Hybrid distributed acoustic sensing and Kramers–Kronig communication system over a two-mode fiber

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Abstract: We report on the co-propagation of distributed acoustic sensing (DAS) and Kramers–Kronig communication scheme over a two-mode fiber, achieving DAS with a signal-to-noise ratio larger than 2 dB and gross data rate of 2.04 Gbps.

1. Introduction

Distributed fiber-optic sensing is progressively overtaking other sensing technologies as a live-tracking solution to monitor simultaneous physical phenomena interacting with an optical fiber at multiple locations. In particular, Φ-OTDR-based distributed acoustic sensing (DAS) has been receiving considerable attention for its high potential in seismic and structural health monitoring [1]. Moreover, using submarine and terrestrial communications optical fiber can significantly widen the scope of the current monitoring schemes. To date, researchers have approached this matter in two different ways, i.e., by employing single-mode dark fiber for DAS [2], or co-propagating sensing and communication signals through the same fiber via wavelength division multiplexing (WDM) [3]. The latter approach has the advantage of providing widely deployed fiber-optic communication networks with the capability of detecting vibrations in their surroundings, which would open the doors for a plethora of novel applications in different fields.

However, mode-division multiplexing (MDM) has been under development in recent years with the premise of enlarging the transmission capacity of current WDM communication systems by exciting different optical fiber spatial modes to co-propagate independent signals [4]. Currently, most communications systems fundamentally operate on two principles: Intensity Modulation/Direct Detection (IM/DD) and coherent detection. Whereas coherent detection communication systems require a local oscillator and allow for signal phase detection, IM/DD systems usually require only a photo-diode (PD) and communicate based on intensity modulation. To date, most of the implemented optical communications systems have been based mainly on the IM/DD on-off keying or Real-Valued orthogonal frequency-division multiplexing (ROFDM) schemes due to operational complexity and cost prohibition of the coherent systems. The recently proposed scheme, i.e., a Kramers–Kronig (KK) coherent receiver [5,6] has the potential to become an economical way to transmit complex-valued signals in optical communications while using only one PD at the receiver end. KK operates on the principle that for the single-sideband, minimal phase (SSB MP) signals, their phase can be uniquely recovered from the amplitude. As such, it required only one PD to transmit a complex signal. In this work, we report on the implementation of MDM in the design of a hybrid DAS and communication system using the KK scheme and two-mode fiber (TMF) whose non-linearity power threshold and intermodal crosstalk lie in between the ones present in standard single-mode fibers (SMF) and multi-mode fibers (MMF).

2. Experimental Setup

Figure 1(a) illustrates the schematic diagram of our proposed design, where a photonic lantern serves as a mode multiplexer/demultiplexer in which the modes LP_{01} and LP_{11a} are excited to co-propagate the communication and DAS signals, respectively, along a ∼1-km-long TMF as a proof-of-concept demonstration. Near the fiber distal end, a ∼10-m section is wind around a piezo-electric transducer (PZT) vibrating at predetermined frequencies of 600 Hz or 900 Hz to mimic the acoustic signals. Furthermore, acknowledging that DAS acoustic detection is based on Rayleigh backscattered light and the pump pulses do not accomplish any other purpose and fade away after propagating along the fiber, a short SMF segment is connected to the TMF distal end to filter out the LP_{11a} mode and feed only the LP_{01} to a receiver unit to demodulate the communication signal. To ensure that our system relies only on MDM, the DAS and communication signals co-propagate at the same wavelength, as shown in Fig. 1(b).

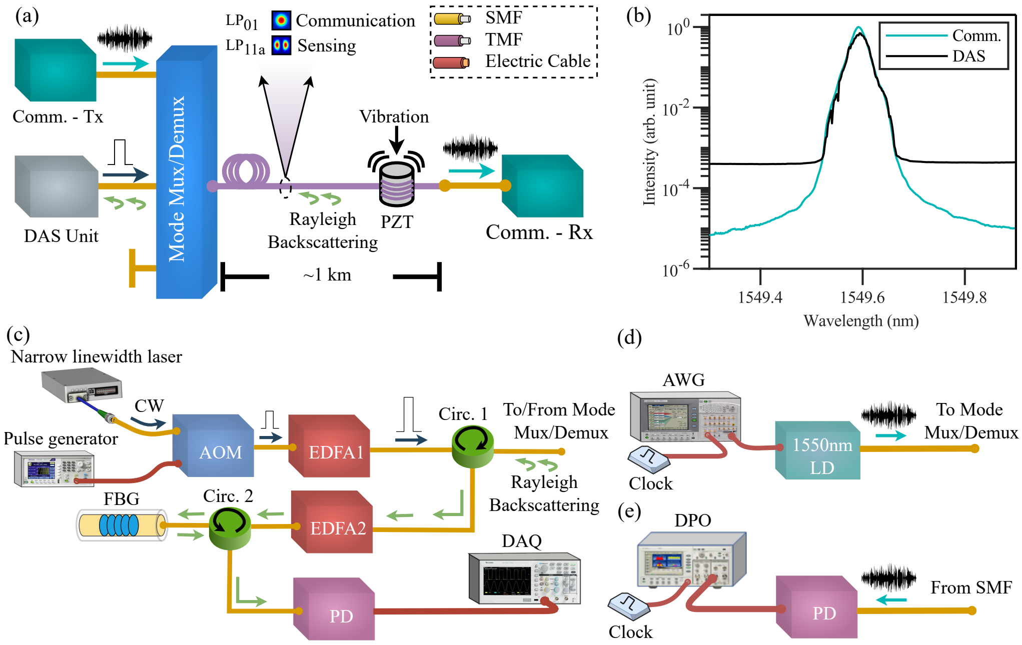

Fig. 1: (a) Schematic design of the DAS and communication over the TMF. (b) Matching of operation wavelengths between the sensing and communication signals. (c) Experimental setup of the DAS unit. (d) Transmitter and (e) receiver units of the communication system.

The schematic of the DAS setup is shown in Figure 1(c), where a 40-mW narrow linewidth laser feeds an acousto-optic modulator (AOM) with a continuous wave (CW) signal. The AOM converts the CW light into optical pulses of a 5-kHz repetition rate and a 50-ns pulse width. Then, the modulated signal is injected throughout a circulator (Circ. 1) into the LP_{11a} port of the photonic lantern after being amplified by an erbium-doped fiber amplifier (EDFA1). Consequently, the Rayleigh back-scattered light is retrieved from the same port, boosted by a second amplifier(EDFA2), and propagated throughout a second circulator (Circ. 2) towards a fiber Bragg grating (FBG) to remove the spontaneous emission generated by the EDFA before reaching a photodetector (PD), which transmits the converted electric signal to a digital acquisition system (DAQ). Figures 1(d) and 1(e) illustrate the experimental setup of the transmitter and receiver of the communication system, respectively. On the receiver side, an arbitrary waveform generator (AWG) driven by an internal clock modulates a laser diode (LD) with a wavelength of 1549.6 nm and $\sim$475 μW optical power. At the same time, the receiver which composed of a PD connected to a digital phosphor oscilloscope (DPO) is employed for demodulation of the communication signal. Communication protocol consisted of subsequent OFDM and KK systems, where generated 4-QAM symbols were first processed by a regular OFDM block. Then, the serialized signal was transformed into an SSB MP signal to be recovered after propagation through the fiber. AWG operated at 2.5 GHz frequency, DPO, in turn, operated at 12.5 GHz, and the received signal was then downsampled and aligned in time and power in the post-processing.

3. Results and Discussion

First, the impact of the signals co-propagation on the DAS was measured by comparing the performance of DAS alone and with the presence of the communication signal in the same TMF. Figures 2(a) and 2(c) show the position and power spectrum information obtained for the PZT's vibrations at the frequencies of 600 Hz, and 900 Hz, respectively. Despite the additional harmonics generated due to a nonlinear response of the DAS direct detection method [7], the position and associated vibration frequency of the event are evident. On the other hand, Figs. 2(b) and 2(d) represent the corresponding results obtained when DAS and KK communication were running simultaneously in the same fiber. The event location and frequency can be easily retrieved albeit the noise originated from the communication signal that generates Rayleigh backscattering in the form of all spatial modes, interfering with the LP_{11a} sensing signal. However, the contribution of the mode LP_{11a} sensing signal was dominant in both cases, which can be evidenced in the achieved signal-to-noise ratio (SNR) values in Table 1, which are consistently higher than the 2-dB minimum acceptable value. In communication, a gross bit-rate of 2.04 Gbps was achieved, accounting for the 7% FEC overhead. BER and SNR metrics are provided in the Table 2 for the communication system, SNR here is calculated as $|x_s|^2/|x_s - x_r|^2$, where x_s and x_r are respectively sent and received signals. QAM constellations are provided in the Fig. 3 alongside the power spectral densities of sent and received signals. Nonetheless, it is important to note that the mode channel was not perfectly stable, and the signal was prone to partially propagate through different modes excited by slight angle shifts or bending in the input ports of the photonic lantern. Finally, it is worth highlighting that improved results for the communication system could be obtained in the future using time allocation, as significant time in-between DAS pulses would allow for almost uninterrupted communication and be feasible to be used with higher QAM modulation formats.

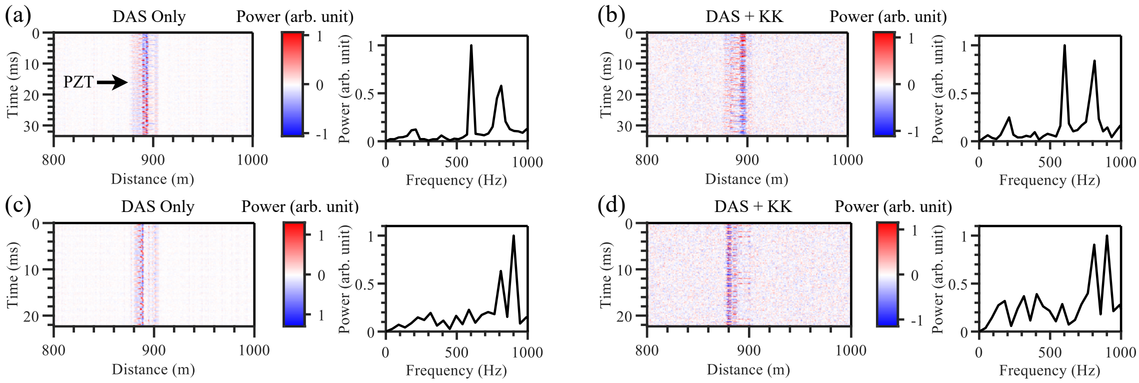

Fig. 2: Position information and power spectrum of the 600 Hz/900 Hz vibration event as detected by the DAS alone (a)/(c), and with KK (b)/(d) communication scheme.

Table 1: SNR values of the DAS system without/with the communication signals

Frequency	DAS only (dB)	DAS-KK (dB)
600 Hz	11.68	8.04
900 Hz	12.37	7.17

Table 2: Communication metrics for KK algorithm transmission without/with the DAS operation.

Metric	Without DAS	With DAS
BER	2.2×10^{-4}	2.9×10^{-3}
SNR (dB)	7.56	2.87

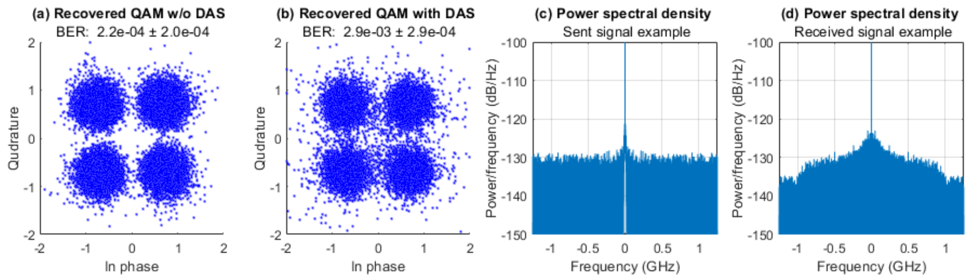

Fig. 3: KK system operation results. Constellation diagrams of 4-QAM (a)with and (b) without DAS operation. Power spectral densities for signal instances of (c) sent signal, (d) received signal.

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