Tur, "Fast Brillouin optical time domain analysis for dynamic sensing," Opt. Express **20**(8), 8584–8591 (2012).

23. Q. Bai, Q. Wang, D. Wang, Y. Wang, Y. Gao, H. Zhang, M. Zhang, and B. Jin, "Recent advances in brillouin optical time domain reflectometry," Sensors **19**(8), 1862 (2019).