Simultaneous Distributed Acoustic and Temperature Sensing Using a Multimode Fiber

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Abstract—Fiber optic distributed acoustic sensor (DAS) and distributed temperature sensor (DTS) are considerably important for many applications. It is challenging to design a hybrid DAS-DTS system using the same optical fiber because the operation principles of the two sensors are different. We here deploy the widespread standard multimode fiber (MMF) for simultaneous distributed acoustic and temperature sensing. In particular, we operate the MMF in a quasi-single-mode (QSM) state to simultaneously fulfill the functionality requirements of the DAS and DTS. The reported design offers simultaneous vibration and temperature monitoring with high accuracy. In particular, the DAS has a 12.98 dB mean signal-to-noise ratio (SNR) and the DTS offers temperature measurements with ± 1 °C accuracy. This technique is significant for many industrial applications because it efficiently tackles a long-standing issue in practical implementation.

Index Terms—Acoustic sensors, Temperature sensors, optical fiber sensors, optical sensors.

I. INTRODUCTION

OPTICAL fiber sensors possess numerous advantages including immunity to electromagnetic interference, harsh environment operation, and miniature size [1], [2]. One attractive category of them is the distributed optical fiber sensors which monitor a certain parameter, such as vibration or temperature, along the entire fiber with a predetermined spatial resolution [2]. Such distributed fiber optic sensors are used in a myriad of important applications including oil and gas industry [3], real-time structural health monitoring [4], aerospace transportation [5], among others.

Optical fiber Raman-based distributed temperature sensor (DTS) and Rayleigh-based distributed acoustic sensor (DAS) have two different operation principles and system requirements [6], [7]. In particular, DTS relies on recording the Stokes and Anti-Stokes Raman backscattered signals from

an optical fiber. Since Raman signal is typically very weak (60-70 dB weaker than the input pump power) [8], high power is required to be launched into the optical fiber in order to have a reasonable signal-to-noise ratio (SNR). Consequently, multimode fiber (MMF) is the preferred platform for the Raman-based DTS. This is mainly because the standard MMF has a large effective area and a high threshold power of nonlinearity which can support the needed high injected pump power, without degrading the DTS system's performance. In contrast, the operation principle of the DAS is based on observing the Rayleigh backscattered signal from an optical fiber [7]. Compared with Raman signal, Rayleigh scattering is relatively stronger and does not require such high needed pump power of the DTS system [9]. Therefore, in terms of being below the fiber's nonlinearity threshold, either single-mode fiber (SMF) or MMF can be used for DAS. However, because the functionality of DAS depends on the coherent interference of the Rayleigh signals reflected by scattering centers along the fiber [7], MMF produces significant noises in DAS systems. This is because the standard MMF supports propagating a large number of modes and each mode has its own interference signature which all produce a resultant Rayleigh signal independent of vibration. As a result, MMF and SMF are ideal for DTS and DAS, respectively.

In comparison to SMFs, MMFs are widespread because MMF-based optical systems are relatively insensitive to alignment and cheaper [10]. Therefore, MMF is more commonly used than SMF, especially for short-distance applications [10]. For example, there are thousands of MMFs already installed worldwide in oil/gas wells for different purposes including distributed temperature sensing [3]. Consequently, using the already installed MMFs to simultaneously monitor temperature and vibration will be more cost-effective than installing new SMFs for vibration sensing. However, this is challenging because the typical MMF opposes the functionality requirements of the Rayleigh-based DAS.

Recently, two trials have been reported in the literature for designing a hybrid DAS-DTS system [11], [12]. In particular, Muanenda et al. experimentally designed a hybrid Raman-DTS and Rayleigh-DAS system based on a cyclic Simplex coding and using a SMF [11]. The coding improves the SNR of the hybrid sensing system to measure vibrations of frequencies up to 500 Hz and temperatures with a resolution down to 0.5 °C. The other design offers hybrid distributed

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detection of vibration, temperature, and strain [12]. In this work, Rayleigh and Brillouin scattering have been simultaneously utilized, when injecting modulated pulses into a SMF. The two systems lack simplicity because of relying on laser coding. Additionally, both avoided using the widespread standard MMF.

We here tackle this challenge: designing a hybrid DAS-DTS using the commercially available MMF. Using a wavelength division multiplexer/demultiplexer, we separate the backscattered Rayleigh and Raman signals used for DAS and DTS, respectively. Meanwhile, light is carefully injected into the MMF to mainly excite the fundamental mode into the fiber. In other words, we set the MMF to operate in a quasi-single-mode (QSM) state. Following this approach, the used MMF satisfies the operation requirements of both DAS and DTS.

We firstly provide a quantitative performance analysis for the MMF-based DAS when the MMF works in the QSM state and when we excite a large number of modes into the MMF. Next, we compare the performances of the standard SMF-based DAS and that designed in this work using a QSM-operated MMF, when launching pulses of a high power level into the fibers. Additionally, we experimentally prove the ability of the reported hybrid DAS-DTS system to simultaneously identify locations along the MMF subjected to vibrations, measure the frequencies of these vibrations, and monitor temperature along the MMF. The work presented here would find many important applications and also can potentially help to increase the sensing range of the typical SMF-based DAS.

II. MMF-BASED DAS

In this section, we investigate the SNR dependency of the MMF-based DAS on the mode composition of the injected light into the MMF. The used experimental setup is shown in Fig. 1 where a narrow linewidth laser produces continuous wave (CW) light of 1535 nm wavelength, 16 dBm optical

power, and 100 Hz linewidth. The CW light is then modulated into optical pulses of 100 ns width and 20 kHz repetition rate, using an acousto-optic modulator (AOM). Next, the modulated pulses are amplified with an erbium-doped-fiber-amplifier (EDFA1) to be injected through a circulator into a 50/125 μm MMF.

In this experiment, we measure the SNR of the DAS in two cases: Launching mainly the fundamental mode or mixtures of many modes into the MMF. The fundamental mode is injected into the MMF using the conventional center-launching method in which the axes of the SMF and MMF are aligned and then the two fibers are joined via a mating-sleeve or fusion splicing [13], [14]. The center-launching method has been widely used in optical communications to improve the bandwidth-distance product in MMF systems [13], [14]. Experimentally, as shown in Fig. 1, we inject the fundamental mode into the MMF by using a SMF-based circulator and joining the circulator's second port with the MMF under test via a mating-sleeve. It is worth mentioning that similar results are obtained when joining the two fibers with fusion splicing instead of the mating-sleeve. On the other hand, a combination of many modes can be excited into the MMF through using a MMF-based circulator. This is because light is guided through free-space optics within the circulator [15] which facilitates launching many modes at the MMF-based circulator's second port and consequently at also the input port of the MMF under test.

The used MMF under test is ~ 4 km long and, near its output port, we wind a 10 m section of the MMF around a vibrating piezoelectric transducer (PZT) cylinder driven by a radio frequency (RF) function generator. PZT cylinders are conventionally used to calibrate DAS systems because the vibration frequency of the PZT can be well controlled by the driven function generator [16]. The output intensity profile of the MMF is captured using an objective lens (50 $\times$, NA = 0.45) and a near-infrared CCD camera [Fig. 1]. As the optical pulses propagate along the MMF, Rayleigh signals are backscattered

Fig. 1. Experimental setup of the MMF-based DAS. Circ., circulator.

to be directed through the circulator towards another erbium-doped-fiber-amplifier (EDFA2). The EDFA2's amplified spontaneous emission (ASE) noise is then discarded using a fiber Bragg grating (FBG), and finally the filtered Rayleigh signals are respectively detected and sampled using a photodetector (PD) and an oscilloscope.

When injecting an lm mode into a MMF, the temporal power of backscattered Rayleigh signal received as $l'm'$ mode at the MMF's input port can be approximated as [17]:

$$P_{l'm'}^{lm}(t) = P_i \gamma_s B_{l'm'}^{lm} \bar{v} \Delta T e^{-2\alpha \bar{v} t}, \quad (1)$$

where t is the time, P_i and ΔT respectively denote the power and width of an optical pulse injected into the MMF as lm mode, and γ_s represents the ratio of the total Rayleigh scattered power to the incident power.

$\bar{v} = (v_g^{lm} v_g^{l'm'}) / (v_g^{lm} + v_g^{l'm'})$; v_g^{lm} and $v_g^{l'm'}$ are respectively the group velocities of the lm and $l'm'$ mode, and α is the optical attenuation coefficient. The overall capture fraction $B_{l'm'}^{lm}$, which quantifies the ratio of the scattered power into $l'm'$ mode to the total scattered power, is given by [17]:

$$B_{l'm'}^{lm} \propto \int_0^{2\pi} \int_0^\infty E_{lm}^2(r, \phi) E_{l'm'}^2(r, \phi) r dr d\phi, \quad (2)$$

where $E_{lm}(r, \phi)$ and $E_{l'm'}(r, \phi)$ are the spatial near field distribution of the lm and $l'm'$ mode, respectively. Based on Eqs. (1) and (2), when an optical pulse is injected into a MMF as lm mode, the backscattered Rayleigh signal is dominated by the lm mode. This is because the overall capture fraction $B_{l'm'}^{lm}$ is maximized when $lm = l'm'$.

In order to mitigate the noise in the MMF-based DAS, one should inject a single spatial mode into the MMF and simultaneously record the Rayleigh signal of the same mode. Furthermore, intermodal coupling within the MMF should also be reduced. Using the experimental setup shown in Fig. 1, we capture the intensity profiles at the MMF's output port when using the SMF- and MMF-based circulator. The intensity profiles are captured while we intentionally perturb the refractive index of the MMF to induce intermodal coupling. This is achieved via continuously blowing air flow produced by a fan onto a freely hanged ~ 1 m section of the MMF. The hanged MMF section is located directly after the MMF's input port and as it shakes, because of the air flow, its refractive index is perturbed. This ~ 1 m fiber section is vertically hanged and its maximum deviation from its stationary position is roughly ± 10 cm, as the fan blows air towards it. Figures 2(a-d) and 2(e-h) show representative examples at different time instances to the output intensity profiles of the MMF captured when using the SMF- and MMF-based circulator, respectively. The results in Fig. 2 indicate that the conventional center-launching method mainly excite the fundamental mode in the MMF. Since the fundamental mode is non-degenerate, it is barely coupled to

Fig. 2. Temporal representative examples of the intensity profiles at the MMF's output port when launching the fundamental mode (a-d) and many modes (e-h) into the MMF.

the other modes and consequently the fundamental mode preserves its shape until the end of the MMF [18]. When using the MMF-based circulator, in contrast, many spatial modes are launched into the MMF. Additionally, the temporal intensity profiles at the MMF's output port are unstable [Figs. 2(e-h)]. This can be attributed to the high probability of including degenerate modes excited within the MMF which can be easily coupled to each other.

Based on Eqs. (1) and (2), exciting the fundamental mode into the MMF should mitigate the noise in the DAS system, in comparison with the case of injecting many modes into the MMF. The input fundamental mode produces Rayleigh signal that is dominated by the fundamental mode. Importantly, in the backscattering direction, the SMF of the circulator's second port acts as a spatial mode filter to only pick up the fundamental mode of the Rayleigh signal and discard the other modes. Therefore, the designed system acts similarly as the SMF-based DAS, but with the presence of minor intermodal coupling which is significantly reduced when injecting the non-degenerate fundamental mode.

To experimentally prove that, we drive the PZT cylinder to vibrate sinusoidally with 5 kHz frequency, while the fan still blows air onto the MMF to perturb its refractive index. Figures 3(a) and 3(c) show 100 consecutive Rayleigh traces recorded when injecting the fundamental mode and many modes into the MMF, respectively. The zoom-in image shown in Fig. 3(b)/3(d) presents the temporal change of the Rayleigh intensities around the PZT location for the QSM/multimode operation case. Using the conventional differential method [7], i.e., subtracting Rayleigh traces in the time domain, we can locate the vibration location as shown in Figs. 4(a) and 4(c) when respectively exciting the fundamental mode and many modes into the MMF. Again, Fig. 4(b)/4(d) shows a zoom-in image of the differential Rayleigh signal around the PZT position for the QSM/multimode operation case. We normalize the differential signals in Fig. 4 for comparison purpose which indicates the background noise when injecting many modes into the MMF is much higher than when exciting the fundamental mode.

In order to quantify this observation for the two cases, we compare the SNR defined as the ratio between the root-mean-square (RMS) value of the differential signal at the PZT position and that along the calm fiber. Figure 5(a) shows the

Fig. 3. 100 consecutive Rayleigh traces recorded during the QSM (a) and multimode (c) operation of the MMF. Zoom-in images of the 100 Rayleigh traces around the PZT position recorded during the QSM (b) and multimode (d) operation of the MMF.

Fig. 4. Vibration position information measured during the QSM (a) and multimode (c) operation of the MMF. Zoom-in images of the vibration position information around the PZT measured during the QSM (b) and multimode (d) operation of the MMF.

temporal changes of the SNR values when injecting the fundamental mode (black circles) and many modes (green diamonds) into the MMF. Each SNR value is calculated along a 50 ms time period and the calculations include 300 different SNR samples [Fig. 5(a)]. This sample is sufficient to have meaningful mean and standard deviation for the SNR values. In Fig. 5(b), we present the relative frequency histograms when choosing a 1 dB bin for the SNR values shown in Fig. 5(a). As shown in Fig. 5(b), the Gaussian distribution fitting of the relative histogram when injecting the fundamental mode (black line) has 12.98 dB mean and 2.66 dB standard deviation. When launching many modes into the MMF, in contrast, the Gaussian distribution fitting of the relative histogram (green line) has 7.74 dB mean and 3.31 dB standard deviation. The results of Fig. 5 conclude that the reported MMF-based DAS is reliable and can be combined with the MMF-based DTS, conditioning that the MMF operates in the QSM state.

Fig. 5. (a) Temporal change of the SNR values during the QSM and multimode operation of the MMF. (b) Gaussian distribution fittings of the SNR relative frequency histograms associated with the QSM and multimode operation of the MMF.

III. COMPARING THE PERFORMANCES OF THE SMF- AND MMF-BASED DAS/DTS

In this section, we aim to compare the performances of the SMF- and MMF-based DAS/DTS when injecting optical pulses of high power levels. The high-power optical pulses are used to overcome the challenge of the weak Raman signals used in the DTS systems. We firstly focus on the DAS system described in the experimental setup of Fig. 1 where we here either use a standard SMF (9/125 μm) or the 50/125 μm MMF as a fiber under test. In the two cases, light is injected into the SMF/MMF through a SMF-based circulator. This is to avoid the loss of the core diameter mismatch when using the SMF under test, and to maximize the SNR of the DAS system when using the MMF under test, as described in Section II. As a representative example, we inject optical pulses of $P_i = 32.24$ dBm individually into the two standard fibers. Figure 6(a)/6(c) shows 100 consecutive Rayleigh traces when using the SMF/MMF. For the SMF, the Rayleigh signal degrades along the fiber length. This is attributed to the SMF's nonlinearity which is dominant by the stimulated Raman scattering (SRS)

Fig. 6. (a)/(c) 100 consecutive Rayleigh traces collected when using the SMF/QSM-MMF at 32.24 dBm input power. (b)/(d) vibration position information when using the SMF/QSM-MMF at 32.24 dBm input power.

Fig. 7. Experimental setup of the hybrid DAS-DTS system. Circ., circulator; FUT, fiber under test.

for this meter-scale optical pulses [19]. In contrast, the MMF has a larger effective area and consequently a higher threshold of nonlinearity, compared with that of the SMF [19]. As a result, the Rayleigh traces keep their speckle-like profile along the MMF length [Fig. 6(c)].

Again, we drive the PZT cylinder to vibrate sinusoidally with 5 kHz frequency when using the two fibers at $P_i = 32.24$ dBm. Applying the traditional differential method to locate the PZT location, Fig. 6(b)/6(d) shows the differential Rayleigh signals when using the SMF/MMF. In consistent with the results of Fig. 6(a), the SMF fails to recognize the PZT's vibration event because of the degradation of the Rayleigh signal. On the contrary, the MMF efficiently locates the vibration event even when using such high input power. These results are important since the QSM-operated MMF would be able to increase the sensing range of the typical SMF-based DAS because the MMF supports launching optical pulses of higher power.

To generalize our results, when injecting optical pulses into an optical fiber such that the peak power of the pulses is higher than the fiber's threshold of nonlinearity, the fiber cannot be reliable for vibration sensing. On the contrary, as long as the pulses' peak power is less than the fiber's nonlinearity threshold, the fiber can monitor vibrations. The sensitivity of the latter sensing case relies on many parameters, such as temporal pulse intensity fluctuation, laser phase noise and frequency drift, extinction ratio of the launched pulses, and photodetector thermal and shot noise [2], [7].

We next modify the experimental setup to further record the Stokes and Anti-Stokes Raman signals, for DTS application using either the SMF or MMF. The modified experimental setup is shown schematically in Fig. 7 where a 3×1 wavelength division multiplexer/demultiplexer (MUX/DEMUX) is added between the circulator and the fiber under test. One side of the wavelength division MUX/DEMUX includes three ports to add/drop signals of wavelengths match those of the Rayleigh, Stokes Raman, and Anti-Stokes Raman signals. The other side of the wavelength division MUX/DEMUX comprises a common port which simultaneously supports propagating the Rayleigh, Stokes Raman, and Anti-Stokes Raman signals. Since Rayleigh

scattering is an elastic phenomenon, i.e., it has the same wavelength as the pump signal, the optical pulses are injected into the wavelength division MUX/DEMUX through the Rayleigh port. The optical pulses are then delivered to the fiber under test through the common port of the wavelength division MUX/DEMUX. As the optical pulses propagate along the fiber under test, Rayleigh, Stokes Raman, and Anti-Stokes Raman signal are backscattered, as shown in Fig. 7. The three backscattered signals can be well separated via the wavelength division MUX/DEMUX such that the Rayleigh signal is used for vibration sensing, and Stokes and Anti-Stokes Raman signal for temperature sensing. We use a SMF- and a MMF-based wavelength division MUX/DEMUX when using the SMF and MMF under test, respectively.

We compare the Anti-Stokes Raman, and Stokes Raman signals recorded when using the SMF and MMF under test at three arbitrary high input powers such that $P_i = 32.02$ dBm, 32.24 dBm, and 32.42 dBm. Figures 8(a) and 8(b) respectively show the Anti-Stokes and Stokes Raman signals recorded

Fig. 8. (a)/(c) Anti-Stokes Raman signals when using the SMF/QSM-MMF at different input power levels. (b)/(d) Stokes Raman signals when using the SMF/QSM-MMF at different input power levels.

when using the SMF at room temperature, for different P_i values. Obviously, the SMF's Raman signals are distorted by the SRS, especially at higher input powers, thus unable to perform successful temperature estimation. In contrast, the Anti-Stokes and Stokes Raman signals of the QSM-operated MMF, kept at room temperature, show typical spontaneous Raman scattering feature, as shown respectively in Figs. 8(c) and 8(d). The results of this section conclude that the QSM-operated MMF is the optimum solution to simultaneously satisfy the operation requirements of the DAS and DTS systems.

It is worth mentioning that the peak powers of the injected optical pulses are controlled via tuning the pump current of the pulsed EDFA. We randomly select three different EDFA's pump currents, within various ranges, to clearly demonstrate the nonlinearity behavior of the SMF-based DTS, when injecting powers higher than the SMF's nonlinearity threshold.

IV. SIMULTANEOUS VIBRATION AND TEMPERATURE MONITORING USING THE QSM-OPERATED MMF

In this section, we deploy the QSM-operated MMF to simultaneously provide distributed vibration and temperature sensing along the MMF length. The hybrid DAS-DTS system is shown schematically in Fig. 7 where the MMF is used as the fiber under test. Near the MMF end, we immerse a 10 m section of the MMF in a water bath where its temperature is controllable, and another identical fiber section is wound around the PZT cylinder [Fig. 7]. As a representative example, we again drive the PZT cylinder to vibrate with a 5 kHz frequency. Using the Rayleigh traces recorded by our system, Figs. 9(a) and 9(b) respectively show the vibration location information and power spectrum of the PZT vibration event. These results confirm the ability of the designed hybrid DAS-DTS system to accurately figure out the location and frequency of the PZT vibration event.

Next, we set the water bath temperature to $\sim 7.5^\circ\text{C}$, where this temperature is measured via a commercial thermistor, while we keep the remaining fiber at room temperature. After calibrating our system by linking the ratio between the Anti-Stokes and Stokes Raman signals with the temperature [6], our system measures $\sim 7.2^\circ\text{C}$ temperature at the MMF position located in the water bath [Fig. 9(c)]. The difference between the temperature measured with our system and that one measured with the commercial thermistor is acceptable because most of commercial DTS systems offer $\pm 1^\circ\text{C}$ absolute temperature error [20]. This error is mainly because of the different calibration techniques applied for the optical fiber DTS and thermistor. Similarly, we raise the temperature of the water bath to 49.8°C , as measured by the commercial thermistor, to find our DTS provides 48.3°C [Fig. 9(d)]. Again, the difference between the two measurement systems, DTS and thermistor, is within the acceptable error range. The results shown in Fig. 9 confirm the ability of our system to provide simultaneous distributed vibration and temperature sensing along the QSM-operated MMF.

Fig. 9. Vibration position information (a) and power spectrum (b) of the 5 kHz vibration event. Temperature distribution along the MMF when a fiber section around its end is immersed in hot (c) and cold (d) water bath.

V. CONCLUSION

We tackle a long-standing challenge: designing a hybrid DAS-DTS system using a MMF. In particular, we use the center-launching method to excite the fundamental mode into the MMF. We find that, even under refractive index perturbation of the MMF, the fundamental mode is barely coupled to the other modes and it maintains its spatial intensity distribution until the end of the MMF. Using this mode launching mechanism, the MMF satisfies the operation requirements of the DAS, especially because we only pick up the fundamental mode from the backscattered Rayleigh signal. The reported MMF-based DAS offers 12.98 dB mean SNR. We further modify the system to simultaneously extract the backscattered Rayleigh, Anti-Stokes Raman, and Stokes Raman signals from the MMF. The developed system offers simultaneous accurate vibration and temperature sensing along the QSM-operated MMF. As a representative example, the reported hybrid sensor successfully monitors vibrations of 5 kHz frequency, and 7.2°C and 48.3°C temperatures with $\pm 1^\circ\text{C}$ accuracy.

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