All-Fiber Electro-Optic Dual Optical Frequency Comb for Fiber Sensors

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Abstract: We present a new technique for generating a Dual Optical Frequency Comb and we apply the technique on a Chirped Fiber Bragg Grating sensor to demonstrate quasi-static absorption measurements. In addition, it can be also applied to dispersion measurements. This technique is able to generate RF mapping of two optical frequency combs without the use of an acousto-optic modulator.

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1. Introduction

Frequency combs gathered a lot of attention in the past few years [1, 2]. That is because they allow fast spectroscopic measurements. Their potential leads on the fact that the optical modes are able to extend along a certain wavelength range. The comb has become a tool for signal generation [3], spectroscopy [4], Fiber Bragg Grating (FBG) sensor interrogation [5], and other techniques related with metrology [6].

The natural evolution of the optical combs for sensing purposes has led to the dual comb topology. This topology consists on several modes that overlap along the spectral axis, which produces a beat of the nearer overlapping comb lines of the both combs. The topology has been developed for several years and it has led to several architectures as gain switching generation and other phase and amplitude modulation techniques. All of them are centered in optimizing the response of the comb (bandwidth, flatness) and its behavior (resolution, stability).

The FBG’s have also gathered a lot of attention due to their applications on many fields. They are fabricated in many varieties from chirped to long length FBG’s [7, 8]. Nowadays the functionalization of FBG for chemical concentration measurements is investigated [9].

This work proposes the use of an electro-optic dual comb that has a new feature of not using an acousto-optic modulator. This leads to a more compact dual comb architecture. Taking into account that the system needs a frequency shift for the RF mapping, we achieve it accurately through the phase modulation instead of a typical acousto-optic modulator.

To our knowledge, this is the first electro-optic dual optical frequency comb with no need of an acousto-optic modulator. This feature could lead to in chip integration of the dual comb, compactness, as well as flexibility over the RF mapping frequency of the all-fiber dual comb.

2. All-fiber dual optical frequency comb

The idea is to use the serrodyne technique to shift the light frequency in a quasi-ideal manner [10]. This fact avoids the use of an acousto-optic modulator; it constitutes an improvement since the amount of frequency that the light is shifted can be chosen by just setting the main parameters of the modulating signal. It is an old technique in interferometry and the electro-optic dual comb architecture is intrinsically a Mach Zehnder configuration. Therefore, we applied it to the dual-comb. The proposed scheme is shown in Figure 1.

Figure 1: Serrodyne based dual optical frequency comb generator without acousto-optic modulator.
L: Laser, CO: Coupler, PM: Phase modulation, AQ: Acquisition
The architecture is based on three electro-optic modulations driven by different signals. The PM 1 is driven by a saw-tooth signal whereas the other two-phase modulation processes are driven by two slightly different frequency pure tones.

Each modulator is performing a phase modulation over the light [11,12]:

\[
E_{\text{out}}(x,t) = E_{\text{in}}(x,t) e^{j\frac{V_{\text{drive}}(t)}{\pi n}}
\]  
\hspace{1cm} (1)

Where the \( E_{\text{out}}(x,t) \) is the electric field on the modulator output, \( E_{\text{in}}(x,t) \) is the electric field of the modulator input, \( V_{\text{drive}}(t) \) is the voltage of the driving signal that is injected into the de device and \( V_{\pi} \) is the voltage at which the device is shifting \( \pi \) rad the optical phase.

Conveniently, we can choose \( V_{\text{drive}}(t) = \alpha t \) that if substituted in (1):

\[
E_{\text{out}}(x,t) = E_{\text{in}}(x,t) e^{j\frac{\alpha t}{\pi n}} = E_{\text{in}}(x) e^{j(\omega t + \phi_0)} e^{j\frac{\alpha t}{\pi n}} = E_{\text{in}}(x) e^{j\left(\omega + \frac{\alpha}{\pi n}\right)t + \phi_0}
\]  
\hspace{1cm} (2)

Therefore, \( \Delta \omega = \frac{\alpha}{V_{\pi}} \) constitutes a constant frequency shift. Accordingly, this signal is injected into the PM1 to achieve a frequency displacement, this leads to the generation of a carrier signal that allows the one to one univocal mapping of the optical modes into electronic harmonics around the carrier frequency. Accordingly, \( \alpha \) is the slope of the sawtooth signal such that \( \alpha = V_{pp}/f_{\text{sawtooth}} \). Where \( V_{pp} \) is the peak-to-peak voltage and \( f_{\text{sawtooth}} \) is the frequency of the sawtooth. If \( V_{pp} = V_{\pi} \) we obtain that \( \Delta \omega = f_{\text{sawtooth}} \) which is the frequency we are adding at the light carrier frequency. It is noteworthy that if the \( V_{pp} = nV_{\pi} \) the amount of frequency the light is shifted is \( \Delta \omega = n f_{\text{sawtooth}} \).

On the other hand, the other two-phase modulators are used as multicarrier generators. That generates two combs with different repetition rates and at the same time shifted with respect each other. This process leads to the RF mapping at a selectable frequency along a span limited by the ramp generator bandwidth, and the phase modulation bandwidth.

Another important equation is the one that relates the input with the output of a phase modulator when a pure sinusoidal frequency is driving the device.

\[
E_{\text{out}}(x,t) = E_{\text{in}}(x,t) e^{jA_2 \sin(\omega_{\text{drive}} t)} = E_{\text{in}}(x) \sum_{n=-\infty}^{\infty} J_n \left( \frac{A_2}{V_{\pi}} \right) e^{j\left(\omega n \Delta t + \phi_0 \right)}
\]  
\hspace{1cm} (3)

Where \( A_2 \sin(\omega_{\text{drive}} t) \) is the signal injected into the device, and \( J_n(\alpha) \) denotes the Bessel function of the first kind and order \( n \) of argument \( \alpha \). If we apply the expression for the irradiance \( I = \langle E^*E \rangle \) with all phase modulation processes (a total of two pure sinusoidal and one sawtooth we obtain that):

\[
I \propto E_{\text{in},3}(x) E_{\text{in},2}(x) \operatorname{Re} \left( e^{j\frac{\Delta}{V_{\pi}} \omega_{\text{drive},2} t} \right) \sum_{n=-\infty}^{\infty} J_n \left( \frac{A_2}{V_{\pi}} \right) J_n \left( \frac{A_3}{V_{\pi}} \right) e^{j\left(\omega_{\text{drive},2} - \omega_{\text{drive},3} \right) n t}
\]  
\hspace{1cm} (4)

The \( A_2 \) and \( A_3 \) represent the voltage amplitude with which we are modulating, while \( \omega_{\text{drive},2} \) and \( \omega_{\text{drive},3} \) are the frequencies of modulation for the second and third modulating processes from figure 1. Accordingly, \( E_{\text{in},3}(x) \) and \( E_{\text{in},2}(x) \) are the electric strength of the light beam of the input of the modulators of the upper and lower arm of the interferometer.

It is noteworthy to point out that \( E_{\text{in},3}(x) J_n \left( \frac{A_3}{V_{\pi}} \right) \) is the optical amplitude of the \( n \)-th harmonic in the upper arm of the interferometer while \( E_{\text{in},2}(x) J_n \left( \frac{A_2}{V_{\pi}} \right) \) is the optical amplitude of the \( n \)-th harmonic in the lower arm of the interferometer. Finally, \( e^{j(\Delta t)} \) denotes the carrier frequency made by the sawtooth serrodiene shift. The expression (4) states that the output irradiance of the dual comb is proportional to the both optical combs. It is noteworthy to mention that other terms arise in the complete form of the equation (4), nevertheless they can be neglected since their pulsing frequency is higher than the bandwidth of the photodetector.

In the end, the modulation for obtaining the frequency shift is a multi-harmonic signal. We have also tried with a PGC signal (that is a pure tone) but lower spectral efficiency was obtained. The spectral efficiency can be improved with similar technique as the one proposed in [13] that is a non-uniform slope saw-tooth signal.
3. Simulation

Utilizing the previous equations, we observe the response of the mode generation on optical and electrical domain (Figure 2). Since the optical separation of the comb lines is 1GHz or 0.8 pm we cannot resolve such a small resolution with the state of the art average optical spectrum analyzers. However, the model resolution can be adjusted and the modes can be seen in simulation (Figure 2a)).

On the other hand, in electrical domain we can perfectly distinguish the amplitude of each mode and compare the simulated results with the measured results. The simulated results were experimentally confirmed and are overlapped with the simulated spectra in (Figure 2 b)).

4. Application to a Chirped FBG sensor

In figure 3 the complete system is shown, PM3 and PM2 are two sinusoidal tones at 1GHz, and 0.99997 GHz, respectively, and PM1 is a sawtooth signal at 4 MHz with 1.775 V of peak-to-peak voltage.

The direct application of this technique is for measuring absorption of the lines of the comb, in our case we have placed a three teeth comb in the slope of a chirped FBG sensor that allows us to detect in three different points separated a width of 8pm. The measurements are shown in the figure 4. In the figure 4a, we can observe the FFT of the introduced signal to the FBG as well as the reflected signal from the chirped FBG.

It can be seen how much each line is attenuated in a different manner according to the absorption profile of the sensor. The input signal spectra has the information of the optical comb lines that are injected into the chirped FBG sensor. On the other hand, figure 4b has the information of the lines that are back reflected from the sensor. The central mode has an attenuation -30dB, while the left harmonic has -29dB of attenuation and the right harmonic has been totally removed from the reflected spectra achieving an attenuation around -30 dB.
These measurements demonstrate that there is a mapping of the optical modes into electrical domain. Particularly, optical carrier (THz) and comb teeth (1 GHz separated) are detected as electrical carrier of 4MHz and electrical harmonics (30 kHz separated in this case). Moreover, the relationship is linear due to the expression (4).

5. Conclusions

A new dual comb architecture has been simulated, implemented and tested with a chirped FBG sensor. This architecture does not need an acousto-optic modulator for shifting the frequency a constant amount. The shift is performed with a phase modulator that is driven with a sawtooth signal at 4MHz. The displacing frequency can be set by just choosing the proper amplitude and frequency of the sawtooth driving signal. The frequency shift of 4 MHz was performed with a total harmonic distortion of 0.2% that is a quasi-ideal shift on the optical domain.

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