Energy Recycling from Distributed Fiber-Optic Sensors

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Abstract—Distributed fiber-optic sensors (DFOS) have been widely deployed in a wide range of applications. The operational principle of such DFOS typically relies on monitoring light backscattered due to pumping optical pulses in an optical fiber. Once the DFOS’ optical pump pulses reach the distal end of the optical fiber, the power carried by each pulse is conventionally wasted and dissipated to the medium surrounding the fiber without a benefit. Here, we report on energy harvesting from the DFOS’ optical pulses to recycle the wasted optical power for electric-consuming devices supply. We demonstrated the feasibility of this concept by harvesting energy from a fiber-optic distributed acoustic sensor (DAS) and a distributed temperature sensor (DTS). The study further investigates the impact of changing the pulse repetition rate within the 5–25 kHz range on the harvested power. Without any disturbances in the DFOS functionalities, power values of up to 0.871 mW were harvested as a proof-of-concept demonstration.

Index Terms—Distributed acoustic sensing (DAS), distributed temperature sensing (DTS), energy harvesting, power-over-fiber, energy.

I. INTRODUCTION

Distributed fiber-optic sensors (DFOS) have gained recognition with the academic and industrial communities; they are considered the most promising fiber-based sensing technologies of the past decade [1]. DFOS came into the field to overcome the cost-efficiency challenge of the already existing point-wise optical sensors. Multiple advantages over electronic sensors, such as immunity to electromagnetic interference and high resilience against harsh environments, make DFOS an ideal option for anyone seeking a practical yet robust approach to sensing many external parameters [2]. These distributed sensors can offer accurate live tracking of multiple variables along an optical fiber with a high spatial resolution over more than 100 km of distance [1], [2].

The operation principle of a conventional DFOS involves the injection of pump optical pulses into the fiber to retrieve a scattered light from the opposite direction to the input signal propagation. External stimuli changes, such as temperature or vibration, interacting at any position along the fiber induce alterations in the backscattered light that an interrogator can characterize at the near end [2]. Nevertheless, the injected signal does not fulfill any other function on the distal fiber end. It instead fades once reaching the distal end of the fiber, representing a waste of power that could be used to supply energy to remote devices. For this reason, and given the growing worldwide energy consumption, it is important to harness DFOS potential and take full advantage of what this technology can offer. On the other hand, researchers have been conducting experiments to deliver energy over optical fibers since the late 1970s. Features such as being lightweight and resistant to corrosion make optical fibers an attractive option to enhance existing power supply systems by merging telecommunication and sensing with power transmission infrastructure in a so-called power-over-fiber system (PWoF) [3].

Conventional PWoF systems comprise three main components: an optical source, an optical fiber, and a photovoltaic power converter (PPC). All the current state-of-the-art covers the report of several trials to achieve the best performance by comparing systems employing different types of fibers, power converters, or input wavelengths [4]. Single-mode fibers (SMF) and multi-core fibers (MCF) are the most commonly used fibers in PWoF systems. For instance, a 1064-nm centered wavelength light source was used to launch a 60-W input optical power into six cores of a MCF [5]. This design delivered a 33-W optical power at the fiber distal end, retrieving up to 11.5-W (~1.92 W per core) electrical power. Another example is a SMF-based PWoF that included a 5-W input optical power at a 1480-nm centered wavelength, delivering 2.24-W optical power and 226-mW electrical power at the fiber’s far end and [6]. Nonetheless, the small diameter in single-mode cores makes these systems prone to exceed the fiber non-linearity threshold, compromising the maximum deliverable power and integrity of the system. Alternatively, multimode fibers (MMF) allow for higher power transmission than the PWoF systems based on SMF cores while simultaneously carrying data signals. As a proof of concept demonstration, MMF-based PWoF systems fed with 808 nm [7] and 1550 nm [8] centered high-power lasers reported up to 2.34 W of electrical power delivered to remote units. However, the simultaneous transmission of data and power signals in these systems degrades the telecommunication link because of the crosstalk noise induced between the two signals. [9]. Optimizing the high-power laser (HPL) instabilities, optical fiber length, and PWoF power levels can improve the performance of the shared scenario (co-transmission of both PWoF and data signals) and mitigate the shared scenario’s nonlinear effects typically limited by stimulated Raman scattering (SRS) [10].
Double-clad fibers (DCF) started to play an essential role in PWoF systems. The internal architecture of a DCF increases the power transmission capacity of PWoF systems and reduces the intermodal crosstalk by assigning the inner cladding and single-mode core as separate channels to simultaneous high-power feed and data transmission. For example, a DCF-based PWoF system of a 150-W input optical power and a 808-nm wavelength delivered a 7.08-W electrical power.

Harvested power is recycled from either a system that has power for another purpose or a source that is always available like the sun during the day. In all previous reports of PWoF systems, light sources are used specifically for optically feeding remote nodes without applying the energy harvesting (EH) concept. Yet, to the best of our knowledge, only our recently published work reported harvesting energy from optical sensing signals. We briefly presented a proof-of-concept demonstration of EH from a fiber-optic distributed acoustic sensor (DAS). In this work, we report on an EH framework that can be applied to DFOS, regardless of the operation principle, whether based on Rayleigh, Brillouin, or Raman backscattering. Additionally, compared to the work reported in [12], this study investigates the impact of changing the pulse repetition rate of DFOS on the harvested power.

As illustrated in Fig. 1 an interrogation unit available in DFOS typically comprises a light source that pumps optical pulses into an optical fiber and a detector that characterizes the backscattered light retrieved through a circulator. In a conventional DFOS, the distal end of the fiber converges into an optical terminator that leads the propagating optical pulses to extinguish. In contrast, we propose to replace the terminator with an EH unit that converts the pump signal power, which is subsequently injected through a circulator (Circ. 1) from a SMF to the fundamental mode (LP01) of a ~1-km long TMF using the center-launching method. The TMF has a 0.22-dB/km attenuation at the 1550-nm wavelength. The injected pulses propagate along the TMF toward the EH unit while inducing Rayleigh backscattered light that is directed toward a second EDFA (EDFA 2) (Amonics, AEDFA-23-M-FA). We then demonstrate EH from another DFOS using a MMF-based distributed temperature sensor (DTS).

II. EXPERIMENTAL METHODOLOGY

Fig. 2(a) shows a schematic representation of a TMF-based DAS designed using the phase-sensitive optical time-domain reflectometer (Φ-OTDR) [2]. In this configuration, a narrow-linewidth laser (NKT Photonics, 15E) produces a continuous wave (CW) light of a constant 40-mW optical power, a 1550-nm centered wavelength, and a 100-Hz linewidth. The CW light is modulated into 100-ns-long optical pulses by an acousto-optic modulator (AOM) (G&H, 1200AF-DINA) driven by an arbitrary wave generator (AWG) (Spectrum Instrumentation, M4i.6620), offering a ~10-m spatial resolution. Following the AOM, an erbium-doped fiber amplifier (EDFA 1) (Amonics, AEDFA-NS-200-20-25-M-FA) increases the pump signal power, which is subsequently injected through a circulator (Circ. 1) from a SMF to the fundamental mode (LP01) of a ~1-km long TMF using the center-launching method. The TMF has a 0.22-dB/km attenuation at the 1550-nm wavelength. The injected pulses propagate along the TMF toward the EH unit while inducing Rayleigh backscattered light that is directed toward a second EDFA (EDFA 2) (Amonics, AEDFA-23-M-FA) using the same circulator placed at the TMF input end. However, amplified spontaneous emission (ASE) noise often comes as a byproduct after amplifying optical signals using an EDFA. Therefore, the ASE noise requires filtering with the help of a fiber Bragg grating (FBG) before being transmitted to a photodetector (PD) and a data acquisition device (DAQ) (Spectrum Instrumentation, M4i4480) employing a second circulator (Circ. 2).

Besides harvesting energy from the TMF-DAS, Fig. 2(b) illustrates the operation of a MMF-based Raman DTS whose
pump signal is harvested under the same scheme used for the TMF-DAS DFOS. Similarly to the φ-OTDR DAS, the CW laser, which has a constant 40-mW optical power, and the AOM generate the DTS-pulsed pump signal with a 1550-nm central wavelength and pulse width (100 ns, ∼10-m spatial resolution). The pulses are then injected into a 3 × 1 wavelength division multiplexer/demultiplexer (WDM Mux/Demux) (Ideal-Photonics Inc., CJT 1450/1550/1660 50/125 multimode WDM) after being amplified by the EDFA. Subsequently, the pump signal is launched through the WDM Mux/Demux into a 50/125 µm MMF of a ∼1-km length and 0.28-dB/km attenuation at 1550 nm. The Raman signals are backscattered along the MMF and retrieved by the WDM Mux/Demux, such that the Stokes and Anti-Stokes Raman signals are delivered to two different avalanche photodetectors (APD1, APD2) and, finally, to the DAQ. The measurable temperature range of the DTS is determined by the fiber’s primary coating material. For example, the HT Acrylate coating offers a -40 °C to +180 °C temperature range [14].

Both TMF-DAS and MMF-DTS DFOS inject their forward-propagating input optical power (\(P_{\text{in}}\)) into the fiber under test (Figs. 2(a) and 2(b)). Then, the average optical power at the fiber’s distal end (\(P_{\text{out}}\)) is retrieved by the EH unit depicted in Fig. 2(c). The harvesting unit, therefore, converts the optical pulses into electric current using a 1550 nm-centered InGaAs photodiode (Thorlabs, FGA01FC) operating in the photoelectric mode and the photodiode here is zero-biased. After the photoelectric conversion, a supercapacitor (SC) charging process is enabled through the charging circuit illustrated in Fig. 2(c), where \(R_s\), \(R_{sh}\), and \(C_j\) respectively denote the photodiode’s series and shunt resistances and junction capacitance, while \(C_\text{L}\) is a 10 F SC and ESR represents the equivalent series resistance of the SC.

III. RESULTS AND DISCUSSION

We test the performance of both DAS and DTS when connecting the EH units at their distal ends. Focusing on the DAS system, Figs. 3(a)-(c) show the detection of an induced vibration of 500 Hz around a 10-m fiber section wound around a piezoelectric transducer (PZT), with a fixed peak-to-peak voltage (5 V) applied to the PZT, when sweeping the pulse repetition rate \(f_s\) to 5, 10, and 25 kHz. The 500-Hz vibration event is within the DAS detection frequency range of up to \(f_s/2\). In all three cases, the DAS successfully identifies the position of the PZT and the vibration frequency after applying the normalized differential method [15], and a fast Fourier transform (FFT) to the retrieved Rayleigh traces. The DAS signal-to-noise ratio (SNR) is defined as the ratio between the root-mean-square differential intensity detected at the PZT location (\(I_{\text{PZT}}\)) and that of a 10-m calm fiber section (\(I_{\text{calm}}\)):

\[
\text{SNR} = 10 \log_{10} \left( \frac{I_{\text{PZT}}}{I_{\text{calm}}} \right).
\]

The calculated SNR values for each repetition rate are given in Table I and all these values are greater than the minimum acceptable 2-dB SNR for a DAS system [15].

Secondly, we test the performance of the DTS when harvesting the pump signal injected through the MMF at a constant

<table>
<thead>
<tr>
<th>Repetition rate (f_s) (kHz)</th>
<th>SNR (dB)</th>
</tr>
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<tbody>
<tr>
<td>5</td>
<td>13.44</td>
</tr>
<tr>
<td>10</td>
<td>13.87</td>
</tr>
<tr>
<td>25</td>
<td>13.14</td>
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</tbody>
</table>

Fig. 3. Detected vibration position information and power spectrum of the 500 Hz vibration event by the DAS using repetition rates of (a) 5, (b) 10, and (c) 25 kHz. (d) Warm water bath location detected by the DTS.

\(f_s = 10\) kHz. Fig. 3(d) shows the successful DTS detection of an experimental heat source. To conduct the DTS experiment, we immersed a 10-m MMF section near the far end of the fiber in a hot water bath, reaching an overall temperature near 60 °C. The temperature increase at the start of the fiber is an artifact occurring because of the fiber front facet reflection.

We then compare the power harvested from the four sensing scenarios (DAS using \(f_s = 5\), 10, and 25 kHz, and DTS using \(f_s = 10\) kHz). Figures 4(a)-(c) show the SC charging curves obtained for the DAS cases, evidencing a steady increase in the transient voltage when rising the repetition rate. This behavior is observed due to the RC nature of the equivalent charging circuit, where the longer time between each pulse allows a larger discharge of the SC. Additionally, the SC charging through the DTS system exhibits minor ripples while increasing the voltage (Fig. 4(d)). The noise exists because the photodiode used in the charging circuit is optimized for SMFs. In other words, the large core diameter of the DTS MMF partially delivers light out of the active area of the photodiode, causing instability in the received power values.

The photodiode’s average current, \(I_{\text{out}}\), and the average optical power at the fiber’s distal end (\(P_{\text{out}}\)) are correlated by the 1.003 A/W responsivity given in the manufacturer’s datasheet (Thorlabs-FGA01FC). Therefore, the total electrical

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Table II

<table>
<thead>
<tr>
<th>Energy Harvested from the DFOS.</th>
<th>( \text{DAS} )</th>
<th>( \text{DAS} )</th>
<th>( \text{DAS} )</th>
<th>( \text{DTS} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_s (\text{kHz}) )</td>
<td>( P_{\text{in}}^{\text{opt}} (\text{mW}) )</td>
<td>( P_{\text{out}}^{\text{opt}} (\text{mW}) )</td>
<td>( I_{\text{out}} (\text{mA}) )</td>
<td>( V_{\text{out}} (\text{V}) )</td>
</tr>
<tr>
<td>25</td>
<td>8.91</td>
<td>7.90</td>
<td>7.92</td>
<td>11.0</td>
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<tr>
<td>10</td>
<td>3.32</td>
<td>3.10</td>
<td>3.17</td>
<td>3.0</td>
</tr>
<tr>
<td>25</td>
<td>1.50</td>
<td>1.30</td>
<td>1.35</td>
<td>2.0</td>
</tr>
<tr>
<td>20</td>
<td>1.76</td>
<td>1.65</td>
<td>2.2</td>
<td>0.14</td>
</tr>
</tbody>
</table>

harvested power \( (P_{\text{out}}^{\text{elect.}}) \) from a DFOS is given as follows:

\[
I_{\text{out}} = 1.003 \times P_{\text{out}}^{\text{opt}} \rightarrow P_{\text{out}}^{\text{elect.}} = I_{\text{out}} \times V_{\text{out}},
\]

where \( V_{\text{out}} \) denotes the steady-state voltage at the output terminals of the capacitor. Table II summarizes the values of \( P_{\text{in}}^{\text{opt}}, P_{\text{out}}^{\text{opt}}, I_{\text{out}}, \) and \( V_{\text{out}} \), along with the corresponding electrical harvested power for all the carried experiments. As expected, based on the discussion above about the supercapacitor charging, the DTS system provides the lowest harvested power because of the mismatching between the MMF core diameter and the active area of the photodiode. Finding a photodiode optimized to fully couple with larger devices would be ideal for increasing the amount of recycled energy from high-power DFOS. However, the overall results prove the concept of EH from DFOS without disturbing their main functionalities. Besides, it is worth highlighting that similar power level adjustments of \( P_{\text{opt}}^{\text{in}} \) used in this work were deployed for DAS/DTS [16] but without energy harvesting.

The high compatibility of this idea in different applications beholds the motivation to continue investigating better practices to reuse DFOS pump signals. For instance, underwater communication systems can benefit from fiber-optic EH, as they require an external source to supply electric power to the devices in the network. Although the reported power harvested from DFOS is low, it is expected to provide many ultra-low-power devices, such as Internet of Things (IoT) devices powered by 100s of \( \mu \text{W} \) range [17] and ultra-low-power vision systems in IoT wireless sensor nodes with a reported average consumption as low as a few tens of \( \mu \text{W} \) [18]. In addition, the power of the EH unit could be enhanced by cascading a boost converter and an autonomous power management unit [19].

IV. Conclusion

We deployed EH to recycle the wasted power of DFOS’ optical pulses at the end of optical fibers without impacting the main sensing functionalities of DFOS. The feasibility of our design was demonstrated by harvesting energy from fiber-optic DAS and DTS. For example, at a 25-kHz pulse repetition rate for the DAS, we harvested a power value 0.871 mW. By characterizing the performance of the EH unit, we found that increasing the repetition rate of DFOS pump signals yields an increase in the harvested power. This new study opens the door for further investigation to reuse the DFOS pump signals’ energy in various applications.

REFERENCES