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Multimode Optical Fiber Sensing

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The vast majority of fiber optic strain sensors use single mode fiber, yet multimode fiber offers many advantages. Multimode fiber has a higher nonlinear threshold which enables higher light levels and lower noise while the diversity of spatial modes can be used to develop sensors that are inherently immune to signal fading. All of these advantages can help to decrease noise levels and increase sensing capabilities. In my research conducted during my Karles fellowship, I built sensors that exploited these advantages to develop new sensing architectures. The sensors presented here achieved a linear strain response, pico-strain-level noise floor, and kHz of bandwidth.

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MULTIMODE OPTICAL FIBER SENSING

Matthew J. Murray

ABSTRACT

The vast majority of fiber optic strain sensors use single mode fiber, yet multimode fiber offers many advantages. Multimode fiber has a higher nonlinear threshold which enables higher light levels and lower noise while the diversity of spatial modes can be used to develop sensors that are inherently immune to signal fading. All of these advantages can help to decrease noise levels and increase sensing capabilities. In my research conducted during my Karles fellowship, I built sensors that exploited these advantages to develop new sensing architectures. The sensors presented here achieved a linear strain response, pico-strain-level noise floor, and kHz of bandwidth.

INTRODUCTION

The goal of my Karles Fellowship research was to develop detection, interrogation, and data processing techniques that leverage the unique features of multimode fibers to build next-generation fiber sensors with increased functionalities and performance.

Distributed fiber optic sensors have been developed at the Naval Research Lab and elsewhere for a variety of applications including structural health monitoring, perimeter security, seismic sensing, and underwater acoustic arrays [1–7]. Many successful fiber sensors take advantage of Rayleigh scattering using a technique known as phase-sensitive optical time domain reflectometry (Φ-OTDR). These systems operate by detecting the backscattered light in an optical fiber that results from random fluctuations in the index of refraction. Changes in the strain along the fiber are monitored by detecting changes in the backscattered light.

The vast majority of Rayleigh-based OTDR sensors use single mode fiber (SMF) and are limited by two significant disadvantages. First, Rayleigh scattering is a weak process and so single mode fiber sensors are often limited by low light levels. Higher input light levels could mitigate this issue, but nonlinear thresholds limit the optical power that can be injected into a fiber. Second, Rayleigh-based SMF sensors are susceptible to signal fading which occurs when the backscattered light destructively interferes with itself, degrading sensor performance.

In order to make quantitative measurements of the strain along the fiber, most existing Rayleigh sensors measure the phase of the backscattered light. These phase-measuring systems require coherent detection of the backscattered light and localize detection by measuring the phase difference between two reflecting regions. The length of the reflecting regions depends on the pulse duration and so optimizing spatial resolution drives the need to use short pulses of light, which reduces backscattered light levels and increases noise. Laser phase noise can also be a significant limitation in this approach since coherent detection is required. In contrast, systems that detect only the amplitude of the backscattered light have the potential to have reduced noise levels. These amplitude-measuring systems can use longer pulses of light since the reflecting region and localized sensing region are now one and the same, which also reduces the dependence on laser phase noise. However, in general, the amplitude has a nonlinear dependence on the strain and so traditional amplitude-measuring systems cannot make quantitative measurements.

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The use of multimode fiber offers several advantages over single mode fiber in OTDR sensors. Multimode fiber has a higher power threshold for nonlinear effects and larger capture fraction of backscattered light, which can enable lower noise measurements. In addition, the rich diversity of spatial modes in the fiber provides additional useful information. First, by measuring the entire backscattered speckle pattern, which is a summation of light from all the spatial modes, signal fading can be eliminated. Furthermore, the information contained within the amplitude of all the spatial modes is sufficient to extract a linear strain response. This insight enabled a new type of OTDR sensor that only uses the amplitude of the backscattered light to make quantitative strain measurements. My research shows that multimode-fiber-based OTDR sensors can provide functionality and performance beyond what is possible with single mode fiber.

MULITMODE FIBER SENSORS

Speckle-based Strain Sensing in Multimode Fiber

The first major effort during my Karles fellowship was the demonstration of a quantitative multimode-fiber-based OTDR sensor. This demonstration was published in Optics Express [8] and led to a patent application.

In a multimode fiber, the Rayleigh backscattered light is distributed among many spatial modes. Interference between these spatial modes produces a seemingly random pattern of bright and dark grains, known as a speckle pattern. Our approach treats each speckle grain as if it were an independent interferometer at an arbitrary and unknown bias point. As strain is applied to the fiber, the amplitude of each of the speckle grains fluctuates and this fluctuation carries information about the strain on the fiber. The challenge is that the change in amplitude for a given strain is different for each speckle grain and is constantly changing. In addition, the sign of this response (whether the amplitude increases or decreases with increasing strain) is different for each grain and can also change with time. During my Karles fellowship, I developed and experimentally validated an algorithm capable of recovering quantitative strain information from the dynamic evolution of the speckle pattern in a multimode fiber.

To extract a linear strain response, we first make the assumption that all the speckle grains are responding to the same strain. Under this assumption, we can combine the information from the entire speckle pattern to achieve a linear strain response despite the nonlinear and unpredictable response of individual speckle grains. A linear response is achieved in three steps: first, we assign each speckle grain a flag (±1) at each instant in time indicating whether the amplitude increases or decreases with strain. Second, we average the amplitude response over the entire speckle pattern while using the flags to correct for the sign of the strain response on each speckle grain. Third, we introduce a responsivity coefficient to convert the average change in amplitude to a change in strain. Since the amplitude response will eventually change, we implement a test to determine whether the flags need to be updated at a given point in time. Details of this speckle tracking algorithm are given in the resulting publication on this experiment [8].

The speckle tracking algorithm was experimentally validated by recording the time varying speckle pattern backscattered from a multimode fiber under strain. For this proof-of-principle demonstration 532 nm light was used in order to leverage existing camera technology. Continuous wave light from a high power fiber laser was directed into an acousto-optic modulator (AOM) which carved 100 ns pulses with about 1 W peak power. Using a beam splitter, about 80% of the light was directed into 2 km of graded-index multimode fiber, while the remainder was directed into a reference arm. The reference arm allowed us to optically select the light from a specific region within the fiber and also helped to mitigate camera dark noise. The Rayleigh scattered light from the multimode fiber was directed to a high speed camera, which collected 128 x 128 pixel images at a frame rate of 40 kHz. At the camera, the Rayleigh scatter interfered with the light from the reference arm and off-axis holography was used to recover the time-dependent amplitude of the backscattered speckle pattern.

To test the sensor a PZT was wrapped with 9 m of multimode fiber and positioned 14 m into the fiber under test. The sensor is inherently immune to signal fading and achieves a linear localized strain response. The sensor has a noise floor of 2.9 pε/√Hz, a bandwidth of 20 kHz, and a dynamic range of 74 dB at 1 kHz. This work resulted in a publication in Optics Express and more information about the sensor can be found in the paper [8]. This work also resulted in a patent application.

Quantitative Strain Sensing in a Multimode Fiber using Dual Frequency Speckle Pattern Tracking

During the second half of my Karles fellowship, I followed up on the initial demonstration described above by developing an electronically reconfigurable multimode fiber sensor operating at 1550 nm. This sensor provided additional functionality by enabling measurements of the algebraic sign of the strain and I was able to demonstrate measurements at a range of 2 km. This work was published in Optics Letters [9].

The speckle-based strain sensor described above successfully achieved a linear response to strain and a pico-strain level sensitivity. However, the architecture used a physical fixed delay line to temporally align the reference pulse with the backscattered light from the desired sensor region in the fiber. While this allowed us to demonstrate the sensing principle, probing the strain at different locations in the fiber required changing the length of the physical delay line. In addition, as with most standard Φ-OTDR systems, the sensor could not determine the algebraic sign of the strain. While this is acceptable for many acoustic sensing applications, the sign of the strain is critical for structural health monitoring. In this work, we demonstrate an amplitude-measuring multimode fiber OTDR system that uses alternating optical frequencies to calibrate the strain response and measure the algebraic sign of the strain. In addition, by taking advantage of the technology at the telecom wavelengths we could dynamically reconfigure the position of the sensing region without the need to change any hardware.

Optical frequency shifts and changes in strain have an analogous effect on the Rayleigh backscattered speckle pattern. For example, if we measure the speckle pattern at two nearby frequencies, we can assume that if the amplitude of a given speckle grain increases with increasing frequency, it will also increase with increasing strain. Therefore, by measuring the response of the speckle pattern to a change in optical frequency, we can perform an *in situ* calibration and predict the pattern's response to strain. Not only does this calibration provide a means to correctly assign the pixel flags and recover quantitative strain information, but it also allows us to determine the overall algebraic sign of the strain.

To demonstrate this approach we constructed a multimode fiber Φ-OTDR sensor. Continuous wave 1550 nm light was split into an interrogation arm and reference arm via a 50:50 fiber coupler. In each arm an electro-optic modulator (EOM) carved a 90 ns pulse at a repetition rate of 40 kHz. The pulses in each arm are coupled to an AOM, which increased the extinction ratio and also modulated the optical frequency of the pulses. The drive frequency of the AOMs alternated between 54 MHz and 56 MHz. The frequency separation of 2 MHz was selected to introduce a measurable change in the speckle pattern while being small enough such that the speckle patterns remained correlated. The pulses in the interrogation arm were amplified to a peak power of 7 W and coupled into a multimode fiber. The backscattered light was collected on a high-speed camera, where it interfered with light from the reference arm. As with the first system, off-axis holography was used to optically select the light from a specific region in the fiber. However, in contrast to the earlier system, by electronically adjusting the delay between the pulses generated in the interrogation and reference arm, the sensor could be positioned anywhere within the 2 km fiber without requiring changes in hardware.

To verify that the sensor correctly identifies the algebraic sign of the strain, a fiber-wrapped PZT, which was positioned 25 m into the fiber, was driven with an asymmetric saw tooth waveform. The recovered strain from 20 separate measurements showed that the sensor correctly identified when the strain was increasing and when the strain was decreasing. The strain noise at a position of 25 m and 2 km into the fiber was measured to be 4.7 pε/√Hz and 10.2 pε/√Hz, respectively. This variation in strain noise over the fiber length suggests that multimode fibers may be susceptible to additional noise sources in long lengths of fiber and future studies will need to examine these effects in more detail. Nevertheless, this demonstrates that pico-strain-level noise floors over 2 km of multimode fiber are possible. In this work we presented a sensor that can be positioned at any location along a 2 km fiber, exhibits a linear strain response, reaches a noise floor of 10.2 pε/√Hz, achieves a bandwidth of 10 kHz, and correctly measures the algebraic sign of the strain. This work resulted in a publication in Optics Letters and more information about the sensor can be found in the paper [9].

CONCLUSION AND IMPACT

Based upon the above work it is clear that OTDR systems that use multimode fiber are capable of quantitative low-noise strain measurements. While it was known that the speckle pattern from a multimode fiber could contain a large quantity of information about strain in the fiber, it was unclear at the outset of this work whether mode mixing and modal dispersion would prohibit measurements with a linear strain response. In this work we took advantage of the diversity of spatial modes present in multimode fibers to help pioneer a new type of OTDR sensor that uses only the amplitude of the backscattered light to make quantitative strain measurements. These new quantitative amplitude-measuring sensors have the potential to decrease noise levels when compared to more traditional phase-based approaches. This work represents foundational technology upon which other sensing architectures continue to be built. For example, a single mode fiber sensor that extracts quantitative strain information from the backscattered amplitudes measured with several optical frequencies uses the same algorithm originally developed here for use with multimode fiber [10]. Ultimately, this work can help to increase the performance of a variety of sensors critical to the Navy.

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