Homebrew: Optical Polarization Change Detection for Ground Motion Sensing

Joseph Catudal*, Zhenhao Zhou, Weijun Pan, Paul Barford, Dante Fratta, and Herb Wang

University of Wisconsin - Madison, Madison, WI 53706, USA

*catudal@wisc.edu

Abstract: We examine laser light polarization measurements using our own novel polarimeter design for ground motion sensing and show that efficacy is highly dependent on the coupling of fiber routes to vibration sources.

1. Introduction

The prospect of using deployed Internet fiber optic infrastructure as a global vibration and deformation sensing platform is tantalizing. Several recent studies have considered the efficacy of using the measurement of polarization transients in light transmission through fiber for ground motion and environmental sensing. Examples include identifying earthquake signatures in subsea cable infrastructure [1], detecting temperature changes and high-speed trains crossings [2, 3] and detecting vibrations induced by adhering a portion of an optical fiber to speakers [4]. Although these studies have demonstrated the utility of polarization transience measurement for sensing, they have benefited from fiber optic cables placed in relatively low noise settings with strong coupling between cables and the environment, and where large dynamic disturbances are plainly visible. However, Internet fiber optic cables in long-haul and especially metro environments are potentially noisier and more mechanically uncoupled from the signals that we wish to detect.

Our study introduces a new 'homebrew' polarimeter for use in urban environments toward the goal of enabling the broad deployment of polarization-based sensors in Internet infrastructure. Specifically, we developed and examined a novel low-cost, four-arm system that can provide detailed polarization transience measurements at high sampling rates. We deployed this system in two different fiber cable configurations to assess its ability to capture events such as train traffic on nearby tracks. Our findings show that the polarization-based detection of train traffic in an urban environment is highly dependent on the coupling of fiber to infrastructure subjected to ground motion and that the use of optical fiber used in Internet communications may not be universally effective.

2. Homebrew Polarimeter Description

Although commercial polarimeters provide complete information on polarization state, they can also be prohibitively expensive for the purpose of creating a network of Internet-based fiber optic sensors. Therefore, our goal was to construct a low-cost polarimeter that can sample polarization state at a rate sufficient for measuring a wide range of ground-motion signals. Previous studies [2, 5] have developed low-cost, two-arm polarimeters to monitor transient events. By passing the input light through a Polarization Beam Splitter (PBS) and a balanced amplified photodetector, the Polarization Rotation Rate (PRR) can be calculated from the outputs. However, the sensitivity of these systems is a function of the polarization axes of the incoming light relative to the orientation of the PBS. Large areas of the Poincaré sphere can have reduced sensitivity to polarization transients [2].

To improve the sensitivity and expand capability, we developed a polarimeter design that includes an optical tap to evenly split the incoming light into two independent two-arm measurements, as seen in Figure 1. We placed mechanical polarization controllers before the PBS of each branch. We manually configured the polarization controllers to send an even amount of energy (sum of balanced detector channels) through each of the four arms. We then induce a small test vibration on the fiber under test and ensure that the balanced output from each branch is near zero and tuned to maximum and minimum sensitivity to the test. Our key innovation is that adding a second, two-arm system with a different axis orientation enabled us to maintain sensitivity when a single PBS might have missed a rotational change. The total cost of the components in our system was less than $9,000, comparable to low-end polarimeters, and can achieve sampling rates of 500 kHz in short-term measurements and 1 kHz for long-term measurements.

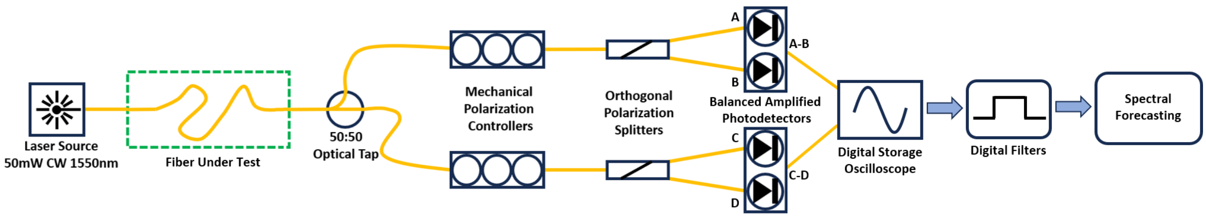

Fig. 1. Four-arm polarimeter design used in these experiments. The incoming polarization for both arms are controlled to align the orthogonal split along a different axis, enabling a higher range of detection for polarization transients.

3. Experiments

We began by performing laboratory tests to assess and calibrate our system. In order to determine the impact of fiber coupling in polarization-based sensing, we then conducted a series of experiments by varying the cable coupling to a vibration source. First, we attached a section of 20-meter indoor fiber optic cable to the inside of a basement exterior wall with utility tape. The wall is approximately 15 meters from the freight rail and travels roughly parallel along the measured length. The fiber was attached to this wall in sections 1-, 2-, and 4-meters long. This room was not temperature controlled and had moderate amounts of ambient noise that was emitted from building cooling systems and equipment.

Second, we captured the polarization transients on a 4-kilometer urban campus fiber route. This route passes underneath and next to active freight railway tracks and under several campus and city roads through conduit and returns along the same path via a fiber loopback adapter at the distant end. Our homebrew polarimeter was placed at the fiber termination point in a temperature-controlled telecommunications room with large amounts of acoustic and airflow noise compared to the basement wall configurations.

During data collection, we used readings from a vertical-axis geophone [6] at the same basement location as the wall configurations to determine the amount of vibration produced by passing trains. Our system collected samples at 1 kHz from the balanced outputs of our homebrew polarimeter, as well as a single monitor reading from each balanced photodetector to calculate PRR [2]. By taking a weighted average of the two balanced filtered outputs based on a spectral forecasting algorithm [7], we found that the maximum of the band-filtered spectrogram clearly showed train events.

4. Results

Over a 35-day period, we captured 19 responses from passing freight trains on our polarimeter and geophone, with 14 responses on our basement wall configuration, and five on the 4-km campus route. Each collection was carried out continuously over several days with the same calibration and fiber configuration and contains between two and five train traffic events. The strongest responses to passing trains are recorded when the freight engine passes near the building, followed by the trailing freight cars. The responses recorded by the polarimeter contained occasional peaks associated with low-frequency vibrations when the fiber was disturbed so as to cause the fiber to set in a new position. During the passing of the freight engine, occasional peaks were seen at 60 to 70 Hz. However, the predominant and consistent responses were localized from 24 to 32 Hz during the train event, as seen in Figure 2a. The results of the comparison of the mean spectral power maximum over 30 minutes after the start and end of a clear train response are shown in Figure 2b.

Depending on the configuration of the optical fiber route, the spectral response of the passing train was more pronounced against the ambient polarization transience. To quantify the level of response, Pearson's correlation coefficients were calculated on the responses of the polarimeter from 22 to 38 Hz and the geophone two minutes after the start and end of the train vibration, as shown in Figure 2c. We quantified any correlation greater than 0.4 to signify a positive response from our polarimeter. The tests recorded on the campus fiber route did not show a response to vibrations from train traffic on our polarimeter. However, our indoor basement installations show a distinct short-term transience during train events that correspond to the readings on our local geophone. The 4-m fiber route with the longest wall coupling length was more pronounced and consistent in each response to a passing train. Shorter-length couplings were less responsive and inconsistent in recording a response.

A slow polarization transience was observed for up to 24 hours after installation as the fiber cable settled to a new resting position after being disturbed. Our four-arm design was able to capture train responses in one or both arms despite long-term changes in polarization. In some events, sensitivity banding of the train response can be seen when the vibration changes the polarization parallel to an arm's orthogonal split. PRR was calculated for every train event. However, PRR responses to train traffic events were not distinguishable above the ambient rotation rate and were not an effective metric to measure small fiber strain responses.

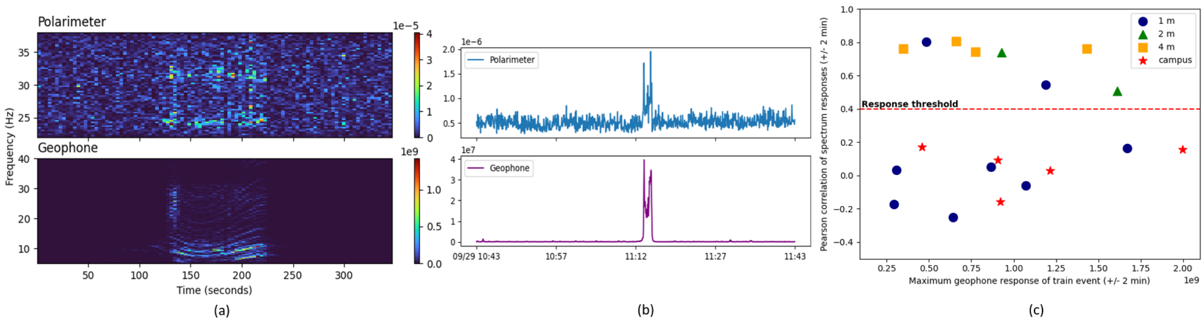

Fig. 2. (a) Spectrogram of signal responses during a train event from the polarimeter combined output (top) and the geophone (bottom). (b) Plot of mean spectral power maximum for one hour with train event from the polarimeter (top) and the geophone (bottom). (c) Recorded train events are plotted by coupling length (color), maximum geophone response (x-axis), and Pearson correlation between geophone and polarimeter response for two minutes before and after train event (y-axis).

5. Discussion

The results of these experiments show both the possibility of ground motion sensing through internet infrastructure in an urban environment and the obstacles that prevent sensitive measurement. Measurements taken from the 4 meter strongly wall-coupled fiber optic path show strong consistent responses to train events. Two responses were successfully recorded on the 1 meter coupled route, but incurred a low accuracy rate. Sometimes, responses were predominantly seen on one arm, indicating a more robust sensing range.

Campus route collections were unable to detect vibrations caused by train traffic. We believe this is due to two reasons; that the portion of the fiber run susceptible to vibrations from a passing train has been engineered to reduce the coupling to ground noise in order to allow minimum interference for optical communication, and building noise, such as other communications equipment or air conditioning systems along the route, introduce unwanted polarization transience, which raises our noise floor above the desired signal response. For Internet fiber optic routes to be useful for ground sensing, they must be tightly coupled to a vibrating medium where a response is expected. This level of coupling required for effective sensing on urban fiber optic routes may need to be individually evaluated for sensing applications.

Our polarimeter was effective in detecting small, fast vibrations emitted by passing freight trains on the highly coupled fiber path. Additionally, the two paths that split on different axes enabled detection over a wider range of polarization versus a two-arm system. Although our system shows increased sensitivity to polarization transience, there are some challenges that we will address in future work. In particular, we are investigating how to improve calibration of our system by removing the need for manual adjustment of the polarizing paddles and optimizing perpendicular axes to capture the fullest possible range of polarization transience.

References

1. Zhongwen Zhan, Mattia Cantono, Valey Kamalov, Antonio Mecozzi, Rafael Müller, Shuang Yin, and Jorge C. Castellanos. Optical polarization–based seismic and water wave sensing on transoceanic cables. *Science*, 371(6532):931–936, February 2021. Publisher: American Association for the Advancement of Science.
2. Peter Barcik and Petr Munster. Measurement of slow and fast polarization transients on a fiber-optic testbed. *Optics Express*, 28(10):15250–15257, May 2020. Publisher: Optica Publishing Group.
3. Petr Dejdar, Vojtech Myska, Petr Munster, and Radim Burget. Trains Detection Using State of Polarization Changes Measurement and Convolutional Neural Networks. In *2021 IEEE International Symposium on Inertial Sensors and Systems (INERTIAL)*, pages 1–4, March 2021. ISSN: 2377-3480.
4. Martin Šlapák, Josef Vojtěch, Ondřej Havliš, and Radan Slavík. Monitoring of Fibre Optic Links With a Machine Learning-Assisted Low-Cost Polarimeter. *IEEE Access*, 8:183965–183971, 2020. Conference Name: IEEE Access.
5. Jesse E. Simsarian and Peter J. Winzer. Shake before break: Per-span fiber sensing with in-line polarization monitoring. In *2017 Optical Fiber Communications Conference and Exhibition (OFC)*, pages 1–3, March 2017.
6. Raspberry Shake. Rs3d — vertical & lateral motion seismograph. https://shop.raspberryshake.org/product/turnkey-iot-home-earth-monitor-rs-3d., 2023. Accessed on October 20, 2023.
7. Paul A. Gagniuc, Constantin Ionescu-Tirgoviste, Elvira Gagniuc, Manuella Militaru, Lawrence Chukwudi Nwabudike, Bujorel Ionel Pavaloiu, Andrei Vasilăţeanu, Nicolae Goga, George Drăgoi, Irinel Popescu, and Simona Dima. Spectral forecast: A general purpose prediction model as an alternative to classical neural networks. *Chaos: An Interdisciplinary Journal of Nonlinear Science*, 30(3):033119, 03 2020.