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A Compact Source for a Distributed Acoustic Sensor using a Miniaturized EYDFA and a Direct Digital Synthesis Module

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ABSTRACT

Distributed Acoustic Sensing (DAS) is a ubiquitous technique which enables concurrent, real-time measurement of fault or event-induced vibrations over long distances. Although there has been focused research in increasing the performance of DAS based on Phase-Sensitive Optical Time Domain Reflectometry (Φ-OTDR), the cost of conventional schemes remains high due to the complexity of the opto-electronic components in the sources used in the interrogator for high coherent Rayleigh scattering visibility, which rely on optical amplifiers designed for wideband telecom networks and multi-purpose waveform generators. However, probes in DAS use narrow linewidth lasers, whose fluctuations are well below the bandwidth of a single ITU grid and the driving waveforms can be generated by compact RF sources.

In this contribution, we propose and experimentally demonstrate the design of a compact DAS interrogator using a miniaturized Erbium-Ytterbium-Doped Fiber Amplifier (EYDFA) commonly used in CATV networks together with an integrated Direct Digital Synthesis (DDS) module which can generate readily programmable waveform probes with a bandwidth of up to 1.4 GHz. The DDS module is suitable for use with any digital acquisition system for real-time acquisition of traces. Optical pulse probes generated with the DDS an a miniaturized EYDFA were used to obtain coherent Rayleigh backscattering traces with high SNR and interference visibility, allowing the measurement of a generic vibration at the end of a 10-km fiber. The proposed technique enables the simplification of DAS systems and paves the way toward their scalable development for wider use in among others environmental, seismic and structural health monitoring systems.

Keywords: Distributed Acoustic Sensing, Compact Optical Amplifiers, Coherent Rayleigh Scattering, Direct Digital Synthesis, Vibration Monitoring

1. INTRODUCTION

The advantages of fiber-optic sensors in contrast to electrical ones are that they are lightweight, small, immune to electromagnetic interference and resistant to harsh environments[1]. As a result, they can be used in fire alarm systems with combustible mixtures and in the presence of strong electromagnetic fields. Distributed optical fiber sensors (DOFS) have a special place among fiber optic sensors and represent a highly potent technological tool with application in metrology and scientific research[2] as well as the monitoring the safety and integrity of the environment and large infrastructure constituting vital components of the energy, transportation, and security sectors[3, 4]. They also constitute a key aspect of cyber-physical systems in Industry 4.0, in which the integration of the physical and digital worlds, with data storage and processing, will lead to increased automation and control, predictive maintenance and production efficiency[5]. Among others DOFS techniques, DAS is becoming an essential sensing technique, and its potential application market is steadily growing due to its interesting applications in perimeter security[6], railway transportation[7], leakage detection, linear infrastructures monitoring[8], and geophysical prospecting. The three main types of scattering phenomena in an optical fiber commonly utilized in distributed sensing are Rayleigh, Brillouin, and Raman scattering. The backscattered radiation's characteristics (such as amplitude, frequency, and polarization) depend on the physical parameter to be monitored[1, 2]. Specifically, DAS is based on the observation of phase and intensity changes in coherent Rayleigh scattering in an optical fiber and enables real-time monitoring of events such as intrusions, vibrations, and temperature changes [9].

Phase-sensitive Optical Time Domain Reflectometry[10] (Φ-OTDR) is a commonly used implementation of DAS. A typical Φ-OTDR scheme uses Arbitrary waveform generator (AWG) and a modulator to turn a continuous light wave into an optical pulse sequence [11]. More complex chirped pulses with long pulse duration and a large bandwidth are also employed

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in monitoring along distances of up to 10 km. However, integrated DDS modules have more reliable performances for real-time applications while also consuming less power and being easier to be integrated into compact interrogators compared to bulk AWGs and their parameters are easier to dynamically control and adapt to any application. More specifically, the phase accumulation technique gives the DDS generator an advantage over a conventional AWG enabling it to produce frequency sweeps or adjustments much more efficiently. A sweep function is also easier to set up in a DDS device since the latter's output frequency is independent of the number of waveform data points.

Although ample research has so far been dedicated to the study of DAS configurations with improved performance including sensing distance[13], polarization fading[14], vibration precision and spatial resolution[15], there are limited efforts toward simplifying the interrogation units to reduce the high cost and complexity so as to widen the practical use of the technology by small enterprises and individual customers.

The high price of existing DAS interrogation units limits the possible, wider application of DAS and hence there is a need to address the technical difficulties and reduce the production cost of the different implementation schemes. The simplification can target both the optical and electrical components at the source and receiver. In this work we propose and experimentally demonstrate a mechanism to render DAS sources more compact. First, owing to the narrow linewidth of the probe, whose spectral central wavelength cannot exceed the ITU grid even during a long period of operation, miniaturized optical amplifiers used in CATV applications without stable wideband gain are sufficient to boost modulated pulses, rendering the scheme one with much lower size and power consumption. In addition, the amplification scheme at the source can combine these with a high-fidelity integrated DDS device, and the optical pulse probe source can be rendered more compact and cost-effective while being flexibly synchronized with standardized acquisition and processing units.

2. BASIC WORKING PRINCIPLES OF DIRECT DIGITAL SYNTHESIS (DDS)

Direct Digital Synthesizer (DDS) is a signal generation technique that uses digital devices to generate frequency-variable and phase-variable signals from a fixed frequency reference clock signal. DDS is a type of frequency synthesizer [16] used for creating waveforms from a single, fixed-frequency reference clock. Since operations within a DDS device are primarily digital, it can offer fast switching between output frequencies, fine frequency resolution, and operation over a broad spectral range. The output frequency of the generated signal is closely related to the sampling rate of the generator and the number of samples that define the waveform.

Typically, a Direct Digital Synthesizer consists of a frequency reference, a numerically controlled oscillator (the core of a highly flexible DDS device) and a digital-to-analogue converter (DAC). Figure 1 shows the functional block diagram of a DDS[17]. The key component is the phase accumulator whose contents are updated once each clock cycle. Each time the phase accumulator is updated, the digital number, M, stored in the delta phase register is added to the number in the phase accumulator register. The truncated output of the phase accumulator serves as the address to a sine (or cosine) lookup table. Each address in the lookup table corresponds to a phase point on the sinewave from 0° to 360°. The lookup table contains the corresponding digital amplitude information for one complete cycle of a sinewave. It therefore maps the phase information from the phase accumulator into a digital amplitude word, which in turn drives the DAC. For an n-bit phase accumulator, there are 2^n possible phase points. The digital number in the delta phase register, M, represents the amount the phase accumulator is incremented each clock cycle.

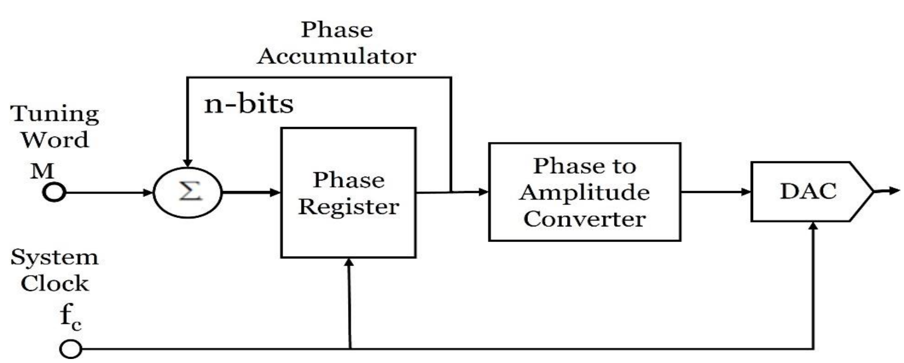


Figure 1. Block diagram of a DDS system.

If f_c is the clock frequency, then the frequency of the output wave is equal to:

$$f_o = M \times \frac{f_c}{2^n} \tag{1}$$

where: f_o is the output frequency of the DDS, M is the binary tuning word, f_c is the internal reference clock frequency (system clock) and n is the length of the phase accumulator, in bits. Changes to the value of M result in immediate and phase-continuous changes in the output frequency. The frequency resolution of the system is equal to $f_c/2^n$, is highly flexible and has high resolution. DDS has quick frequency response, improved phase noise, and precise output phase control across frequency switching transitions. The output frequency of a DDS is determined by the value stored in the frequency control register.

In this contribution, we demonstrate the use of a DDS and mini-EYDFA for a compact source for pulse probes in a DAS based on Φ-OTDR. The benefits of DDS-based systems including low power, simplicity, compactness and ease of implementation help lower the overall cost of the interrogator. Considering the mini EYDFA too has a low cost and has been commonly used in CATV and FTTx applications as well as the ability to program the output waveform of the DDS, combining the two components presents an attractive alternative for compact and flexible probe waveform generation for DAS interrogators.

3. EXPERIMENTAL SETUP

The schematic of the experimental setup used to demonstrate the proposed technique is depicted in Figure 2. First, a narrow linewidth, laser with a center wavelength of 1560 nm and linewidth < 100kHz was amplified by a miniaturized EYDFA. The signal was then filtered with a manually tunable Optical Bandpass Filter (OBPF) to remove the ASE noise and then modulated by an acoustic-optic modulator (AOM) to produce a short optical pulse. Afterwards, the modulated light pulses were amplified and filtered by an Erbium-doped fiber amplifier (EDFA) and OBPF, and finally launched into the sensing fiber via the second port of the optical circulator. A Direct Digital Synthesizer (DDS) module is used to programmatically generate the pulse signal to drive the AOM. Modulated optical pulses with duration times of 40 ns-100 ns and a repetition rate of 8.33kHz (corresponding to an RTT of 120 µs) were launched into the sensing fiber through a circulator. At the receiver, the return port of the circulator was connected to a 125-MHz PIN photodetector to retrieve the Rayleigh backscattering signal and feed it to the DAQ comprised of an oscilloscope offering sampling rates of up to 10 GS/s. The Fiber Under Test (FUT) is a spool of a 10-km standard single-mode fiber. To simulate a generic perturbation monitoring scenario, vibration signals were applied to a cylindrical piezoelectric actuator (PZT) on which a small piece of fiber at the end of the FUT was wound.

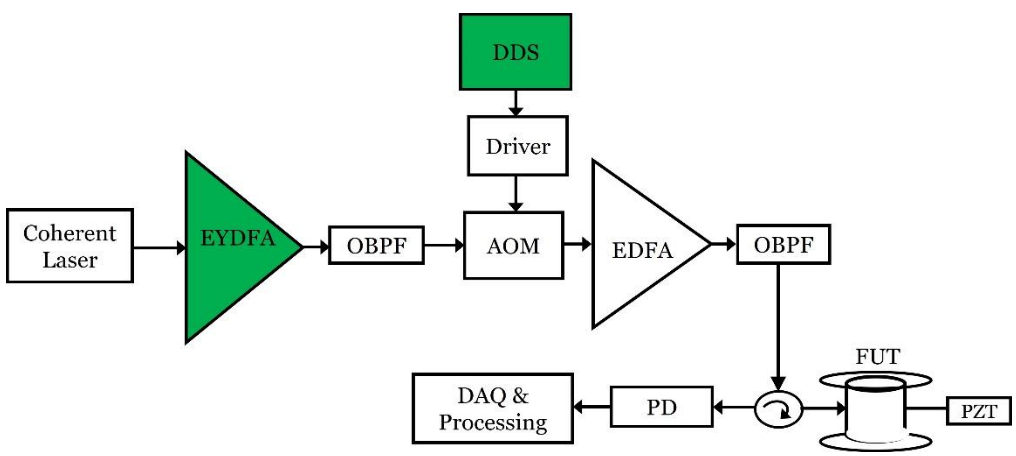


Figure 2. Experimental setup: Erbium-Ytterbium Fiber-Doped Amplifier (EYDFA); Erbium-doped Fiber Amplifier (EDFA); Optical Band-Pass Filter (OBPF); Acousto-Optic Modulator (AOM), Digital Acquisition System (DAQ); Direct Digital Synthesis (DDS); Photo Detector (PD)

4. EXPERIMENTAL RESULTS

Figure 3 shows the different types of probe waveforms that were generated using the DDS device (AD9914). The ability of the integrated DDS to generate waveforms of precise shape and frequency is evident. Considering its suitability for synchronization with DAQ systems comprised of standard oscilloscopes or PXI-based systems for real-time acquisition of traces, the DDS is a suitable alternative for use in DAS and other distributed sensing schemes.

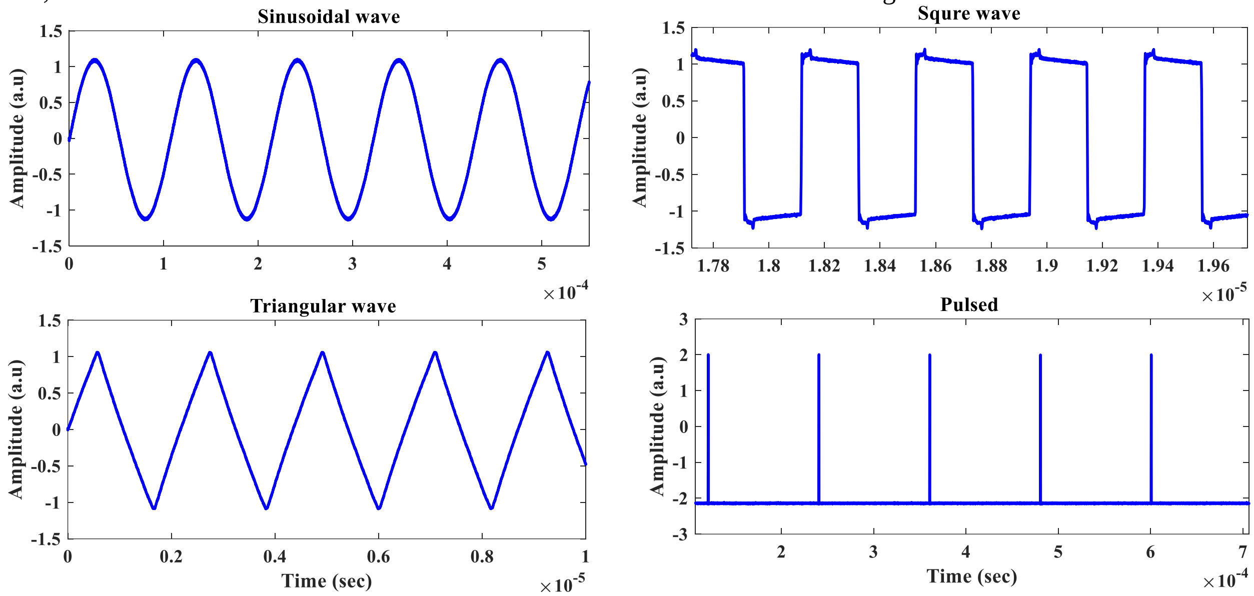


Figure 3. Generation of sinusoidal, square, triangular, and pulsed waveforms using the DDS.

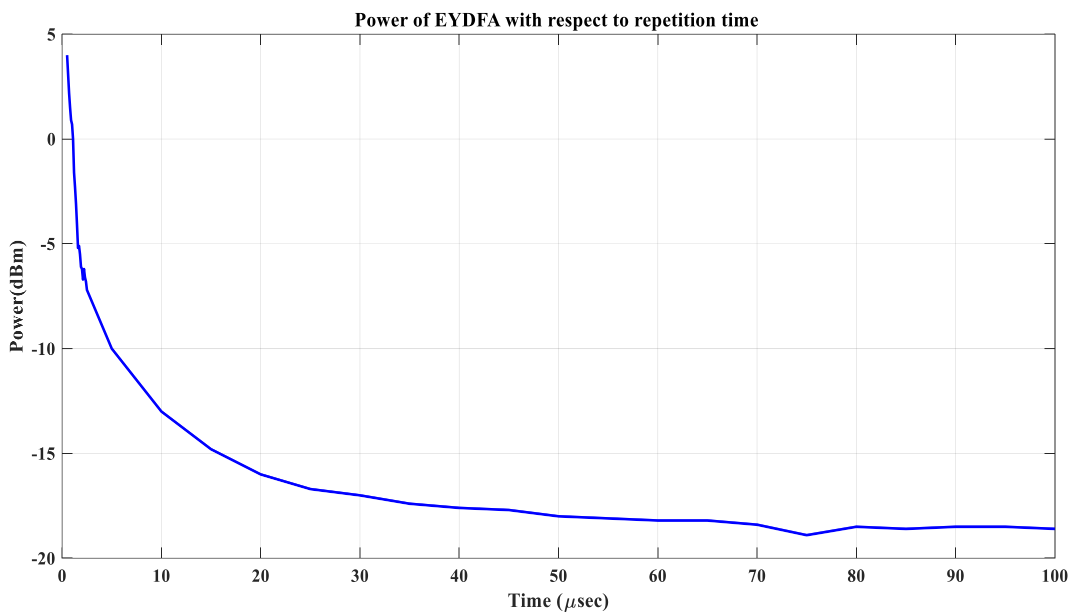


Figure 4. EYDFA power with respect to RTT.

Figure 4 depicts the measurement of the average output power of the pulses after amplification by the EYDFA and subsequent modulation by the AOM for different values of RTT, and shows that, as the RTT goes beyond a few μsec, the power decreases and remains stable for up to 100 μs.

This also shows that the modulation and amplification scheme can be used for optimum sensing with minimal fluctuations due to laser intensity noise in the range of a few 10s of μs up to 100 μs, corresponding to several kilometers of sensing distances. A sample power spectrum of the periodic amplified pulses sent through the test fiber is reported in Figure 5, confirming a desirable good symmetry on both sides of the DC component.

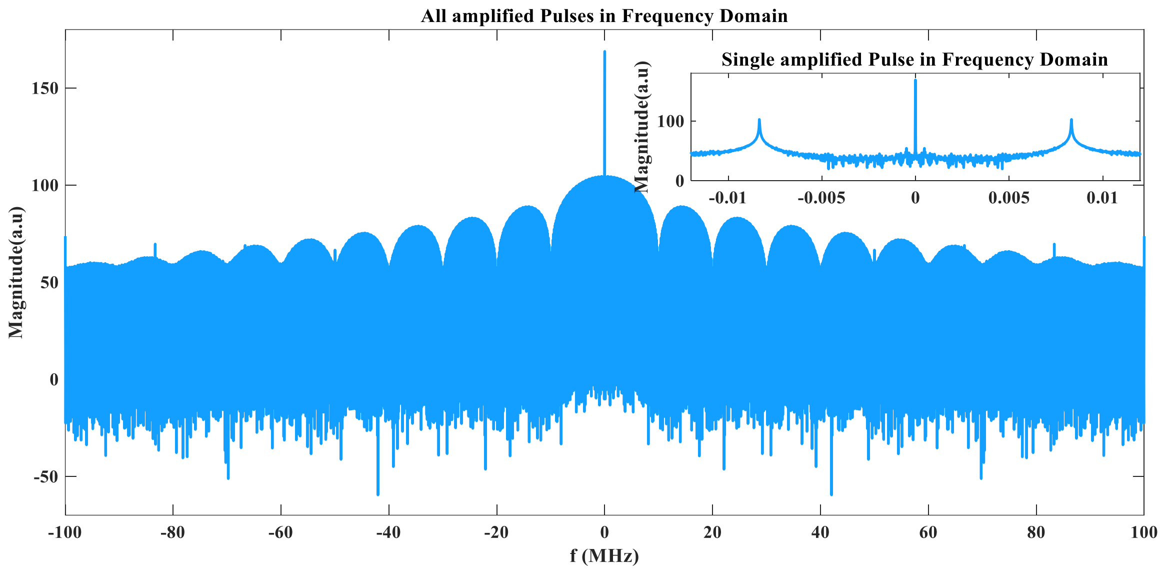


Figure 5. Spectrum of the amplified pulse sent through the test fiber.

Figure 6 shows a few of the interrogating pulses at a spacing of 120 μs sent into the test fiber and the acquired backscattered traces. The parameters such as amplifier power output and filter tuning have been optimized so that the backscattering traces have high SNR, which can seen in the signal levels in the trace having clear separation from dark (no pulse) state at the end of the trace. The interference visibility across the whole range of the fiber too is high thanks to the high extinction ratio of the modulator. The sampling frequency of trace Acquisition is 200 MS/s.

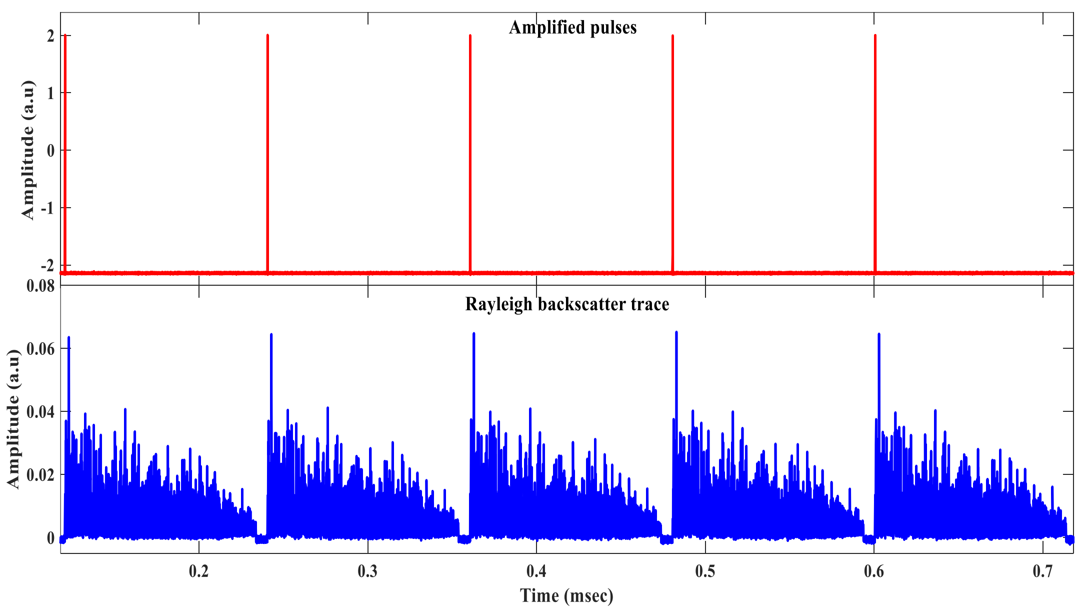
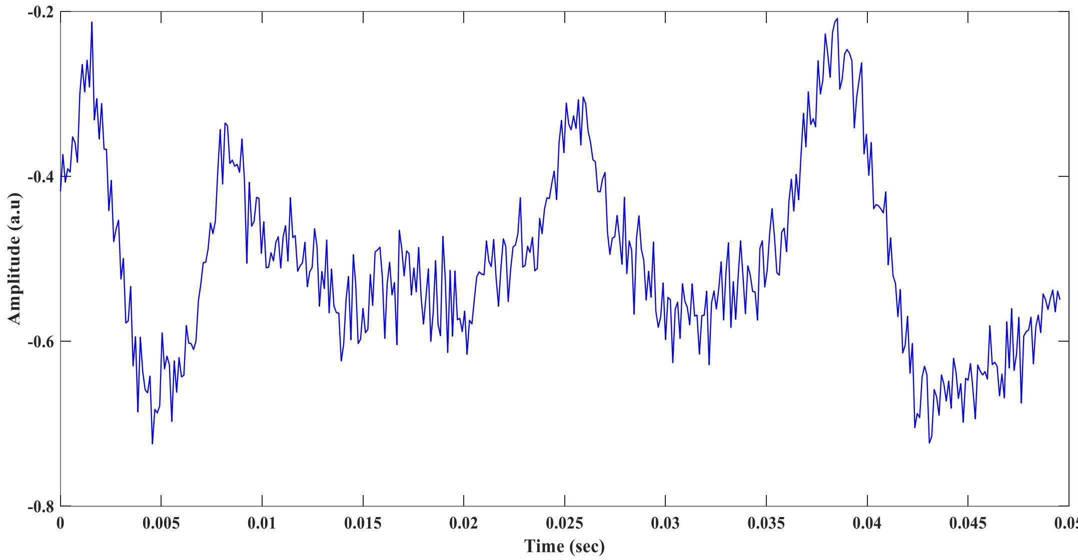
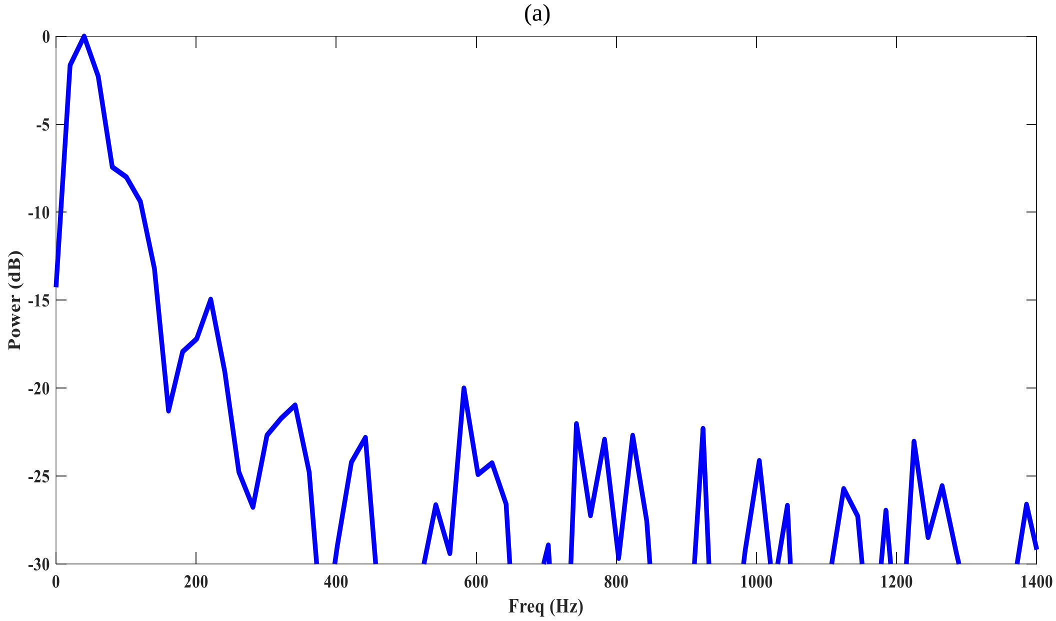


Figure 6. Diagram of sent pulses (red) and Raleigh backscattered traces (blue).

Subsequently, a section of the fiber at the end of the 10 km spool having a length of ~1.5 m was wound around cylindrical PZT with a known nonlinear response. A signal with peak-to-peak voltage of 2V centered at 50 Hz was then fed from an arbitrary waveform generator to an amplifier driving the PZT. Several traces (416) were acquired for the entire 10-km fiber and the change in intensity of the Coherent Rayleigh scattering at the vibration point was observed. Figure 7 (a) depicts the PZT response in the time domain and 7 (b) shows the single-sided auto power spectrum of the response normalized to the peak, which confirms the dominant frequency component centered around 50 Hz being significantly higher (more than 20 dB) compared to other components.



(a)



(b)

Figure 7. (a) Sample response of the PZT at the end of 10km in time domain and (b) the power spectrum of the response.

Hence, the proposed scheme enables measurement of a generic vibration while offering additional advantages of lower overall cost, complexity, energy consumption as well as more ease of implementation compared to existing schemes based solely on much heavier benchtop optical amplifiers optimized for stable wideband gains and bulky and expensive arbitrary waveform generators.

5. CONCLUSION

To summarize, we proposed and experimentally demonstrated the design of a compact DAS interrogator using a miniaturized, single-channel EYDFA commonly used in CATV networks and an integrated DDS module that can generate readily programmable waveform probes with a bandwidth of up to 1.4 GHz. The proposed source of amplified probes has been used to obtain coherent Rayleigh backscattering traces with high SNR and interference visibility which enable the measurement of generic vibrations along a 10-km fiber.

REFERENCES

[1] Kuznetsov PI, Sudas DP, Savelyev EA. Fiber optic Lossy Mode Resonance based sensor for aggressive liquids. Sens Actuators A Phys. (2021).

[2] Gorshkov BG, Yüksel K, Fotiadi AA, et al. Scientific Applications of Distributed Acoustic Sensing: State-of-the-Art Review and Perspective. Sensors, 22(3), 1-41 (2022).

[3] Barrias A, Casas JR, Villalba S. A review of distributed optical fiber sensors for civil engineering applications, Sensors (Switzerland), 16(5), (2016).

[4] Muanenda Y, Oton CJ, Di Pasquale F. Application of Raman and Brillouin Scattering Phenomena in Distributed Optical Fiber Sensing. Front Phys. 7(October):1-14 (2019).

[5] Javaid M, Haleem A, Singh RP, Rab S, Suman R. Significance of sensors for industry 4.0: Roles, capabilities, and applications, Sensors International, (2021).

[6] Ružička M, Münster P, Dejdar P, Jablončík L. Distributed Optical Fiber Acoustic Sensing System for Perimeter Security, Int. Scientific Journals, vol. 5, 150-152 (2021).

[7] Wagner A, Nash A, Michelberger F, Grossberger H, Lancaster G. The Effectiveness of Distributed Acoustic Sensing (DAS) for Broken Rail Detection †. Energies (Basel), (2023).

[8] Zhu HH, Liu W, Wang T, Su JW, Shi B. Distributed Acoustic Sensing for Monitoring Linear Infrastructures: Current Status and Trends. Sensors. 22(19), (2022).

[9] Magalhães R, Costa L, Martin-Lopez S, Gonzalez-Herraez M, Braña AF, Martins HF. Long-range distributed solar irradiance sensing using optical fibers Sensors (Switzerland;20(3):1-15), (2020).

[10] Wang Z, Lu B, Ye Q, Cai H. Recent progress in distributed fiber acoustic sensing with Φ-otdr. Sensors (Switzerland), 20(22):1-26 (2020).

[11] Chen D, Liu Q, Wang Y, Li H, He Z. Fiber-optic distributed acoustic sensor based on a chirped pulse and a non-matched filter. Opt Express, 27(20), (2019).

[12] Kito C, Takahashi H, Toge K, Manabe T. Simplified and fast acquirable BOTDA with frequency-swept probe pulse. 25th International Conference on Optical Fiber Sensors, (2017).

[13] Rodríguez-Barrios F, Martín-López S, Carrasco-Sanz A, et al. Distributed brillouin fiber sensor assisted by first-order raman amplification. Journal of Lightwave Technology, (2010).

[14] Bakhtiari Gorajoobi S, Masoudi A, Brambilla G. Polarization fading mitigation in distributed acoustic sensors based on a high-speed polarization rotator. Opt Lett., 47(5), (2022).

[15] Li W, Bao X, Li Y, Chen L. Differential pulse-width pair BOTDA for high spatial resolution sensing. Opt Express, 16(26), (2008).

[16] R YS, Kulkarni S, Kumara B. Waveform Generation using Direct Digital Synthesis (DDS) Technique, *International Research Journal of Engineering and Technology*, (2019).

[17] Rick C, *A Technical Tutorial on Digital Signal Synthesis*, (1999).