Hybrid Distributed Acoustic-Temperature Sensor Using a Multimode Fiber

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Abstract: We report on simultaneous measurements of vibration and temperature along a multimode fiber (MMF). The MMF operates in a quasi-single-mode (QSM) state to satisfy the operational requirements of the distributed acoustic and temperature sensing systems.

1. Introduction

Giving the unique characteristics of optical fibers including harsh environment operation, miniature size, and immunity to electromagnetic waves, distributed fiber optic sensors are considered significantly important for many applications [1] [2]. Fiber optic distributed acoustic sensor (DAS) and distributed temperature sensor (DTS) have attracted significant attentions because they have been included in important applications, such as oil and gas industry [3], structural health monitoring [4], aerospace transportation [5], etc. In oil and gas industry, for instance, DAS and DTS can offer drilling and production optimization, fluid identification, pipeline surveillance, among others [3].

Focusing on the oil and gas industry, standard multimode fibers (MMFs) are widespread in wells for mainly the purpose of temperature sensing. Recently, monitoring vibrations within an oil/gas well’s environment is highly needed for different purposes [6]. Unfortunately, DAS typically requires using a single mode fiber (SMF). Installing new SMFs in oil/gas wells is a very difficult and expensive process, especially for productive wells. As a result, there is a strong motivation to use the already installed MMFs for vibrations sensing. However, the operation requirements of the DTS and DAS systems are quite different. In particular, DTS utilizes the backscattered Stokes and Anti-Stokes Raman signals for temperature sensing. The backscattered Raman signals are relatively weak, 60-70 dB below the pump power, which requires injecting optical pulses of high power into the used optical fiber [7]. Therefore, MMF is the preferred platform for DTS since it has a large core diameter and a high threshold of nonlinearity to support temperature measurements without distortion [8]. In contrast, the operation of DAS relies on the coherent interference of the Rayleigh signals reflected by scattering centers along the fiber [9]. Since MMF supports propagating many spatial modes, each mode would have its own interference signature which would create significant noise for DAS. Consequently, SMF is typically used with optical fiber DAS. Recently, two techniques have been reported to design a hybrid DAS-DTS system using a single optical fiber [10]. However, these reported techniques lack simplicity because of using laser coding and further use SMFs instead of the widespread MMFs.

In this work, we simultaneously measure vibrations and temperatures using the widespread standard MMF. We start with proving the possibility of designing a DAS system using a MMF. The used experimental setup is shown schematically in Fig. 1a where a narrow linewidth laser source generates a continuous-wave (CW) light of a 1535-nm wavelength and a 40-mW optical power. An acousto-optic modulator (AOM) is then used to convert the CW light into optical pulses of a 100-ns width and a 20-kHz repetition rate. The optical pulses are amplified with an erbium-doped fiber amplifier (EDFA1) and launched using a SMF-based circulator into a standard 50/125 µm
MMF of a ~4.15-km length. Light is launched into the MMF using the center-launching technique such that the axes of the SMF and MMF are well aligned and then the two fibers are splices or joined with a mating-sleeve. This center-launching technique is typically used in optical communication to mitigate the modal dispersion effect in MMFs [11]. Around the MMF’s end, we wrap a 10-m section of the fiber around a piezoelectric transducer (PZT) tube to act as a vibration source. PZT tubes are conventionally used to calibrate DAS systems because the amplitude and frequency of the PZT can be predetermined using a driven function generator [12]. The output beam intensity profile from the MMF is captured using a 50x objective lens and a CCD camera.

The backscattered Rayleigh signal from the MMF is directed towards the SMF of the circulator such that this SMF acts as a spatial mode filter to pick up only the fundamental mode from the Rayleigh signal and filters out the other higher order modes. The filtered Rayleigh signal is then amplified with another erbium-doped fiber amplifier (EDFA2) which amplified spontaneous emission (ASE) noise is discarded using a fiber Bragg grating (FBG). Afterwards, the Rayleigh signal is recorded with a photodetector (PD) and sampled with an oscilloscope.

Figures 1b and 1c show two representative examples of the temporal intensity profiles at the MMF’s output port, when using the center-launching method. Clearly, the transmitted power along the MMF is dominated by the fundamental mode which is relatively stable in the time-domain. In contrast, when exciting many modes within the MMD, the transmitted optical power is randomly distributed among the spatial modes and the beam profiles rapidly change, at the MMF’s output port [Figs. 1(d-e)]. This is attributed to the intermodal coupling between the spatial modes, especially the degenerate ones [13]. The results of Figs. 1(b-e) demonstrate the ability of our system to make the MMF works in a QSM state when using the center-launching method, which is necessary for the DAS operation.

Using QSM-operated MMF. A zoom-in image of these Rayleigh traces around the PZT cylinder position is shown in Fig. 2a shows 100 consecutive Rayleigh traces recorded when using the fundamental mode, which is accomplished by our experimental setup. Based on Eqs. (1) and (2), the backscattered Rayleigh signal is always dominated by the injected mode into the MMF because $B_{m'n'}^{in}(t)$ is maximized when $m'n'=mn$. Consequently, to mitigate the noise in the MMF-based DAS, one should inject an individual mode into the MMF and meanwhile collect the Rayleigh signal of the same injected mode, which is accomplished by our experimental setup.

To experimentally prove the capability of our system to detect vibrations, we drive the PZT tube to vibrate sinusoidally with a 500-Hz frequency. Figure. 2a shows 100 consecutive Rayleigh traces recorded when using the QSM-operated MMF. A zoom-in image of these Rayleigh traces around the PZT cylinder position is shown in Fig. 2b which clearly demonstrates the temporal changes of the Rayleigh intensities at the vibration position. Using

![Fig. 1. (a) Experimental setup of the MMF-based DAS. Temporal representative examples of the intensity profiles at the MMF’s output port when launching the fundamental mode (b-c) and many modes (d-e) into the MMF.](image)
the normalized differential method [15], we can locate the vibration location [Fig.2c]. For further clarification, a zoom-in image of the differential Rayleigh signal around the PZT position is provided in Fig. 2d which clearly shows the ability of our system to identify the vibration location.

Fig. 2. Consecutive Rayleigh traces (a) and zoom-in image of the Rayleigh traces around the PZT position (b) when using the QSM-operated MMF. Vibration information (c) and Zoom-in image of the vibration information around the PZT position (d).

3. Simultaneous Vibration and Temperature Monitoring Using The QSM-Operated MMF

In this section, we deploy the QSM-operated MMF to simultaneously offer distributed vibration and temperature sensing. The modified setup is shown schematically in Fig. 3a which is similar to Fig. 1a with the exception of adding a Raman wavelength-division-multiplexing (WDM) filter between the circulator and the MMF. The function of the WDM filter is spectrally splitting the backscattered Rayleigh, Stokes Raman, and Anti-Stokes Raman signals. The Rayleigh signal is used as aforementioned for vibration sensing, while the Stokes and Anti-Stokes Raman signals are compared with each other for the temperature sensing purpose [16].

Fig. 3. (a) Hybrid DAS/DTS setup (b)Vibration position information (c) Vibration frequency (d)Temperature distribution along the MMF while its end is immersed in cold and hot water bath.

Around the MMF’s end, we immerse a 10-m section of the MMF into a water bath with a controllable temperature [Fig. 3a]. Meanwhile, another identical fiber section is wrapped around the PZT cylinder, as shown in Fig. 3a. When driving the PZT cylinder with a 500-Hz frequency, our system can accurately locate the vibration position [Fig. 3b] and the frequency of vibration [Fig. 3c]. The harmonics shown in the spectrum of Fig. 3b is a common drawback of the direct detection method [17]. We then set the temperature of the water bath to 49.8 °C, as measured by a commercial thermistor, while we keep the remaining fiber at the room temperature. Using the recorded Stokes and Anti-Stokes Raman signals, our sensor measures a 48.3 °C temperature at the MMF’s section immersed in the water bath. The difference between the temperatures measured by the commercial thermistor and our sensor is likely attributed to the various calibration procedures of the two sensors. The results of Figs. 3b-d confirm the ability of our system to provide simultaneous distributed vibration and temperature sensing along the QSM-operated MMF.
4. Conclusion

In summary, we designed a distributed MMF-based sensor that simultaneously measures vibration and temperature. In order to satisfy the operation requirements of the DAS and DTS, we use the center-launching technique to mainly excite the fundamental mode into the MMF, and meanwhile we spectrally split the Rayleigh, Stokes Raman, and Anti-Stokes Raman signals. As a representative example, the reported system accurately measures a 500-Hz vibration frequency and a 48.3°C temperature at different locations along the MMF. This work would find significant interests from many important applications.

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