Non-destructive measurements of root traits and their soil-water environment using Fiber Bragg Grating-based fiber optic sensors

Binder Steven[1], Yang Mei[1], Qiu Victor[1], Bucksch Alexander[1], and Fok Mable[1]

[1]University of Georgia

November 16, 2022

Abstract

Underground monitoring of root morphology and their interactions with the environment is critical to understand the overall performance of a plant. Such understanding allows plant breeders to develop plants that are resilient to the adverse effects of climate change and potentially even improve yields for food, fuel, and fiber. We propose and experimentally demonstrate the use of fiber Bragg grating-based fiber optic sensors as a non-destructive technology to measure width and depth of a root-like object and monitor the change in groundwater level as an indicator for soil-water content. Low-cost and continuous remote monitoring analyzed the spectral shift induced optical power change in the fiber optic sensors.

Non-destructive measurements of root traits and their soil-water environment using Fiber Bragg Grating-based fiber optic sensors

Steven Binder[1], Mei Yang[1], Victor Qiu[1], Alexander Bucksch[2], and Mable Fok[1]
[1]Lightwave and Microwave Photonics Laboratory, College of Engineering,
University of Georgia, Athens, GA 30602, USA
[2]Department of Plant Biology, Warnell School of Forestry and Natural Resources,
Institute of Bioinformatics, University of Georgia, Athens, GA 30602, USA

ABSTRACT

Underground monitoring of root morphology and their interactions with the environment is critical to understand the overall performance of a plant. Such understanding allows plant breeders to develop plants that are resilient to the adverse effects of climate change and potentially even improve yields for food, fuel, and fiber. We propose and experimentally demonstrate the use of fiber Bragg grating-based fiber optic sensors as a non-destructive technology to measure width and depth of a root-like object and monitor the change in groundwater level as an indicator for soil-water content. Low-cost and continuous remote monitoring analyzed the spectral shift induced optical power change in the fiber optic sensors.

Keywords: Underground sensing, Fiber optic sensors, fiber Bragg grating, Root phenotyping, Underground water monitoring

1. INTRODUCTION

The growth of fibrous lateral and deep roots are important traits that relate to overall performance of a plant. Being able to monitor the growth of roots could provide critical information to help us understand the factors that drive acclimatization to drought and nutrient deprived environments. Unfortunately, current methods like Shovelomics[1] for phenotyping roots are usually destructive, labor intensive, and does not allow continuous monitoring of roots over time. Current root phenotyping methods usually involve the uprooting of plants for manual or image-based trait measurements.[2,3] These techniques provide accurate data at the expense of the plant and environmental destruction. Ground penetrating radar (GPR) has also been used for root measurement; however, it is prone to electromagnetic interference and a large footprint is required.[4] Therefore, an innovative technology that can non-destructively phenotype plant roots and can provide continuous monitoring capability of root growth will be critical for the development of the field.

Fiber optic sensors are well known for their small size, ability to work in harsh environments, as well as their remote and continuous monitoring capability. They have been implemented in a wide range of applications including structural health monitoring, biomedical, and aerospace sensing. In particular, fiber Bragg grating (FBG) based fiber optic sensors are of particular interest because of their high sensitivity to their surroundings, simplicity, and multiplexing ability. A FBG fiber optic sensor is a small section of optical fiber where a periodic pattern with Bragg period (Λ) has been imprinted to alter the refractive index of that region[5]. As illustrated in Figure 1(a), light with a wavelength that satisfies the constructive interference condition will be reflected, referred to as the Bragg wavelength (λ_B). Any strain experienced by the FBG would cause the Bragg wavelength to shift spectrally. While FBG is a popular fiber optic sensor choice for a wide range of applications, the use of FBG for underground root growth monitoring has not been explored.

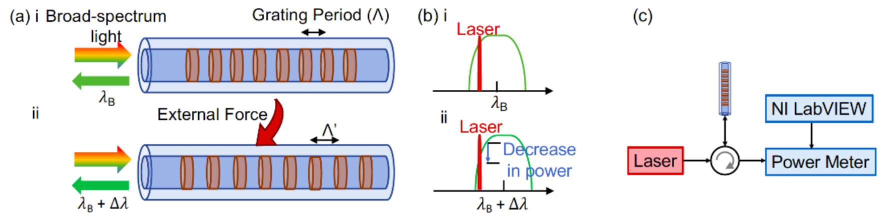

Figure 1: (a) Structure of FBG before and after force is applied. (b) The reflected Bragg wavelength before and after force is applied. The red line corresponds to the wavelength of the laser. (c) FBG fiber optic sensor monitoring system.

In this paper, we propose and experimentally demonstrate the use of FBG sensors as a non-destructive approach for continuous and long-term underground monitoring of penetration depth and width of a root-like object in soil, as well as monitoring of the change in underground water level. The proposed FBG based fiber optic sensing approach could potentially open the doors for non-destructive ways to investigate the performance of plants through the study of underground roots traits.

2. PRINCIPLE AND EXPERIMENTAL SETUP

Figure 1(c) shows the experimental setup of the FBG sensor system. A single wavelength laser source is launched to a FBG via an optical circulator. The laser wavelength is set such that it is aligning with the linear edge of the FBG reflection spectrum (Figure 1(b) i). This ensures that both left and right shifts of the FBG spectrum will result in a similar amount of optical power change. As the Bragg wavelength is reflected by the FBG, it is directed to a Thorlabs PM101 optical power meter via the optical circulator. The power meter is controlled by National Instruments LabVIEW at a sampling rate of 10 Hz to allow for real time and continuous data monitoring. When a force is applied to an FBG, the Bragg period (Λ) changes, resulting in a left or right shift of the FBG reflection spectrum which in turn changes the amount of optical power being reflected at the laser wavelength, as illustrated in Figure 1(b).

The orientation of FBG sensors in the soil is an important factor in how the FBG detects an applied force or strain. Each experiment described below had been attempted multiple times with different FBG orientations to investigate the optimal setup for monitoring each root trait. From the preliminary experiments, it is determined that a horizontal orientation is desirable for measuring penetration depth and width. This is because more of the FBG's surface area will be exposed to the applied force. Additionally, vertical orientation is preferred in groundwater level measurement as a higher spatial resolution and longer detection region can be achieved by the sensor.

The small size of an optical fiber (i.e. 250 µm in diameter) does not significantly alter soil composition. However, the small size of the FBG does not allow it to collect significant amount of strain or pressure when placed bare into soil. Therefore, each FBG was taped to a thin 1.5cm by 3cm sheet of plastic where the sensor is detecting a penetrating force. The thin sheet acts as an amplifier for the sensor as the increased surface area allows for the detection of more force. A cylindrical glass vessel of 13cm tall and 7cm in diameter was used to contain the FBG sensors and the soil for all experiments.

3. RESULTS AND DISCUSSION

3.1 Depth Experiment

To monitor the penetration depth of the taproot-like object, two FBGs (FBG 1 and FBG 2) at 1550 nm and 1552 nm are embedded 12 cm and 6 cm from the soil's surface, respectively (Figure 2a). FBG 1 is centered and is 1 cm above the bottom of the jar while FBG 2 is located slightly offset from the region where the taproot-like object was inserted into the soil to observe the effect when the object is passing the FBG. The laser wavelength is set to 1549.876 nm and 1552.308 nm for FBG 1 and FBG 2, respectively. A pointed rod with a diameter of 6 mm is used as the taproot-like object for the experiment. It is slowly pressed into the soil, with 10-second intervals between each 1-cm depth increase for data stabilization. The experiment continued until the rod had reached a maximum depth of 12 cm.

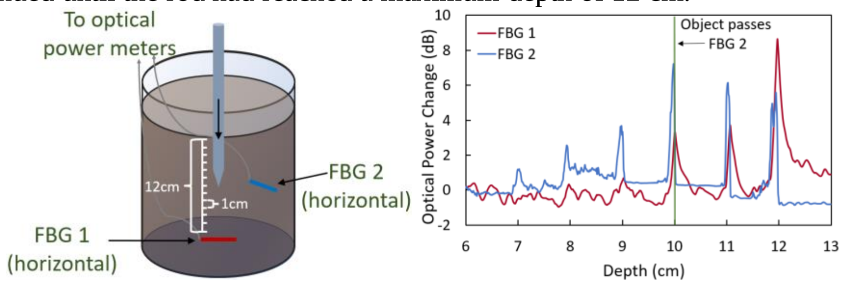

Figure 2: (a) Experimental setup for monitoring the penetration depth of a taproot-like object pressed into soil. (b) The measured optical power change against the penetration depth.

Figure 2(b) shows the experimental results where the red and blue curves correspond to the power change observed in FBG 1 and FBG 2, respectively. A spike in power change is observed when the rod is pressed deeper. As penetration depth increases, FBG 1 shows an increase in optical power change as the distance between the FBG and the rod is smaller than 6 cm. FBG 2 also exhibits a spike in power change during the increase in penetration with the power change increases as the rod is approaching FBG 2. Once the rod passes the depth of FBG 2 (i.e. 10 cm), a decrease in power change at the spikes is observed. With the height of each FBG known, the depth of the rod can be inferred by analyzing the change in optical power, providing a non-destructive approach to monitor taproot growth effortlessly and effectively.

3.2 Width Experiment

To test the effectiveness of FBG on monitoring the expansive force created by the increase in root size of a plant, a thin cylindrical balloon is used in this experiment to create an expansive force. As shown in Figure 3(a), the balloon is located in the middle of the glass jar with two FBGs embedded horizontally on both sides of the balloon. FBG 1 is 3 cm from the balloon while FBG 2 was 4 cm away.

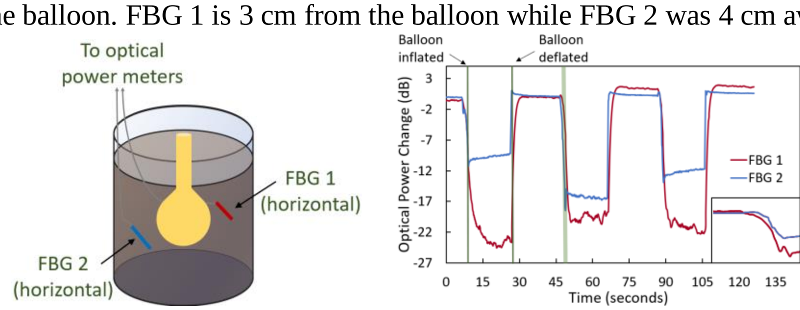

Figure 3: (a) Experimental setup for monitoring the expansion force of a root ball-like object. (b) Measured optical power change against expansion. Inset: Power change during 3s of inflation.

The balloon is inflated with a flow rate of 8.33 mL/s for 3s and held filled for 17s before deflation. The balloon's width increases from 0.5 cm to 7 cm upon inflation. The experimental results are shown in Figure 3(b), in which the red curve corresponds to the closer FBG 1 while the blue curve corresponds to the further FBG 2. The large drop in reflected optical power seen in both FBGs is due to the expansive force. As seen in the close-up view (Figure 3(b) inset) of the power change plot during inflation, the rate of power change is consistent with inflation duration. The closer FBG 1 has a large power change (about 20 dBm) over the course of inflation due to a stronger strain experienced. According to the observed results, the magnitude of power change from each FBG is related to the width of the underground object and the distance between the two. While the actual root ball would take up a much smaller space in the soil, the FBGs high sensitivity can pick up small changes in the root mass. By analyzing the optical power change in both FBGs, the width of a root mass could potentially be estimated using a series of FBG sensors.

3.3 Underground Water Level Experiment

With the FBG sensors buried underground, they can also be used for remote monitoring of underground water level. To mimic a rising water level in soil, a hollow cylindrical tube was placed in the center of the glass vessel before being filled with soil, as shown in Figure 4(a). Both FBG sensors were fixed to the side of the vessel such that the wall acts as an anchor for the sensors. FBG 1 is 10.5 cm from the soil surface while FBG 2 is 8 cm from the surface. A constant flow of water is added into the vessel for a full minute, before being stopped for another minute to allow the soil to absorb the added water. This alternation continued for 36 minutes, at which the soil was fully saturated. At the end of the experiment, 325 mL of water had been added to the jar. The entire duration of the experiment was recorded to determine the exact height of water level within the soil and its relative distance from the FBG locations.

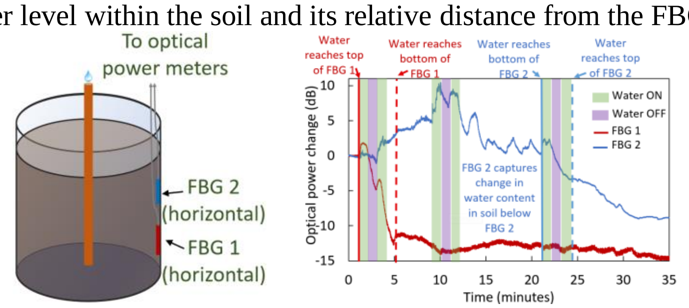

Figure 4: (a) Experimental setup for monitoring underground water level. (b) The measured optical power change against the change in water level.

Water level reaches the bottom of FBG 1 one minute after the experiment had begun. The increasing water level generated the large power change exhibited by FBG 1 (Figure 4(b)). Once the water level passes the top of FBG 1, it no longer senses any other change in water level. In FBG 2, the water level does not reach it until the 21s mark. However, it is sensitive enough to record whether water is flowing into the system. This is indicated by the peaks between 3s and 21s. Water reaches the bottom of FBG 2 at 21s and reaches the top of FBG 2 at 24s. A large but smooth decrease in power and a steady power level are observed after the 24s mark indicating the soil at the FBG 2 level is saturated. The information from both FBG sensors provides additional data on the interaction between soil and water. Since the height of each FBG had been known, the underground water level can be inferred when a large power loss and the lack of fluctuations is seen by the FBG sensors.

4. CONCLUSION

The use of FBG based fiber optic sensors in underground monitoring of penetration depth and width of a root-like object has been proposed and demonstrated. Downward and expansion force has been successfully sensed and monitored underground through the analysis of wavelength shift induced change in optical power at the FBG. These preliminary results suggest that FBGs could be used to sense root morphologies and their interactions with environments like water-stress. FBGs offer a unique approach that allows for continuous, remote, and non-destructive monitoring of multiple in-soil variables.

DATA AVAILABILITY STATEMENT

Requests for measurement data may be directed to mfok@uga.edu

ACKNOWLEDGMENTS

S.B. is supported by a research assistantship from the Center of Undergraduate Research Opportunities at UGA. The research was supported by the NSF Award No.1653525 to M.F. and the NSF CAREER Award No. 1845760 and USDOE ARPA-E ROOTS Award Number DE-AR0000821 to A.B. Any Opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect those of the funders.

REFERENCES

[1] Burridge, James, et al. "Legume shovelomics: high—throughput phenotyping of common bean (Phaseolus vulgaris L.) and cowpea (Vigna unguiculata subsp, unguiculata) root architecture in the field." Field Crops Research 192 (2016): 21-32.

[2]Bucksch, Alexander, et al. "Image-based high-throughput field phenotyping of crop roots." Plant Physiology 166.2 (2014): 470-486.

[3] Suxing Liu, Carlos Sherard Barrow, Meredith Hanlon, Jonathan P. Lynch, Alexander Bucksch, DIRT/3D: 3D root phenotyping for field-grown maize (Zea mays), Plant Physiology, Volume 187, Issue 2, October 2021, Pages 739–757, https://doi.org/10.1093/plphys/kiab311

[4] Liu, Xiuwei, Xuejun Dong, and Daniel I. Leskovar. 2016. "Ground penetrating radar for underground sensing in agriculture: a review." *International Agrophysics* 533-543.

[5] Othonos, Andreas. 1997. "Fiber Bragg gratings." *Review of Scientific Instruments* 4309 - 4341.

[6] Kuang, KSC, and WJ Cantwell. 2003. "Use of conventional optical fibers and fiber Bragg grating in damage detection in advanced composite structures: A review." *Applied Mechanics Review* 493 - 513.