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Yonas Muanenda
Claudio J. Oton
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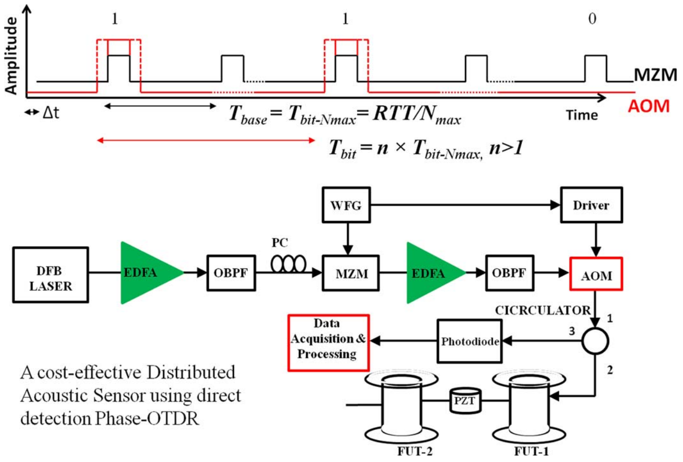
Fabrizio Di Pasquale



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A Cost-Effective Distributed Acoustic Sensor Using a Commercial Off-the-Shelf DFB Laser and Direct Detection Phase-OTDR

Yonas Muanenda, Claudio J. Oton, Stefano Faralli, and Fabrizio Di Pasquale

Scuola Superiore Sant'Anna, TECIP Institute, 56124 Pisa, Italy

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Abstract: We propose and experimentally demonstrate the use of cyclic pulse coding for enhanced performance in distributed acoustic sensing based on a phase-sensitive optical time-domain reflectometry (ϕ-OTDR) using direct detection. First, we present a theoretical analysis showing that to make cyclic pulse coding effective in ϕ-OTDR, the laser linewidth and stability must be optimized to simultaneously guarantee intrapulse coherence and interpulse incoherence. We then confirm that commercial off-the-shelf distributed feedback (DFB) lasers can satisfy these conditions, providing coding gain consistent with theoretical predictions. By externally modulating such lasers with cyclic pulse coding, we demonstrate a distributed acoustic sensor capable of measuring vibrations of up to 500 Hz over 5 km of standard single-mode fiber with 5-m spatial resolution with ~9-dB signal-to-noise ratio (SNR) improvement compared with the single-pulse equivalent. We also show that the proposed solution offers sensing performances that are comparable to similar sensors employing highly coherent and stabilized external cavity lasers and a single-pulse ϕ-OTDR.

Index Terms: Fiber optics sensors, Rayleigh scattering, lasers, linewidth.

1. Introduction

Among distributed optical fiber sensors, Distributed Acoustic Sensors (DAS), which are based on the use of an optical fiber to measure vibrations over an extended region, are becoming increasingly attractive for a wide range of industrial applications. These include monitoring oil and gas pipelines, ensuring railway safety and perimeter security, and performing industrial process control [1]. DAS systems involve the real-time observation of the properties of the Rayleigh backscattered signal in a coherent optical time-domain reflectometer (also known as phase-sensitive OTDR or ϕ-OTDR), and have become viable alternatives for long distance, distributed dynamic safety monitoring. Although several techniques have been proposed to implement DAS systems based on ϕ-OTDR, their high cost and complexity often hinder potential applications in large volume markets.

For instance, distributed intrusion detection systems have been demonstrated using a direct detection scheme [2] and a phase-sensitive interferometric system [3]. Solutions for distributed vibration measurement using coherent detection have also been proposed using polarization maintaining configurations [4] to detect vibrations of up to 2.5 kHz across a few tens of meters of sensing fiber. Since the Rayleigh back-scattering signal is characterized by a state of polarization that is uncontrolled along the fiber, such systems necessitate the use of rather complex and expensive polarization maintaining configurations. Advanced signal processing techniques, including moving averaging and moving differential methods, were shown to enhance the measurement capabilities in such sensors but at the cost of significant processing overheads. A digital demodulation technique, able to detect both the amplitude and phase of the beating signal after additional processing at the receiver, has also been demonstrated [5]. Wavelet denoising has also been proposed, offering signal-to-noise ratio (SNR) enhancement in the Rayleigh backscattered signal [6]. Both techniques reported in [5] and [6] improve the SNR of the backscattered signal at the expense of reduced dynamic capabilities due to the required additional post processing.

More recently, a high visibility phase-sensitive OTDR for high-frequency vibration measurements has been demonstrated using a Semiconductor Optical Amplifier (SOA) as a modulator [7]. This solution relies on the reduction of coherent noise by the high extinction ratio of the SOA driven as a modulator, and on the high suppression of the sidemode noise due to spectral hole-burning inside the same. Besides the challenges in driving the SOA as a modulator, this solution does not address the modulation instability issues affecting vibration measurements at long distance, in which high peak power values are required [8]. Finally, a technique exploiting a dual-pulse phase modulation scheme in the probe signal is shown to provide SNR enhancements while avoiding the use of an additional interferometer at the receiving end [9]. Although sensors which are able to quantitatively detect both amplitude and phase of the vibration exist, they are affected by significant drawbacks; they either require difficult post-processing [10] and complex receiver schemes with consequent limited performance [5] or the use of highly coherent lasers [5], [9], with typical sensing distances limited to less than 1 km. Recently, an enhanced-SNR distributed vibration sensor using Polarization OTDR has been proposed [11], but the demonstrated vibration frequency was limited to only 11 Hz.

In this paper, we propose and experimentally demonstrate a cost effective ϕ-OTDR system based on cyclic pulse coding and a simple direct detection receiver to accurately determine the frequency of vibration along a 5 km single-mode fiber at a spatial resolution of 5 m. We provide theoretical coherence analysis and experimental demonstration, showing that the use of cyclic coding with a commercial off-the-shelf (COTS) distributed feedback (DFB) laser significantly improves the SNR of vibration measurement while reducing the overall cost of the source compared to conventional single pulse systems [12]. The theory of cyclic coding in the proposed phase-OTDR system is presented in Section 2, while the design of the source and the experimental setup of the sensor are reported in Section 3. The detailed noise characterization of the laser is provided in Section 4, followed by the results for the measurement of vibration in Section 5. We also quantitatively compare the performance of direct detection DAS systems based on COTS DFB and highly coherent lasers.

2. Cyclic Pulse Coding in Phase-OTDR

Phase OTDR is based on the observation of the coherent Rayleigh backscattering signal from light pulses sent into the fiber to detect the phase changes induced by local perturbations. When using a light source which is coherent within the pulse width, the electric field of the backscattered signal at the receiver $E(t)_{z=0}$ consists of coherent speckles generated by the interference from M Rayleigh backscattering centers in the section of the fiber located in the range $z \in [(tv_g - w_p)/2,\ tv_g/2]$, where v_g is the group velocity, and w_p is the pulse spatial width [7]. The field is given by

$$E(t)_{z=0} = E_0 e^{-2\alpha\bar{z}} e^{j\omega t} \sum_{m=1}^{M} r_m e^{j\phi_m} \tag{1}$$

where $\bar{z} = 1/2[tv_g - w_p/2]$ is the corresponding position of the centre of the pulse from which the signal is backscattered, $r_m \in [0, 1]$ is each scattering center's reflectivity, and E_0 is a reference amplitude.

Pulse coding has been implemented for various types of sensors including conventional OTDR [12], Raman Distributed Temperature Sensors (RDTS) [13] and Brillouin Optical Time Domain Analysis (BOTDA) [14]. It involves sending a sequence of pulses with a known pattern into the fiber in such a way that they remain inside the fiber concurrently. As a result, the contribution of the backscattering for a single position in the fiber will be a superposition of that from many pulses. In case of Simplex coding [13]–[15], the equivalent of the single pulse trace is subsequently obtained from the coded traces by a linear decoding process which involves a single multiplication between a matrix and a vector. The resulting signal is characterized by a higher SNR compared to the one from the single pulse and the SNR improvement, also known as the coding gain G, scales with the length of the codeword N according to $G = (N+1)/2\sqrt{N}$.

The use of pulse coding, more specifically Simplex cyclic coding [13], for a DAS system based on ϕ-OTDR is motivated by several factors. First, the properties of Simplex cyclic pulse coding provides SNR enhancement allowing effective decoding in less than a single fiber round trip time (RTT) [15], without degrading the DAS dynamic performance. This is a fundamental condition for performing vibration measurements at high speed. Besides, the use of coding enables sending more energy into the fiber compared to using a single pulse without detrimental non-linear effects. The resulting SNR improvement has an additional benefit of making commercial off-the-shelf (COTS) DFB lasers suitable for DAS measurements. In conventional ϕ-OTDR sensors, more expensive, frequency stabilized and narrow linewidth lasers are required to obtain the coherent Rayleigh backscattering signals used to perform vibration measurements.

However, in a ϕ-OTDR using a narrow linewidth laser, the effective implementation of pulse coding can be problematic. The back-scattering given in (1) from a pulse p_i can potentially interfere with that of a subsequent pulse p_j according to

$$I_{ij} = I_i + I_j + 2\sqrt{I_i I_j}\cos\phi_{ij} \tag{2}$$

where I_i and I_j are the backscattered intensities from the two pulses, and ϕ_{ij} is the phase difference between them. For a Lorentzian line shape, the coherence length of a laser L_{coh} is given by [16]

$$L_{\text{coh}} = \frac{c}{\pi n \Delta\nu} \tag{3}$$

where $\Delta\nu$ is the laser linewidth, n is the group refractive index of the fiber, and c is the speed of light in free space.

To use pulse coding in a ϕ-OTDR, the choice of the laser linewidth is subject to two interference conditions which determine its upper and lower bounds such that $\Delta\nu_{\text{min}} \leq \Delta\nu \leq \Delta\nu_{\text{max}}$. The first one is the intra-pulse coherence condition which demands that the pulse be coherent within the pulse width τ, i.e., the time period required for backscattering signals from a single reflection center to interfere at the receiver. Noting that $T_{\text{min-coh}} = \tau$ (during which the pulse travels twice the distance of the spatial resolution) and using $t_{\text{coh}} = L_{\text{coh}}/(c/n)$ in (3), we obtain

$$\Delta\nu \leq \Delta\nu_{\text{max}} = \frac{1}{\pi \times \tau}. \tag{4}$$

On the other hand, the inter-pulse incoherence condition requires that the backscattering signals from two consecutive pulses not be coherent with respect to each other. This second condition can be clearly satisfied by cyclic coding with inter-pulse distance larger than the coherence length of the laser. In other words, for a given sensing distance and corresponding RTT, the coherence time of the laser should be lower than the bit time of the longest codeword

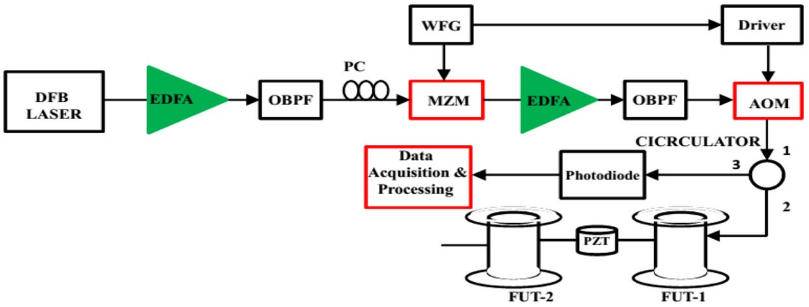


Fig. 1. Experimental setup of phase-OTDR with coding.

N_{max} used for cyclic coding, i.e., lower than $T_{\text{max}-\text{coh}} = \text{RTT}/N_{\text{max}}$. Using (3), this condition can be written as

$$\Delta\nu \geq \Delta\nu_{\text{min}} = \frac{N_{\text{max}}}{\pi \times \text{RTT}}. \tag{5}$$

If the choice of the source satisfies the conditions in (4) and (5), the beating component in (2) will be eliminated. This in turn means that the contribution of the various pulses to the total intensity in the backscattering signal at the receiver will be a superposition of the delayed intensity contributions from individual pulses,. i.e.,

$$I_{\text{total}}(t)_{z=0} = \sum_{i=1}^{N} p_i \times I(t + (N - i + 1)t_b) \tag{6}$$

where $P = \{p_i \in \{0,1\} : i = 1, 2, 3 \ldots N\}$ is the cyclic pulse pattern, $t_i = t + (N - i + 1)t_b$ represents the delay in the backscattering intensity contribution for the i-th pulse at the receiver, t_b being the bit duration, and $I(t) = I(t + Nt_b)$ is the periodic backscattering intensity trace from an individual pulse containing the coherent speckles. A few rearrangements to (6) yield a set of linear equations which can be solved using a single multiplication between a matrix and a vector to perform the decoding process and obtain the equivalent of the single pulse fiber response, using analyses similar to the one given in [12].

It is worth noting that, according to our analysis, a highly coherent source prevents the use of coding for the Rayleigh trace reconstruction. However, a COTS DFB laser, which can easily satisfy the conditions given by (4) and (5), has the double advantage of having a lower cost and allowing the use of coding for SNR improvement. Besides, in conventional long distance ϕ-OTDR, the use of high peak power levels, which is required for achieving acceptable SNR values in the Rayleigh backscattering signal, has been shown to result in detrimental non-linear effects such as modulation instability [8]. This means that an alternative solution based on pulse coding and using lower peak power levels to obtain given sensitivity and sensing distance requirements would be preferable. In our work, we experimentally demonstrate that the use of cyclic Simplex coding in ϕ-OTDR with COTS DFB lasers effectively reduces the DAS measurement noise leading to dynamic performances comparable to the ones achievable with highly coherent sources.

3. Experimental Setup and Design of Source for ϕ-OTDR With Coding

To test our proposed scheme for a phase-OTDR based on cyclic coding, we used the experimental setup shown in Fig. 1. Light from a COTS DFB laser is amplified with an Erbium Doped Fiber Amplifier (EDFA), filtered via a narrow Optical Bandpass Filter (OBPF) and then modulated by a pattern of continuous pulses in the "1" state using a Mach-Zehnder Modulator (MZM) driven by a Waveform Generator (WFG), while the state of polarization is controlled by a Polarization Controller (PC). Then, the pulses are further amplified and filtered with the second EDFA

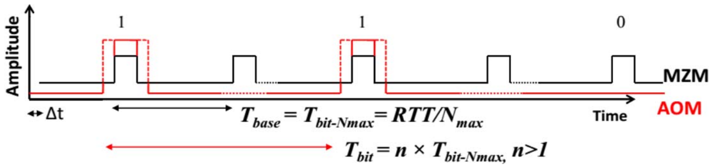


Fig. 2. Implementation of the modulation scheme in the source for ϕ-OTDR with coding.

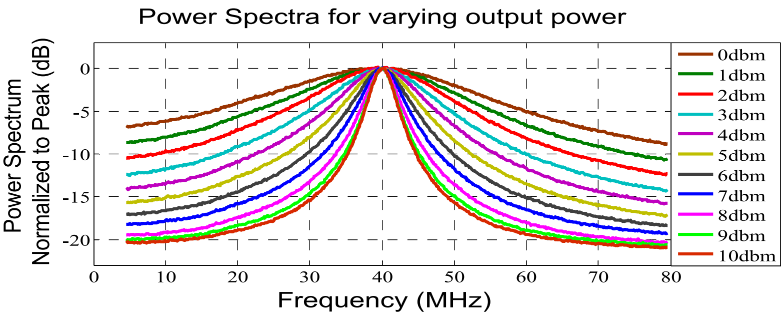


Fig. 3. RF spectra corresponding to laser emissions at different output power.

and OBPF, respectively, before being input to a high extinction ratio (ER) Acousto-optic Modulator (AOM) used as a gating element to generate the cyclic pulse codeword pattern. The coherent Rayleigh backscattering signal is input to a simple direct detection receiver consisting of a 125 MHz PIN photodiode which precedes the data acquisition block consisting of a 200 MS/s oversampling ADC and a fast digital acquisition board.

The design of the source for implementation of the cyclic coding in a ϕ-OTDR is made in such a way that the coherence noise in the backscattering signal is minimized by using suitable combination of modulation, amplification and filtering, as shown in the schematic given in Fig. 2. Note that the MZM and the AOM suppress the residual zero-level amplified spontaneous emission noise at the input of the second EDFA and at the fiber input, respectively. The high ER of the AOM provides an additional benefit of suppressing the coherence noise [7]. The MZM is driven by a continuous pattern of bits all in the “1” state, which would then be turned either on or off by the AOM, depending on the pulse pattern. Note that, in order to make a sensible performance comparison between single pulse and coded ϕ-OTDR, the noise and peak power of the signal after the second EDFA should have the same value for different codewords and a single pulse. This is achieved by the experimental set-up described in Fig. 1 and by the scheme described in Fig. 2 by always generating a sequence of pulses in the “1” state, with the same bit time T_{base} which corresponds to the longest codeword used. The selection of a specific codeword will then take place in the AOM depending on the specific codeword pattern and length. The delay Δt in Fig. 2 corresponds to the locations of the two modulators in the experimental setup.

4. RIN and Frequency Noise Characterizations

Before testing the effectiveness of our DAS system based on cyclic Simplex coding, we characterized a COTS DFB laser at 1549 nm from NetTest and a narrowband stabilized external cavity laser (ECL) from Advantest, in terms of linewidth, frequency stability and Relative intensity Noise (RIN). Fig. 3 shows the RF spectra of the COTS DFB laser measured using a delayed self-heterodyne technique [17] at different output power levels, where the FWHM is half the one reported in the figure. It is evident that the linewidth of the laser is strongly dependent on the laser operating conditions and, specifically, the output power should be adjusted so that the emission width is suitable for accurate vibration measurement based on pulse coding. We have verified that operating the laser at 2.5 dBm output power provides a FWHM of ~4 MHz which guarantees the intra-pulse coherence and inter-pulse incoherence conditions required for a

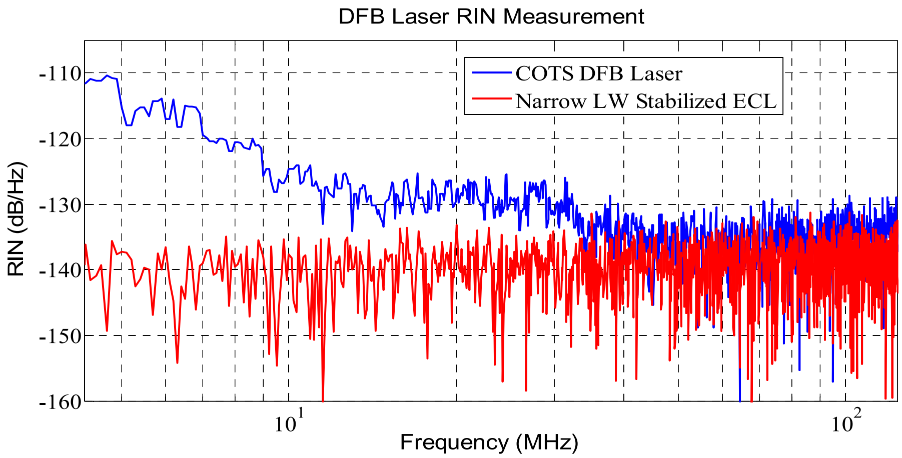
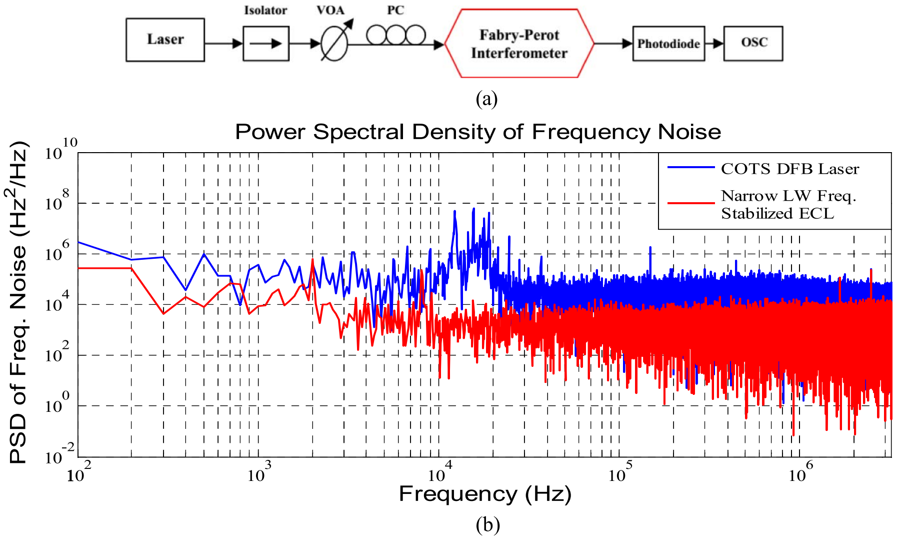


Fig. 4. Measured RIN of the COTS DFB laser and stabilized narrow linewidth ECL.



(a)

(b)

Fig. 5. (a) Experimental setup for characterizing laser frequency stability. (b) Measured power spectral density of frequency noise using the DFB laser and a frequency stabilized, narrow linewidth ECL.

coded phase-OTDR (the laser linewidth is within the range 1 MHz–6 MHz, which is required to guarantee both coherence conditions with 6 km sensing fiber, 50 ns pulses, and maximum codeword length $N_{\mathrm{MAX}} = 255$). For comparison, we have also measured the linewidth of the highly stabilized ECL to be ∼50 kHz, confirming that this laser cannot be used for coded ϕ-OTDR due to inter-pulse coherence.

We have also made a characterization of the relative intensity noise (RIN) of the COTS DFB and stabilized external cavity lasers, which are reported for comparison in Fig. 4. As shown, both lasers are characterized by low RIN values at frequencies corresponding to the time scales of our measurement, providing accurate intensity values within the measurement bandwidth of 125 MHZ. Specifically, the integral of the RIN over frequency in the spectral range of our measurement is inversely proportional to the SNR and hence low value of measured source RIN implies higher SNR of measurement using the overall sensing system.

The COTS DFB laser used in our coded phase-OTDR and the highly stabilized ECL have also been characterized in terms of frequency stability using the interferometric scheme described in Fig. 5(a) [18]. As shown, the output of the laser passes through an isolator followed

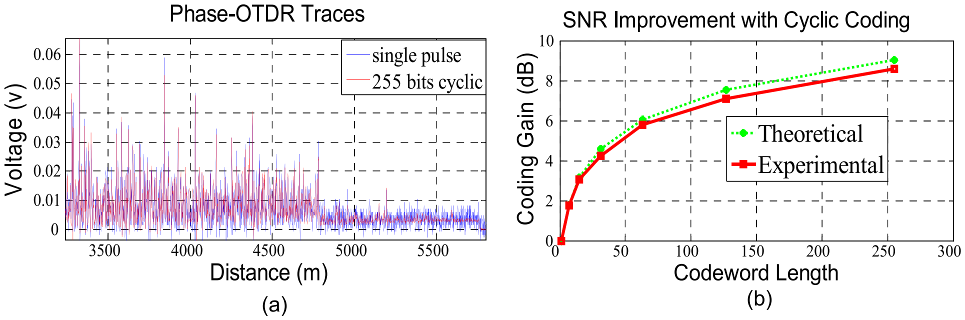


Fig. 6. (a) Individual phase-OTDR traces for single-pulse and 255-bit cyclic coding showing denoising with coding. (b) Theoretical and experimental coding gain for varying codeword length.

by a variable optical attenuator (VOA), which controls the power from the laser. A Fabry–Perot interferometer (FPI) is used to convert laser frequency fluctuations into intensity changes, and a polarization controller (PC) is employed to obtain the optimum state of polarization in the FPI. Then, a PIN photodiode and an oscilloscope have been used to acquire the intensity changes at the output of the interferometer, which are then converted back to the corresponding frequency changes by inverting the transfer function of the FPI. The measured values of the power spectral density (PSD) of the frequency noise for the two lasers are reported in Fig. 5(b), which confirms the higher overall frequency stability for the ECL compared to the DFB laser. Note that the central frequency of the laser should not drift during consecutive measurements and that the required frequency stability depends on the laser linewidth. For instance, if the desired linewidth range is 1–5 MHz, not only should the laser emission remain within these limits, but also should its center frequency not vary by more than 5 MHz. This factor determines the impact of frequency noise of the source on the overall performance of the sensing system. This is clearly reflected in the result of the frequency noise measurement in Fig. 5(b), which shows that the COTS DFB laser has an emission spectrum stable enough to guarantee accurate measurement of the phase-OTDR intensity. The effect of noise on the performance of the sensing system can be summarized as follows: low measured RIN in Fig. 4 combined with low frequency noise shown in Fig. 5(b) for the light source used in our sensor means that the sensor spatial resolution will be preserved and cyclic coding can be effectively implemented with reduced measurement noise.

5. Experimental Results

We have tested the effectiveness of the DAS system using the COTS DFB laser and cyclic Simplex coding. We used 6 km of standard single mode fiber in which a 1.5 meter section at around 5 km was wound on a Piezoelectric Tube (PZT), so that low amplitude vibrations can be applied at different frequencies using a WFG driven by an amplifier, to simulate external interferences. A number of coded traces were then acquired at a repetition rate corresponding to the fiber RTT (16.67 kHz). Subsequently, each trace was decoded and the time variation of the intensity of the point of vibration was studied. The limit of frequency of vibration that the sensor can measure is determined by the RTT of light along the fiber, which depends on the sensing distance while the RTT and codeword length determine the duty cycle. Fig. 6(a) shows a comparison of an averaged single pulse trace and a 255-bit averaged decoded trace at the end of the sensing fiber, with 50 ns pulses and just 10 moving averages, clearly showing the presence of coherent speckles and the benefit of pulse coding in terms of noise suppression. Note that the properties of cyclic coding allow effective decoding in less than a single RTT without degrading the DAS dynamic performance [14].

The decoding process can be taken as a kind of sampling in the optical domain that occurs many times within a single RTT at intervals of the bit time and helps to perform fast denoising of

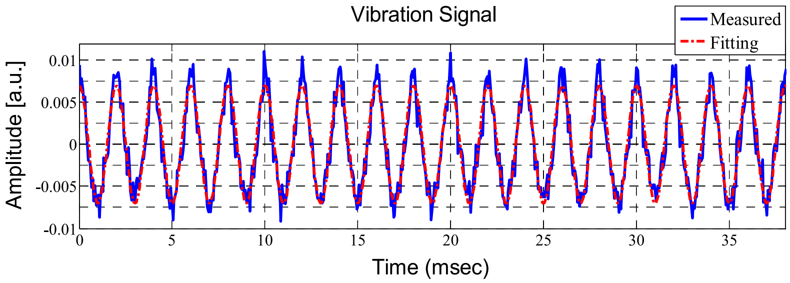


Fig. 7. Time-domain plot of a 500-Hz sinusoidal vibration at the PZT.

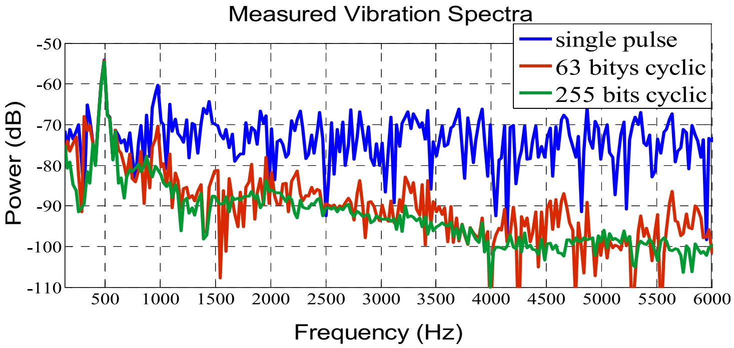


Fig. 8. Measured vibration spectra with the DFB laser using single-pulse, 63- and 255-bit cyclic coding.

the backscattering signal. Even though the end result of using cyclic coding can be equivalent to that of averaging in terms of the denoising, the process happens within a single round trip time, and hence, this makes it particularly important for fast denoising. It also significantly reduces the number of averages required to obtain a given SNR. It is important to follow the theoretical analysis given in Section 2 for the actual implementation of the pulse coding scheme since it is not straightforward in the case of a phase-OTDR system which uses a coherent source. The experimental and theoretical coding gain values as a function of codeword length for pulse width of 50 ns and peak power of 27 dBm are shown in Fig. 6(b), which points out the close agreement between theory and experiment. The slight difference between the two for long codewords can be explained by the fact that, when the code length increases, the bit-time which is defined in Fig. 2 decreases and the backscattered signal from each bit in the codeword starts to interfere more with adjacent ones. We have experimentally confirmed that coherent interference among the Rayleigh back-scattering from the different pulses in the codeword is avoided by choosing the source according to the theoretical coherence analysis given in Section 2. When cyclic coding is used with a narrow linewidth laser, the coherent Rayleigh backscattering signal shows clearly observable oscillations which do not appear when a single pulse is used, making it evident that the interference arises from backscattering among coherent consecutive pulses. On the other hand, when a larger linewidth laser fulfilling the coherence conditions is used, the acquired trace contains clear intensity superposition of contributions from individual pulses, which can then be effectively decoded. Fig. 7 shows the detected sinusoidal signal in time domain for a 500 Hz vibration applied at the PZT, when a codeword of 255 bits is used.

To assess the noise reduction due to cyclic coding, a comparison of the various measured spectra when using a single pulse and different codeword length values has also been done and the results are reported in Fig. 8, which clearly shows a reduction in the noise floor of the measurement for varying codeword length values. These results also confirm that the noise suppression induced by pulse coding is consistent with the coding gain reported in Fig. 6(b) (which is ~9 dB with 255-bit codeword).

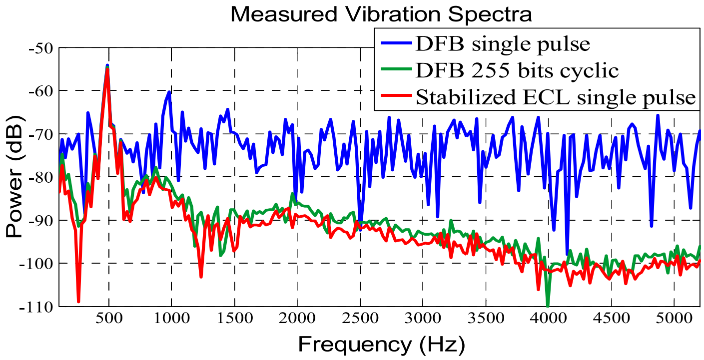


Fig. 9. Vibration spectra using DFB laser and a frequency stabilized ECL.

It is worth noting that, since our sensor monitors the change in the intensity of the backscattering signal, it is mainly suitable for accurate measurement of the frequency of vibration over a long distance. It can be attractive in a number of applications including intrusion detection and identification, health monitoring of structures and leakage detection in the oil and gas industry.

An additional advantage of using cyclic coding is that it increases the total light energy sent into the fiber without having to increase either the pulse width or the peak power. Since the decoding process converts the response obtained by sending the codeword along the fiber into the equivalent of the single pulse, it maintains the spatial resolution. The maximum SNR improvement using cyclic coding depends on the length of the codeword, which in turn depends on the length of the fiber and the source linewidth as defined by the inter-pulse incoherence condition. For a given light source satisfying the coherence conditions, the bit time should be longer than the pulse width and the corresponding length of codeword used will set the limit to the SNR enhancement. The maximum frequency of vibration that can be measured is determined by the round-trip-time of light along the fiber and the number of acquired traces, which is much less when using cyclic coding compared to a single pulse.

Finally, a comparison of the measured vibration spectra obtained with cyclic coding and a DFB laser with FWHM ~4 MHz and that with single pulse and a highly stabilized ECL with FWHM ~50 kHz, were made (the characterizations of both lasers were done, as shown in Figs. 3–5). The measured spectra for a 500 Hz sinusoidal vibration at the PZT with the two lasers using the same parameters including the pulse width, sensing distance and optical power at the input of the FUT are reported in Fig. 9, which clearly shows that the use of cyclic coding with the COTS DFB laser results in a reduction in the noise floor of the measurement to a level comparable to that obtained using the ECL. Note that the proposed sensor is suitable for long distance measurements (enabling vibration frequency measurements at a distance of 5 km resolved by 5 m) and is less costly because of the use of a COTS DFB laser and simple direct detection with minimal post-processing. The cost-effectiveness is evident from the fact that most existing vibration sensing schemes [4]–[6], [9] employ stabilized narrow linewidth light sources, which use external cavities to maintain spectral purity. Compared to simple COTS DFB lasers which have FWHM of a few MHz, such sources are more complex and expensive.

6. Conclusion

We have demonstrated a DAS system using cyclic coding in a direct detection scheme which uses a commercial DFB laser. We have presented theoretical analysis for intra-pulse and inter-pulse coherence conditions which enable cyclic pulse coding to be effective in ϕ-OTDR. Detailed experimental characterizations have also been carried out in order to select suitable sources to be used in improved SNR ϕ-OTDR sensors. We have shown that suitable design of the source to satisfy these coherence conditions relaxes the strict requirement for a stabilized, narrow linewidth laser in conventional phase-sensitive OTDR sensors while at the same time reducing coherent noise and non-linear effects. Experimental results confirm the capability of the proposed technique to perform distributed measurement of vibrations of up to 500 Hz at 5 km distance on standard single-mode fiber, with a spatial resolution of 5 meters.

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