A φ-OTDR using Direct Digital Synthesis of Chirps and Sidelobe Suppression with Nonlinear Frequency Modulation

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Abstract: We experimentally demonstrate a novel φ-OTDR scheme using direct digital synthesis of chirps and advanced matched filtering with nonlinear frequency modulation providing ~16 dB improvement in effective suppression of autocorrelation sidelobes over conventional linear chirping.

1. Introduction

Distributed Acoustic Sensing (DAS) is an interesting technique for the monitoring of safety and integrity in many sectors including the construction, transportation and energy industries. Among other schemes for DAS, Phase-Sensitive OTDR (φ-OTDR), which employs the sensitivity of the local intensity and phase of the coherent Rayleigh backscattering from probing pulses to external perturbations, has become a topic of wide investigation [1]. Recent research on φ-OTDR has been focused on addressing performance enhancements in terms of measurement bandwidth, sensing range, dynamic performance and spatial resolution [2]. Specifically, methods for spatially resolved measurements in φ-OTDR proposed so far mostly employ linear frequency modulated (LFM) pulses for SNR enhancement using chirped pulse amplification techniques and those offering spatial resolution dependent on the total pulse bandwidth content [3,4]. However, the frequency modulation schemes of pulses used in these φ-OTDR configurations are closely coupled to the RF and/or optical components used in the interrogation scheme. It would be desirable to have chirps with modulation schemes which are dynamically adaptable to specific measurement needs, also leveraging the advent of a new generation of compact, high-fidelity Digital to Analog Converter (DAC) systems in the last decade [5], which has been driven by rising demands in digital signal processing in high-speed optical communication systems. In addition, LFM pulses, which have been widely used in fiber optics and radar applications [6], have relatively large sidelobes in autocorrelation functions incurring significant ambiguity of range resolution in compressed responses and leading to errors in extracting actual responses of even simple events. In radiofrequency applications, this has necessitated the use of advanced pulse compression methods employing nonlinear frequency modulated (NLFM) pulses for more effective sidelobe suppression in noisy environments [7]. The optical fiber sensing community can also benefit from further research on such advanced matched filtering techniques for enhanced range resolution with customized optical NLFM pulses which can significantly reduce range ambiguity. In this contribution, we propose and experimentally demonstrate, for the first time to the best of our knowledge, adaptable Direct Digital Synthesis (DDS) of frequency modulated optical pulses for advanced matched filtering with customized NLFM pulses in a φ-OTDR and show that the method offers significant reduction of range ambiguity compared to linear chirps. When used to enhance range resolution in a 50-cm span measurement at ~1.13 km with a compressed 1.2-μs pulse, NLFM matched filtering enables significantly reduced spatial ambiguity in compressed responses thanks to effective suppression in optical pulse autocorrelation sidelobes of ~20 dB, offering an improvement of ~16 dB compared to the use of a conventional LFM pulse.

2. Theory

The method of spatially resolved measurements using frequency modulated pulses in a φ-OTDR owes itself to the concept of matched filtering. Given a signal x (t) at the receiver, representing the echo of a pulse propagating along a channel which introduces additive white Gaussian noise (AWGN), we seek to find the filter h(t) which will maximize the SNR at its output at time t_M. In the frequency domain, the signal at the output of this filter will be $Y(\omega) = X(\omega)\exp(j\omega t_M)H(\omega)$. If the noise power spectral density at the input of the receiver is $N_0/2$, it will become $N_0/2\,|H(\omega)|^2$ at the output. The SNR at time t_M will then be given by [6]:

$$SNR = \left| \frac{1}{2\pi} \int_{-\infty}^{\infty} X(\omega) H(\omega) e^{j\omega t_M} d\omega \right|^2 \Big/ \frac{1}{2\pi} \frac{N_0}{2} \int_{-\infty}^{\infty} \left| H(\omega) \right|^2 d\omega, \tag{1}$$

where the two terms in the numerator and denominator respectively correspond to signal and noise powers at the output of the filter. When Schwartz's inequality is used in the numerator, the SNR becomes:

$$SNR \le \left[\frac{1}{2\pi} \right]^2 \int_{-\infty}^{\infty} \left| X(\omega) \right|^2 d\omega \int_{-\infty}^{\infty} \left| H(\omega) \right|^2 d\omega \Big/ \frac{N_0}{4\pi} \int_{-\infty}^{\infty} \left| H(\omega) \right|^2 d\omega, \tag{2}$$

with equality of the numerators in (1) and (2), and hence maximum SNR, when $H(\omega) = \alpha X^*(\omega)\exp(-j\omega t_M)$, or $h(t) = \alpha x^*(t_M - t)$ for an arbitrary constant α. The filter which maximizes the SNR is said to be matched to its input and hence the term “matched filtering”. Commonly, α = 1 and $t_M = 0$ are used and $h(t) = x^*(-t)$. For an LFM pulse $s(t) = rect\left(t/T\right)\exp\left[\, j2\pi(f_c t + {}^{k}\!/_{2}\, t^2)\right]$, having width T and a chirp rate of k, the output of the matched filter is the convolution of the scaled amplitude response of the fiber with a sinc-like function given by [2]:

$$\Theta(t) = rect\left(t/2T\right) \times T\sin\left[\pi kt\left(T - |t|\right)\right]/(\pi kTt). \tag{3}$$

If B=kT, also known as the signal base, is the total bandwidth of the pulse, the range resolution is given by c/(2nB), where c is the speed of light in free space, and n is the group refractive index.

In this contribution, we first experimentally demonstrate the use of DDS to generate readily customizable and programmable optical chirps for an effective range resolution of a 50 cm span with compressed 1.2 µs LFM pulses. We then show that the linear chirping of probing pulses introduces ambiguity-inducing sidelobes in compressed responses and, by leveraging the flexibility offered by the DDS technique, demonstrate significantly enhanced range resolution with effective autocorrelation sidelobe suppression of ~20 dB in advanced filtering with custom generated NLFM pulses. NLFM chirps are generally identified by the specific law defining the instantaneous frequency variations within the duration of the pulse, which is a nonlinear function of time as opposed to a linear one for LFM pulses. Since the precise features of the autocorrelation functions of pulses determines the ultimate quality of the pulse compression, we made the choice of the nonlinear pulse modulation law for efficient sidelobe suppression in our φ-OTDR based on direct computations of pulse autocorrelation functions both before and after digital synthesis. Out of other options, including those based on arctan and polynomial functions, the employed DDS generated NLFM pulses are those based on a waveform optimized for bandwidth-limited synthesis with a characteristic given by [7]:

$$s(t) = A\ rect\left(\frac{t - T/2}{T}\right)\exp\left[\, j2\pi.\left(\frac{T\sqrt{\Delta^2+4}}{2\Delta} - \left[\frac{T^2(\Delta^2+4)}{4\Delta^2} - \left(t - \frac{T}{2}\right)^2\right]^{1/2}\right)\right], \tag{4}$$

where Δ is the nonlinear frequency span and T is the pulse width.

3. Experimental Setup and Results

The experimental setup used to demonstrate the proposed technique is shown in Fig. 1. Light from a coherent laser having a spectrum with FWHM of 200 kHz is split using a 99/1 coupler and the 99% is fed to an I-Q modulator with a nested Mach-Zhender structure driven in Single-Sideband Suppressed-Carrier (SSB-SC) operation. The modulator is driven with custom LFM or NLFM analogue waveforms, which are first programmatically designed and loaded on the Direct Digital Synthesis (DDS) module with a 10 GS/s DAC to generate the corresponding analogue RF signals. The waveforms are then fed to an electric hybrid driving the two RF ports of the IQ modulator. The SSB-SC modulated chirped signal is amplified and filtered with an Erbium-doped Fiber Amplifier (EDFA) and Optical Band-pass Filter (OBPF), gated using a high-extinction ratio Acousto-optic Modulator (AOM), and further amplified and filtered before being sent via the circulator into the fiber under test (FUT), comprised of two spools separated by patch cords of varying length. At the receiver, the backscattering signal is mixed with the coherent laser and the beating is detected with a 10 GHz photodiode and acquired through the digital acquisition system (DAQ) at 10 GS/s. To check relative fidelity of synthesized chirps, no averages were performed on the acquired traces and pulse waveforms, and the post-processing involves compression of backscattering signals via synchronous matched filtering with the generated optical pulses, which are also characterized through coherent mixing with the same local oscillator used for the backscattering.

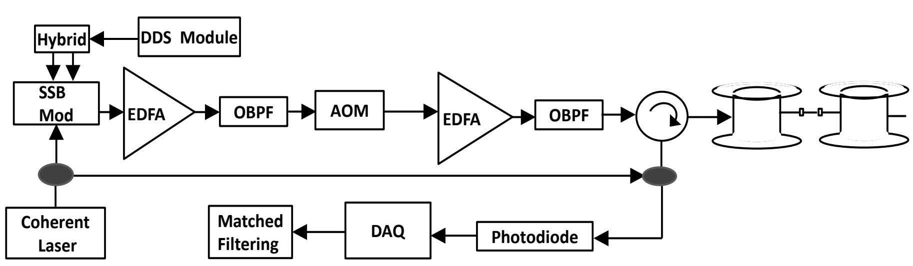
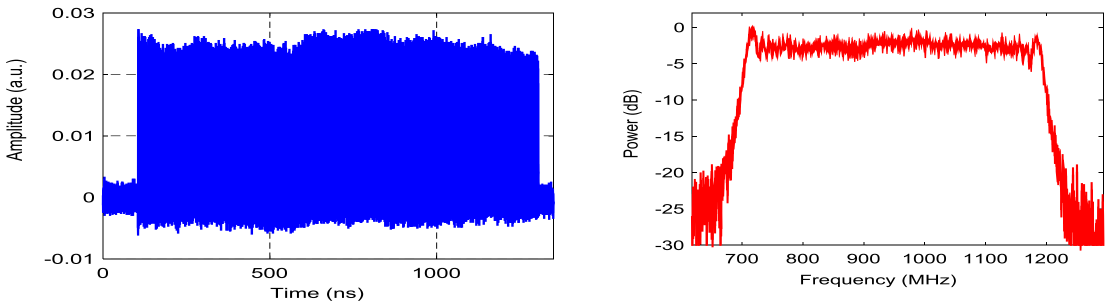


Fig. 1. Experimental setup.

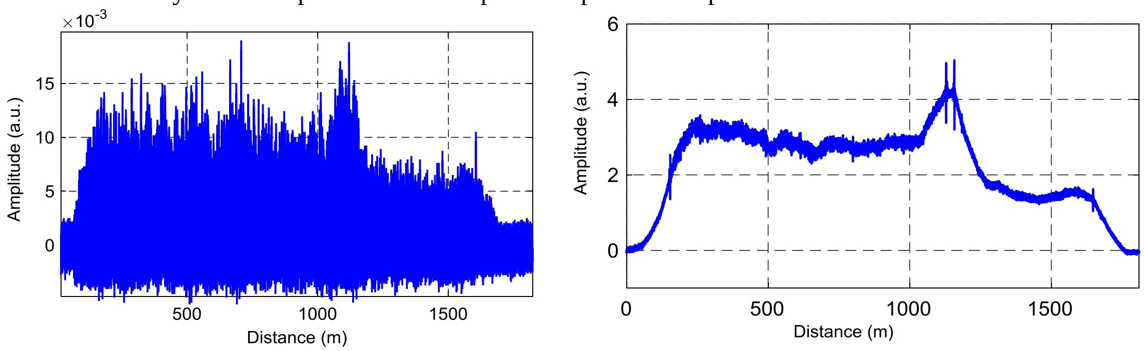
First, the effectiveness of the DDS scheme to generate frequency modulated optical signals with the desired bandwidth and features have been confirmed with characterization of generated optical chirps. The time and frequency domain plots of a sample 1.2 µs LFM pulse with a 500 MHz bandwidth are shown in Fig. 2(a) and (b).



(a) (b)

Fig. 2. (a) Synthesized LFM chirp in time domain (b) Chirp spectrum.

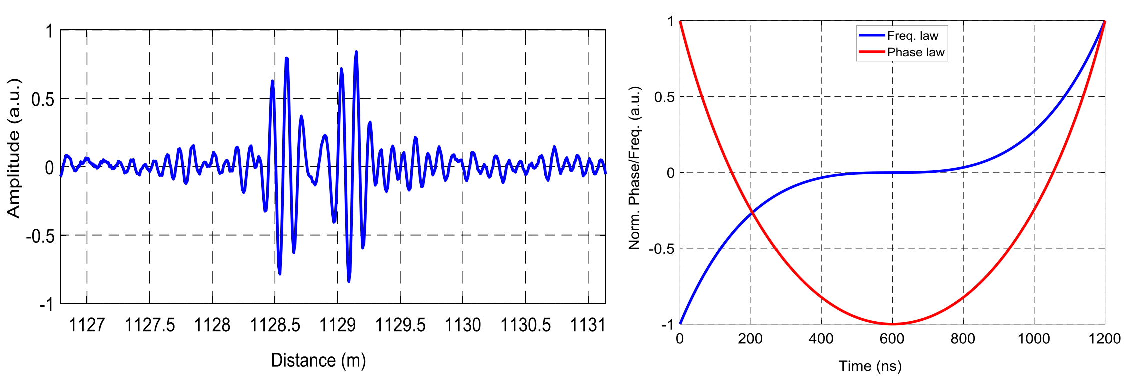
A sample raw φ-OTDR trace and compressed response are shown in Fig. 3(a) & (b), where a patch cord length of 30 m has been used at ~1.13 km. The compressed trace in Fig. 3(b) exhibits peaks of reflections from connectors at both ends of the patch cord, and enhanced SNR thanks to the matched filtering. Subsequently, the length of the fiber was narrowed to a few meters, each time confirming length and positions of patch cords, and ultimately down to 50 cm. The variation of the compressed response from the trace level are depicted in Fig. 4(a), where the two reflections from the connectors at both ends of the 50-cm patch chord are clearly visible, including the sidelobes in the sync-like response of the compressed optical LFM pulse.



(a) (b)

Fig. 3. Sample a) Raw and b) Compressed backscattering responses.

There is a visible non-localization of the compressed response of a reflection known to happen at a fixed point and the undesirable sidelobes of the reflections from the LFM pulses will cause errors in spatially sampled or averaged amplitude or phase responses of more complex events in a φ-OTDR, which generally involves less localized and spatially dispersed footprints. Note also that effective suppression of sidelobes in simple compression scenarios with low back-reflection powers and no averaging can be highly degraded from theoretical values, including down to scales of a few dB [8]. We address this issue by employing the flexibility of our DDS technique to generate customized NLFM pulses with optimized autocorrelation functions offering efficient sidelobe suppression.



(a) (b)

Fig. 4. (a) Compressed LFM response for measurement of a 50-cm patch cord span (b) Phase and frequency modulation laws for NLFM pulse.

The normalized phase and frequency modulation laws for the specific NLFM waveform used in our φ-OTDR scheme as defined by equation (4), which are differentiation-integration pairs, are depicted in Fig. 4(b), which shows symmetric nonlinear variations about the center of the pulse. Note that, due to the highly particular and rigorously defined feature of the modulation laws for effective sidelobe suppression, the controlled generation of the optical NLFM waveforms is possible only with a programmable DDS. Then, a measurement of the length of a 50-cm patch cord is performed when using the synthesized optical NLFM pulse, while maintaining all measurement parameters except the pulse frequency modulation scheme the same as that of the LFM pulse. The plot of the variations of the compressed responses of LFM and NLFM pulses relative to the trace level normalized to the respective peaks are shown in Fig. 5(a). In addition to the expected features of clear connector reflections, a significant reduction of range ambiguity in the NLFM response before, within and after the position of the patch cord is observed. Compared to matched filtering with the LFM pulse, there is significant suppression of the oscillations in the sidelobes.

The source of sidelobe suppression in the NLFM response is evident in the plots of the relative powers in the sideways oscillations with respect to the main lobe levels at the peaks of the autocorrelation functions of the optical NLFM and LFM pulses, which are shown in Fig. 5(b). The effective optical sidelobe suppression is ~20 dB for the NLFM pulse, which is ~16 dB more than that of the LFM one, confirming that reduction of range ambiguity in the compressed response is owed to the advanced matched filtering for improved range resolution using NLFM pulses generated via readily adaptable DDS.

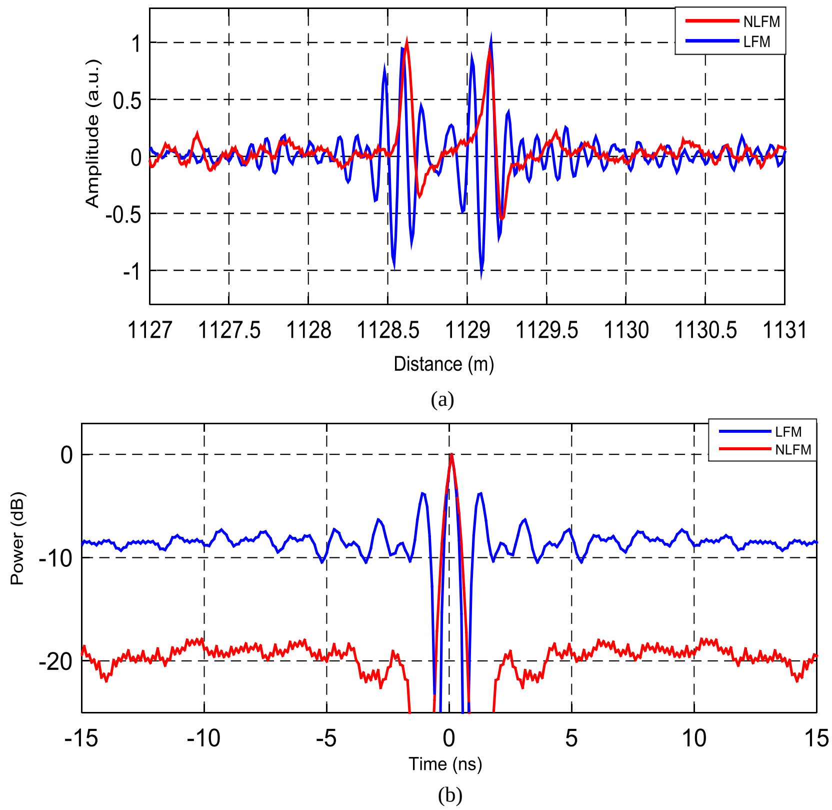


Fig. 5. (a) Compressed NLFM and LFM responses at 50-cm patch chord span (b) Comparison of the relative power levels of sidelobes in autocorrelation functions of LFM and NLFM optical pulses.

Conclusion

In summary, we have proposed and experimentally demonstrated, for the first time to the best of our knowledge, a φ-OTDR for enhanced spatially resolved measurements using a dynamically adaptable frequency modulation scheme based on direct digital synthesis of chirps employing advanced matched filtering with custom NLFM pulses. Significantly suppressed range ambiguity is observed when compressing a 1.2-μs pulse to resolve a 50-cm event, thanks to enhanced features of the autocorrelation function of the synthesized NLFM pulse offering effective optical sidelobe suppression of ~20 dB, with an improvement of ~16 dB compared to the use of a conventional LFM pulse.

References

[1]. Y. Muanenda, "Recent Advances in Distributed Acoustic Sensing Based on Phase-Sensitive Optical Time Domain Reflectometry," J. Sensors, 3897873 (2018).
[2]. W. Zou, *et al.*, "Optical pulse compression reflectometry: proposal and proof-of-concept experiment," Opt. Express **23**, 512-522 (2015).
[3]. Bin Lu, *et al.*, "High spatial resolution phase-sensitive optical time domain reflectometer with a frequency-swept pulse," Opt. Lett. **42**, 391-394 (2017).
[4]. W. Zou, *et. al.*, "Optical pulse compression reflectometry with 10 cm spatial resolution based on pulsed linear frequency modulation," in Optical Fiber Communication Conference (Optical Society of America, Los Angeles, CA, 2015), paper W3I.5.
[5]. Electronic Design, "How New DAC Technologies are Changing Signal Generation For Test," Online source: https://bit.ly/35dxalj (2017).
[6]. M. A. Richards, *Fundamentals of Radar Signal Processing* (McGraw-Hill Education, New York, NY, 2005).
[7]. C. Leśnik, "Nonlinear Frequency Modulated Signal Design," ACTA Phys. Pol. A **116**, 351-354 (2009).
[8]. D. Grodensky, *Laser Ranging using Incoherent Pulse Compression Techniques* (Bar-Ilan University, Ramat-Gan, Israel, 2014), Chap. 3.