A Compact Source for a DAS without Trace Averaging based on a Low Phase Noise DDS and Mini-EYDFA

Almaz Assire Demise¹, F Di Pasquale¹, and Y Muanenda¹

¹Affiliation not available

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A Compact Source for a DAS without Trace Averaging based on a Low Phase Noise DDS and Mini-EYDFA

A. Demise, F. Di Pasquale, and Y. Muanenda

Abstract—We propose and experimentally demonstrate the design of a compact source for DAS systems using a mini-EYDFA commonly used in CATV networks together with an integrated, low-phase-noise Direct Digital Synthesis (DDS) device that can generate readily programmable probe waveforms with a bandwidth of up to 1.4 GHz. The DDS module is synchronized with a NI-PXIe system for real-time acquisition of traces at a rate of up to 200MS/s and, thanks to the low phase noise DDS characteristics as well as high gain and stability of the EYDFA and Jitter-suppressed acquisition of traces, the scheme enables measurements of representative vibration signatures with a bandwidth of up to 4 kHz at a distance of 9.71 km, with an SNR of ~24 dB without trace averaging, offering a performance near the Nyquist limit set by round-trip-time of trace acquisition. Analyzes of the spatial, temporal, and spectral responses of extracted vibrations confirm the distributed dynamic sensing capability of the technique. The proposed configuration enables the simplification of sources used in DAS systems, paving the way toward further miniaturization of the interrogation units and their scalable commercialization for wider use in several safety and integrity monitoring applications.

Index Terms—Coherent Rayleigh Scattering, Direct Digital Synthesis, Distributed Acoustic Sensing, EYDFA, Real-Time Acquisition, Vibration Measurement.

I. INTRODUCTION

Distributed fiber optic sensors (DOFS) are becoming ubiquitous tools in many safety and integrity monitoring systems employed in various applications including the measurement of deformation [1], [2], [3], structural health monitoring (SHM) of concrete structures affected by internal swelling pathologies [4], and temperature monitoring [5]. Specifically, distributed vibroacoustic frequency analysis is commonly used to detect spectral signatures of anomalies that necessitate pre-warning of infrastructure and device damages. Among other DOFS, Distributed Acoustic Sensing (DAS), which is the use of an optical fiber for measuring acoustic vibrations concurrently across a long spatial range, is becoming an essential sensing technique and its market volume has been steadily growing in recent years, thanks to its capacity to measure high-frequency vibroacoustic properties of devices and large structures [6], [7], [8].

A generic DAS sensor is based on the measurement of coherent Rayleigh backscattering of light as it propagates in an optical fiber, wherein its properties including intensity, phase, and polarization state are altered with vibration or a temperature change, owing to the induced change in the optical path length and the refractive index of the fiber. Dynamic events in monitoring scenarios have distinctive vibration footprints and the acoustic field released by an object/event (i.e., its spectral signature) gives critical information regarding its health and integrity. This makes DAS a particularly powerful tool in many sectors such as infrastructure monitoring in railways [9], airports [10], pipeline networks [11], perimeter security [12], geophysical prospecting, microseismical measurements, and hydraulic fracture monitoring [13], as well as bridge monitoring under destructive testing [21]. Recently, real-time vibration measurements have also been used to monitor aircraft production operating under actual service conditions with minimal hardware [22], wherein the sensing was done with a single fiber optic cable with a diameter of 2 mm run through each wing or control surface.

To date, enhanced DAS interrogation schemes have been widely investigated both on singlemode fibers and Ultraweak gratings [15], [16]. A common implementation of DAS employs phase-sensitive optical time domain reflectometry (Φ-OTDR) which involves sending a pulse of coherent laser light in the optical fiber and mapping the coherent Rayleigh backscattering signal intensity or phase with position, using the group velocity of light in the fiber and the time delay of the signal from each point [17], [18]. This allows vibrations to be continuously monitored in real-time via distributed dynamic measurements in both long and short-distance ranges [19], [20].

Existing Φ-OTDR interrogators for long-range sensing mostly employ Arbitrary Waveform Generators (AWGs) to generate the pulses used to probe the fiber. More complex chirped pulses with long pulse durations and a large bandwidth are also employed in high-resolution DAS, but conventional waveform generators with corresponding high bandwidth and synchronization requirements are bulky and very expensive, thereby necessitating further investigation on cost and size reduction for wider commercialization and use including in mobile settings. On the other hand, the past decade has seen rapid advances in the development of integrated circuits for
digital-to-analog converter (DAC) systems, allowing their use in high-frequency applications for high-speed optical communication systems with flexible digital signal processing [24], [25], [26], which also resulted in the commercialization of cost-effective and compact Direct Digital Synthesis (DDS) [27], [28]. These devices also combine both DAC and analog-to-digital (ADC) in one allowing cost-effective alternatives to synchronized signal generation, acquisition, and processing, and are suitable for implementation of interrogators with low power consumption. Such integrated modules are also suitable for real-time applications requiring flexible post-processing of acquired signals for accurate event extraction and identification. The characteristics of the probing signal from the DDS can be programmatically adapted (including, where appropriate, within digital signal processing blocks) to the desired pulse duration, repetition rate, and phase/frequency modulation format without interrupting monitoring scenarios. 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. So far, DDS devices have been used in some sensing schemes, including in a system using such a device for frequency modulation of probing pulses albeit at a short distance of 1.13km of fiber [29], proving the ability of the device to generate high-fidelity chirped waveforms with precise shape and frequency required to suppress detrimental sidemodes in spatially resolved sensing.

In addition, there has been significant advances in the development and commercialization of Erbium-Ytterbium-Doped Fiber Amplifiers (EYDFAs) with very high gains, enhanced linearity, and low noise figures. In such amplifiers, doping with Ytterbium and Erbium ions at suitable concentrations, allows double-cladding pumping schemes with broad area lasers, providing compact low cost and high-power amplifiers. Specifically, the existence of Ytterbium ions near Erbium ones reduces natural clustering in conventional Erbium-doped fiber amplifiers (EDFA), thereby reducing the saturation of the stimulated emission during lasing – a phenomenon known as Pair-Induced Quenching (PPQ), which is a major source of gain loss [30]. Compared to ordinary EDFAs, EYDFAs are more suitable for compact implementation since the addition of Ytterbium ions offer high pumping efficiency for the same length of fiber while at the same time allowing the use of high-power broad area laser pumps operating at a wider wavelength range. These features have also allowed their integration in waveguides for amplification in various optical communication applications, underlining their potential for use in compact sources for long-range distributed fiber sensors [31].

Although ample research has so far been dedicated to the study of DAS configurations with improved performance in terms of parameters including sensing distance, polarization fading [32], and spatial resolution, there have been limited efforts toward simplifying the key components in the source or receiver of the interrogation units which could lead to compact solutions for high-SNR, long distance DAS schemes, also paving the way for possible integration of optoelectronic components and an eventual reduction in their overall cost. In this contribution, we show that an integrated DDS device can be used in a compact source together with a miniaturized EYDFA while being synchronized with a PXI-based system for real-time acquisition of traces in a high-SNR, long distance DAS [33]. We experimentally demonstrate the capacity of the system to measure vibrations of up to 4 kHz at a distance of 9.71 km with an SNR of 23.63 dB without averaging of acquired traces, in a configuration where the upper limit of vibration measurements is set only by the trace acquisition rate determined by the pulse repetition rate. Analyses of the spatial and temporal distributions of the spectra of detected acoustic vibrations around the position where they are applied, confirm the suitability of such a configuration for real-time, distributed monitoring of dynamic events spanning a large range of frequencies and exhibiting complex characteristics.

II. THEORY

Rayleigh scattering is caused by the scattering of light from the constituent material of the waveguide in which it is propagating, or other sources of refractive index fluctuations, with dimensions much smaller than the wavelength of the incident light. The scattering intensity is highly dependent on the incident wavelength and is proportional to $1/\lambda^4$ [32], where $\lambda$ is the wavelength of the propagating optical signal. In a Fiber-OTDR, the probing signal is a short pulse of coherent light that propagates into the fiber to generate phase-sensitive coherent Rayleigh scattering. The round-trip time needed for each pulse to traverse any point $z$ in the fiber and the one for the backscattering to return to the receiver is used to calculate the position $z$ from which that segment of the backscattering trace emanates using (1):

$$ z = \frac{c}{2n_g(z)} t = \frac{v_g(z)}{2} t, $$

where $t$ is the backscattered detection time, $c$ is the speed of light in vacuum, $n_g$ is the group index of the fiber, $v_g$ is the group velocity of the light propagating in the optical fiber, and the factor of 2 is used to denote round-trip time of the pulse and scattering along the fiber.

At its core, an integrated DDS device used in the compact source, whose representative configuration is shown in the schematic depicted in Fig. 1, consists in a tuning word, a reference clock, a DAC, and flexibly controlled oscillator comprised of a phase register and a phase accumulator. Whenever the phase accumulator is updated, the digital number $M$ stored in the phase register is added to the number in the phase accumulator register. Then, the output of the accumulator is used as the address to the phase-to-amplitude converter in a form of sinusoidal lookup table, which serves as an address to a phase point on the sinusoidal in the range from $0^\circ$ to $360^\circ$. The table is structured such that each entry contains digital amplitude information for a complete cycle of the sinusoid. This way, the phase information in the digital amplitude word is mapped to a digital amplitude sequence which is used to drive the DAC. Note that an $n$-bit phase accumulator offers $2^n$ possible phase points, and the number in the delta phase register corresponds to the amount the phase accumulator is incremented in each cycle of the clock. For a reference system
clock frequency $f_c$, binary tuning word length of $M$, the frequency of the output wave $f_o$ is given by:

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

(2)

where $f_c$ is the internal reference clock frequency (system clock) and $n$ is the length of the phase accumulator, in bits. Any change in the value of $M$ results in an immediate, phase-continuous changes to the output frequency, with a resolution of $f_c/2^n$. A key advantage of signal generation with a DDS is that it is possible to generate continuous sweeps from a single clock without sophisticated feedback control and the generated waveforms have low phase discontinuities. This gives rise to precise output phase control across switching transitions. Besides their suitability for low-cost implementation, DDS devices are also suitable for generation of periodic signals with enhanced consistency in different cycles with generally lower phase noise compared to conventional AWG.

**III. EXPERIMENTAL SETUP**

The proposed DAS configuration is shown in Fig. 2, where a low-power, narrow linewidth continuous-wave laser (center wavelength at 1560 nm, linewidth of $\sim$100 kHz) is used as a CW light source. The output power of the laser $\sim$0.57 dBm is amplified by a miniaturized EYDFA by setting the output power to 21 dBm followed by a manually tunable optical bandpass filter (OBPF) with an operating wavelength from 1530 nm to 1560 nm to limit the EYDFA’s amplified spontaneous emission (ASE) noise.

![Block diagram of a DDS system](image)

**Fig. 1.** Block diagram of a DDS system.

Owing to the high coherence of the probe, whose spectral central wavelength cannot exceed the ITU grid even during a long period of operation, the booster EYDFA is a low-cost, miniaturized optical amplifier typically used in CATV applications, without complicated circuitry for optimizations needed for stable wideband gain, as required for WDM optical communication networks, rendering the scheme one with much lower size and cost. The filter output is intensity-modulated using an Acoustic-optic modulator (AOM) with 110 MHz frequency shift with a dedicated driver of the same frequency, which is used to generate 100 ns optical pulses with a repetition rate of 8.33 kHz. The programmable DDS module is used to drive the AOM in such a way that the latter operates at the optimum extinction ratio (ER). The DDS has a sampling rate of 3.5 GS/s, and the characteristics of its output signal can be programatically adapted to the desired pulse duration, repetition rate, and phase/frequency modulation format.

Note that suppression of the ASE via optical filtering in both the 1 and 0 levels of the CW signal, as well as the use of the high ER to suppress both the 0-level ASE noise and the coherent noise sent into the fiber, serve to suppress the two major sources of optical noise. In addition, because operations within a DDS device are primarily digital, it can offer high stability, fast switching between output frequencies, high-frequency resolution, and operation over a broad spectrum of frequencies. Although the mini-EYDFA could output power values of up to 35 dBm, it was driven at a lower value of 21 dBm to avoid damages to the filter and the insertion loss of the AOM and narrowband filter were offset by adding an EDFA whose output power was set to 12 dBm; the signal was filtered using a second pair of OBPF before being fed to the input port of the three-port circulator.

The probe optical pulse with a 21 dBm peak power is then sent through a three-port circulator into the fiber under test (FUT), which is a 9.71 km standard singlemode fiber. A short segment of fiber at the end of the FUT is wound around a cylinder piezoelectric transducer (PZT) on which controlled vibrations from 10's of Hz to 4 kHz were applied. The coherent Rayleigh backscattering light is then detected with a low noise PIN photoreceiver (PD) having a bandwidth of 125 MHz and sampled with a NI-PXIe digitizer with a sampling rate of 200 MS/s.

To avoid any jitter introduced in the measured backscattering signal with respect to the generated probing pulse waveform, a 1% tap of the optical pulse sent in the fiber was photo-detected with a simple PIN photodiode, whose output was used to trigger the trace acquisition. Such a configuration locks the probing optical pulses to the acquisition while at the same time avoiding the requirement of additional synchronization channels and operations as well as clock jitter stabilization requirements in the probing waveform generation devices. The post-processing of the digitized traces was done in real-time, in synchronization with the acquisition and no averaging was performed on the coherent Rayleigh backscattering traces. This way, the limit to the maximum frequency of vibration detected by the DAS will be the one set by the pulse repetition rate corresponding to the desired sensing range. The number of traces acquired, and hence the duration of monitoring the vibration signal at any point in the fiber is set only by the memory size of the acquisition system.

![Schematics of experimental setup for DAS systems using miniaturized EYDFA and DDS](image)

**Fig. 2.** Schematics of experimental setup for DAS systems using miniaturized EYDFA and DDS.
First, we tested the capability of the integrated DDS to generate required modulating signal of arbitrary profiles, and sample sinusoidal and triangular waveforms are shown in Fig. 3 (a), which also depicts sample pulses used for driving the optical modulator for the DAS system, confirming the suitability to generate pulse waveforms used as probes after amplification. We then characterized the output of the amplifier in terms of the variations of the amplified pulse power to determine the optimum operating conditions and sensing distances for which it could be suitable. Fig. 3 (b) shows the average output power of amplified pulses for a 100-ns pulse for different pulse repetition times.

**IV. EXPERIMENTAL RESULTS AND DISCUSSIONS**

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A few cycles of the optical pulse train sent into the FUT are shown in Fig. 4 (a), which shows the time domain plots of the amplified pulse with RTT of 120 µs, demonstrating the relative fidelity of the DDS technique to keep the desired features of the generated analog signal and digitized optical pulse. Fig. 4 (b) shows the ability of the DDS synthesis to generate optical pulsed waveforms as per desired pulse duration without averages.

Subsequently, sinusoidal signals were applied to the PZT at the end of the 9.71 km fiber with low driving voltage power for round-trip times of 40 µs up to 100µs, corresponding respectively to a 4-km and 10-km fiber. This further confirms the suitability of the optical source with a programmable DDS which can be used to dynamically change sensing distance values. A few cycles of the optical pulse train sent into the FUT are shown in Fig. 4 (a), which shows the time domain plots of the amplified pulse with RTT of 120 µs, demonstrating the relative fidelity of the DDS technique to keep the desired features of the generated analog signal and digitized optical pulse. Fig. 4 (b) shows the ability of the DDS synthesis to generate optical pulsed waveforms as per desired pulse duration without averages.

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magnitudes of 400 mV (peak to peak) with different frequencies. To evaluate the dynamic performance of the proposed system, sinusoidal signals of 2 kHz, 2.5 kHz, 3 kHz, 3.5 kHz, and 4 kHz were applied on PZT; a number of traces were acquired, and then minimal post processing was done in real-time on acquired traces to compute the spectral signatures of vibrations within values corresponding to the Nyquist limit set by the employed pulse repetition time, which is 120 µs. The power spectra of the measured vibrations are reported in Fig. 5, which depicts the values normalized to the peak for each vibration response. It can be observed that there are consistent peaks up to the Nyquist limit, with suppressed sidemodes for the higher order harmonics of the vibration signals, confirming the suitability of the DDS and mini-EYFDA for accurate detection of events with different fundamental frequency components without averages. The SNR too has consistent values in varying frequency ranges and the mean value is calculated to be 23.63 dB.

![Pulse sent through the FUT](image)

**Fig. 4.** Pulse train used in DAS system (a) and Rayleigh backscatter trace. (b); RTT=120 µs; pulse duration=100 ns.

![Rayleigh backscatter trace](image)

To further demonstrate the ability of the system to identify acoustic vibrations with frequency components in a narrower frequency range, we changed the frequency of the sinusoidal signal applied on the PZT from 1.5 kHz to 2 kHz with a linear sweep of the frequency duration of 60 milliseconds at the same position along the fiber. The detected vibration waveform and its power are displayed in Fig. 6 (a) and (b), respectively, and confirm the DAS can well measure the complicated vibration signal with consistent peak in the spectra within the chirp bandwidth. To determine the detailed time evolution of the detected response of the PZT, we also computed the STFT for multiple applied vibrations and report a set of spectrograms of the vibration signatures depicted in Fig. 7. As shown, frequency-time responses for 2 kHz, 3 kHz, and 4 kHz sinusoidal vibrations as well as that of the 1.5-2 kHz sweep are clearly visible, confirming suitability of the sensor for event signature identification in a small range of frequency spectra corresponding to dynamic events with distinct spectral contents.

![Frequency spectrum detected from 1.5 kHz to 2 kHz](image)

**Fig. 6.** Frequency spectrum detected from 1.5 kHz to 2 kHz. (a) time domain. (b) frequency domain.

Finally, to understand the spatial distribution of the frequency content of vibration applied to the PZT near the dynamic event, the power spectra of the vibration signals for points in a short segment of the fiber before and after the PZT point were determined and the plots for four different vibration signatures are reported in Fig. 8. We can clearly observe consistent spatial footprints for each of 2 kHz, 2.5 kHz, 3.5 kHz, 4 kHz vibrations. Both the frequency content and spatial distribution of vibrations with respect to the location where they have been applied are clearly visible and are consistent among the different measurement rounds.

![Power spectra of extracted vibration signal when the PZT is driven with 5 sinusoidal inputs in the range 2-4 kHz with a step of 500 Hz](image)

**Fig. 5.** Power spectra of extracted vibration signal when the PZT is driven with 5 sinusoidal inputs in the range 2-4 kHz with a step of 500 Hz.
V. CONCLUSIONS

In summary, we proposed and experimentally demonstrated the design of a compact source for DAS systems using a miniaturized EYDFA commonly used in CATV networks and a compact, low-phase-noise integrated DDS module that can generate readily programmable waveform probes with a generation bandwidth of up to 1.4 GHz. We confirm the potential of the system for continuous real-time monitoring in long-distance vibration measurements by reporting the detection of acoustic vibrations with a frequency of up to 4 kHz, at the far end of a 9.71 km FUT with an SNR of ~24 dB, without averaging of acquired coherent Rayleigh backscattering traces. We also report spatial and temporal analysis of the detected vibration to confirm the suitability of the proposed technique for accurate, real-time identification of the spatiotemporal signatures of dynamic events, which are owed to a combination of a compact low-phase noise DDS and miniaturized EYDFA for the generation and amplification of probing waveforms as well as jitter-suppressing synchronization with photo-detected and digitized optical pulses. The configuration simplifies the size, cost and complexity sources used in a DAS schemes based on Φ-OTDR, and paves the way toward more compact interrogation units, including those combining parts of the optical and electronic components in the source used for probe generation and amplification with photodetection and synchronization subunits into a hybrid integrated circuit.

Fig. 7. STFT spectrogram for vibrations at the PZT with sinusoidal driving signals centered at 2, 2.5, 3.5 and 4 kHz, and a sweep from 1.5 kHz to 2 kHz.

Fig. 8. Spatial distribution of spectral responses near the PZT location for 2-, 2.5-, 3.5- and 4 kHz vibration events.
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