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Fully Adaptable Electro-Optic Dual-Comb Generation

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***Abstract*— In this letter, an all-electronic method that provides a precise control over the number of spectral lines of an electro-optic frequency comb is presented and experimentally validated. This feature, in conjunction with the straightforward configuration of the optical resolution (repetition frequency) inherent to electro-optic combs, enables the generation of optical comb sources with the unique capability of a complete adaptability to the targeted spectral feature/s that could ultimately maximize the SNR of any electro-optic comb-based spectroscopic measurement.**

***Index Terms*— Optical frequency comb, Electro-optic frequency comb, Dual-comb spectroscopy, Adaptable spectroscopy.**

I. INTRODUCTION

ELECTRO-OPTIC (EO) dual-comb (DC) generators have nowadays gathered the interest of the spectroscopic community due to a combination of high-simplicity and performance that is unmatched by any other comb generation method [1–4]. Unlike traditional comb sources, EO comb generation is based on the strong non-linear modulation of the intensity and/or the phase of the monochromatic optical signal of a continuous-wave laser [5]. Hence, by taking advantage of external electro-optic modulators (EOM), two combs (sensing comb and local oscillator comb) with very high mutual coherence (and slightly different repetition rates) can be obtained from the same optical carrier [6,7]. This DC generation approach provides an optical resolution (repetition frequency), only limited by the linewidth of the comb modes, that can be very easily controlled, with absolute flexibility, simply by adjusting the frequency of the RF signals driving the EOMs. Therefore, the difference between the repetition rates of the sensing and local oscillator combs can be made very small, squeezing in this way the whole span of the optical sensing comb into a very narrow RF bandwidth [8,9]. This reduced RF bandwidth (very often a few MHz of bandwidth centered at a frequency well below 100 MHz) enables acquisition rates for the digitization of the RF comb that are orders of magnitude below those required by basically any other dual-comb generation method, and this makes possible not only high-speed measurement rates, but also uninterrupted real-time operation at a low computational cost. Besides this, and because of the use of phase locked signal generators for driving all the modulators employed in these set-ups, the teeth of the RF comb are highly coherent with the reference clock signal (integration times of up to two hours have been demonstrated on a EO DC set-up with a simple stabilization loop) [8]. Therefore, the RF beat notes can be synchronously digitized in a straightforward manner reducing even more the computational load required for amplitude and phase information extraction.

Regarding the optical span of EO comb generators, even though several groups have focused their efforts on comb expansion (using step-recovery diodes for driving the EOMs [10], to systems based on multi-stage modulator arrangements [11] or spectral broadening methods based on nonlinear optical fibers that produce octave spanning comb sources [12]), to our knowledge, no work has been published yet for providing a precise control over the number of optical modes generated. Thus, as the adjustment of the optical resolution of EO combs (repetition frequency) is straightforward, the control of the number of optical modes may enable the generation of comb sources with the unique capability of a complete adaptability to the targeted spectral feature/s.

The approach proposed in this letter for the dynamic control of the number of teeth generated on an EO comb (with a single-phase-modulator arrangement) is based on probing the close correspondence between the proposed analytical model for the calculation of the modes generated on a comb and the actual experimental results. Hence, any of the characteristics of a comb calculated on a simulation, can be replicated on an experimental scenario. Besides this, and in order to improve the accuracy in the management of the number of lines, the use of a RF multi-harmonic driving signal for the phase modulator is proposed. In consequence, the method enables the maximization and control, at a very low implementation cost and a limited RF bandwidth, of the optical coverage of EO DC instruments. This approach keeps the optical design of the instrument as simple as it can be (shifting the complexity to the electronic domain), a very important point to consider in order to carry out the highly desired transition of DC-based systems from the laboratory to the field.

II. FULLY ADAPTABLE COMB GENERATION

The scheme proposed for adaptable EO comb generation is based on driving the phase modulator that produces the comb with a RF multi-harmonic signal consisting on a combination of the fundamental modulation frequency and a given number of higher harmonics, this constrain is necessary for facilitating

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the electronic implementation. The distribution of the amplitudes of the various harmonics for a desired comb configuration is obtained through a very simple numerical simulation (presented below), that enables real-time comb control. Latter in this letter, we demonstrate that the results of the simulations present a very high correlation with experimental measurements.

As presented above, in order to find the combination of harmonics and their amplitudes that are necessary for the generation of any desired number of modes, a straightforward numerical model is proposed. The behavior of phase modulators is modeled in this study using a Matlab (MathWorks Inc, Massachusetts, USA) program in which the laser is assumed to be monochromatic, Eq. 1, being E the optical electric field, E_0 the amplitude and ω_c the optical frequency:

$$E = E_0 \sin\left(\omega_c t\right) \tag{1}$$

When this light source is modulated by a phase modulator, the optical signal can be described by Eq. 2:

$$E = \gamma E_0 \sin\left(\omega_c t + \Delta\varphi\right) \tag{2}$$

where γ represent the losses in the modulator and $\Delta\varphi$ the instantaneous phase:

$$\Delta\varphi = \beta \sum_{i=1}^{n} A_i \sin\left(i\omega_m t\right) \tag{3}$$

being

$$\beta = \pi \frac{V_m}{V_\pi} \tag{4}$$

ω_m is the modulation frequency (equal to the repetition frequency of the optical frequency comb), i represent the number of the harmonic, n the maximum number of harmonics, β the modulation index, V_m the modulation voltage and V_π the half-wave voltage of the modulator.

As said before, and as an easy electronic generation (and with a reduced RF bandwidth) of the modulation signals is highly desired in order to keep a low complexity in the set-ups, the driving signals evaluated in this manuscript have been restricted to combinations of the fundamental modulation frequency and a limited set of higher harmonics (Eq. (3)). Therefore, experimental signal generation can be performed not only by digital signal synthesizers but also by an array of (analog or digital) locked oscillators or even by frequency multipliers.

With the main aim of showing the potential of using an analytical model for comb simulation together with a multi-harmonic excitation signal, on the example that is presented below, the combination of harmonics that provide the highest possible number of modes for various modulation indexes within a 20dB intensity range are calculated. We could, nonetheless, run different simulations aiming for the generation of any given number of teeth within a specified optical intensity level using the lowest possible β in order to optimize the efficiency of the system.

In the example the total number of harmonics has been successively restricted to 3, 5 and 7 for different modulation indexes. In each test the normalized (for an appropriate control over the modulation index β) peak amplitudes of the harmonics that deliver the maximum number of teeth in the comb are obtained by an algorithm that inputs all possible harmonic mixes and finds the absolute maximum. The results are shown in Tables 1-2 for β equal to 2 and 6 respectively.

	Sine	3 harmonics	5 harmonics	7 harmonics
A_1	1	0.39	0	0.37
A_2	0	0	0	0
A_3	0	0.79	0.46	0
A_4	0	-	0	0
A_5	0	-	0.61	0.37
A_6	0	-	-	0
A_7	0	-	-	0.56
Number of optical modes	11	25	37	47
Optical span enhancement	0 %	227 %	336 %	427 %

Table 1. Optimum amplitudes of the harmonics for β=2

	Sine	3 harmonics	5 harmonics	7 harmonics
A_1	1	0.17	0	0
A_2	-	0	0	0
A_3	-	0.91	0.17	0
A_4	-	-	0	0
A_5	-	-	0.86	0.30
A_6	-	-	-	0
A_7	-	-	-	0.73
Number of optical modes	21	63	103	131
Optical span enhancement	0 %	300 %	490 %	623 %

Table 2. Optimum amplitudes of the harmonics for β=6

The number of modes obtained in each case and the factors of enhancement with respect to a single sinusoidal drive signal are also provided. As shown in Table 1, the number of modes generated by the phase modulator for β = 2 increases from 11 for the sinusoidal modulation signal, to the 25 teeth generated by a combination of the first three harmonics. Even though this increment on the number of modes with the increase in the number of harmonics might seem clearly expected and unimportant, it is not trivial that those 25 modes can only be obtained, as predicted by the simulation, by the combination of the first and third harmonics with the exact amplitudes showed on Table 1. Any other combination (encompassing those that include the second harmonic) will result on a smaller number of lines of the EO comb (a good experimental example of this point is shown at the end of the next section). Something similar occurs for the five harmonics limit, generating 37 modes, also for amplitudes of the second and forth harmonics equal to zero and the seven harmonics limit, that represents a more than fourfold increase in the optical span of the comb.

As expected, a higher beta value produces a boost in the number of modes generated, hence, the results from Table 2 ($\beta = 6$) show a higher mode count that in the previous case. A very interesting fact also shows up in this second simulation, as it is that, independently of the limit, the optimum number of harmonics to combine in order to get the maximum possible spectral coverage is two in every case. The factors of enhancement are also higher showing the potential of this approach for comb control and coverage enhancement when higher RF powers are available (an increase in the spectral coverage of the comb superior to a sixfold can be obtained, generating a number of modes similar to that of FP QCLs [13] while maintaining a reduced beta value that ensures low power consumption and high efficiency).

III. EXPERIMENTAL RESULTS

The simulations previously presented have been compared to experimental measurements to test the validity of the model. Hence, the combinations of harmonics obtained by the algorithm were experimentally tested using the set-up shown in Fig. 1 (described in detail in Ref. [2]), that consists on the simplest EO DC set-up (the DC allows the direct mapping of the OFCs generated to the RF domain enabling therefore the visualization of the combs even for optical resolutions that are not reachable for commercial optical spectrum analyzers). The two phase modulators were driven with the same combination of harmonics but at a slightly different repetition frequency in order to map the optical teeth profile of the sensing comb into the RF domain. An acousto-optic modulator is also included in order to avoid mode averaging [8].

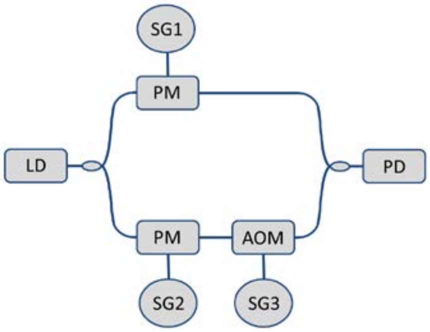

Fig. 1. Scheme of the dual-comb set-up employed in the experimental validation [2]. LD, Laser diode (widely tunable lasers can be equally employed); PM, Electro-optic phase modulator; AOM, Acousto-optic modulator; SG, Signal generator; PD, Photodetector.

The set-up was implemented as described in Ref. [2]. For the generation of the multi-harmonic RF driving signals a two-channels DG4162 (RIGOL Technologies, Inc., Beijing, China) signal synthesizer was used. The multiheterodyne signal was digitized by a 14-bit acquisition board (PDA14, Signatec Inc., California, USA) and processed with a LabVIEW (National Instruments Corp., Texas, USA) program for spectral analysis.

The numbers of modes on the combs that were experimentally generated for the different combinations of harmonics (adding additional data for β equal to 1) are presented in Table 3 together with the results of the simulations. These values are also represented in Fig. 2 for a rapid comparison.

		Sine	3 harmonics	5 harmonics	7 harmonics
$\beta = 1$	Simulation	7	13	17	21
	Experim.	8	14	16	20
$\beta = 2$	Simulation	11	25	37	47
	Experim.	10	28	35	47
$\beta = 6$	Simulation	21	63	103	131
	Experim.	23	68	95	129

Table 3. Number of modes obtained in the simulation and in the experimental validation

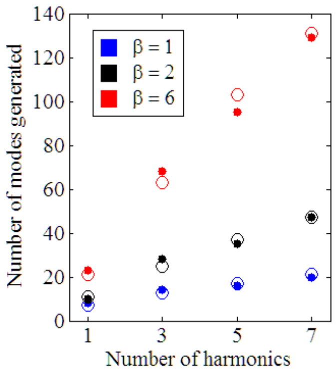

Fig. 2. Comparison between the results from the simulations (circles) and the results obtained in the experimental validation (dots) for β = 1, 2 and 6, number of modes within the 20 dB amplitude range.

The close relationship between the number of modes obtained by the numerical model for comb generation and the experimental results is clear, with a mean accuracy error of roughly two optical modes. The very high correlation between the number of teeth calculated by the model and those that were experimentally obtained confirms the feasibility of predicting, and hence controlling, the number of modes generated on an EO comb just by using the simple simulation model presented on Section II. The use a multi-harmonic driving signals also enables a better control (than that reachable by power control) and the enhancement on the spectral coverage of the generators for a constant level of RF power.

If we focus now on the limitations of the model, those are mainly related to high RF power levels. For high power signals driving the modulators it is necessary to include in the simulation many other parameters of influence, as non-linear effects on power amplifiers or other elements on the RF signal path, that have not been taken yet into account at this point and that ultimately affect the accuracy of the predictions.

Finally, and to better illustrate the capabilities of the numerical simulation with a multi-harmonic excitation signal, the spectra of the RF combs experimentally obtained using the set-up from Fig. 1 for β = 2 for different driving signals (a sinusoidal signal, three harmonics with equal amplitude and three harmonics with an amplitude distribution provided by the simulations) are shown in Fig. 3. It is thus possible to see that, by using three harmonics of the fundamental repetition frequency with equal amplitude, the number of usable modes increases only from 10 to 15. Nonetheless, when those amplitudes are properly adjusted, according to the data provided by the numerical simulations, the number of lines increases to 28, multiplying by two the spectral coverage of the optical comb. The number of modes can be doubled again by increasing the maximum frequency of the harmonics to 7f and multiplied by a factor higher than four by also increasing the amplitude of the modulating signals to a β value equal to 6.

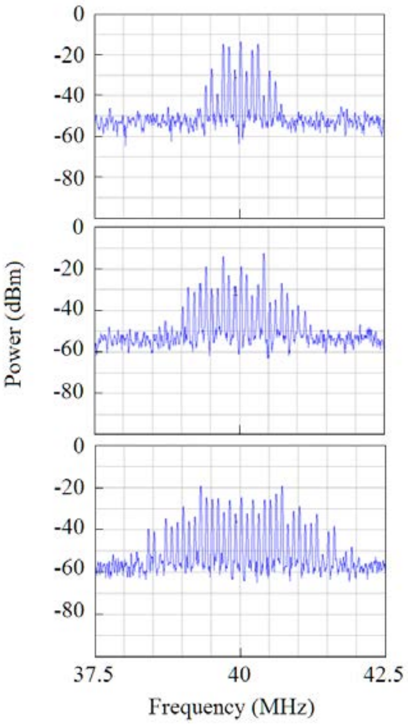

Fig. 3. Spectra of the RF combs experimentally obtained for β = 2 for a sinusoidal driving signal (top), for three harmonics with equal amplitude (center) and for three harmonics with an amplitude distribution calculated on a simulation for maximum coverage enhancement (bottom). An example with a low number of lines has been chosen for clarity.

IV. CONCLUSIONS

New EO DC architectures have generated great interest by providing high performance, high optical resolution and fast spectroscopic measurement rates at a reduced cost, a combination that could bridge the gap of finally bringing DC set-ups to the field. Simple optical architectures are therefore highly desirable in order to ensure the low optical component count that provides reduced cost, stability, robustness and high reliability. In this letter, a novel all-electronic method for a fully adaptable control on the number of lines of a comb, based on driving the modulators by a combination of harmonics of the fundamental modulation signal calculated using a simple numerical simulation, has been presented and experimentally validated. The high correspondence demonstrated between simulations and actual results enables the dynamic calculation, and hence selection, of the number of teeth generated on a comb. This provides an unprecedented control of the balance between SNR and spectral coverage on DC spectrometers. This capability of fully adapting the spectral shape of the comb to the application is in clear contrast to the limitations of other comb generation methods for controlling the number of teeth and the spacing between them.

Besides this, and if a different goal is programed on the simulations, other features of the optical comb, as the flatness, the symmetry or the line intensity within a spectral range, could also be dynamically controlled.

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