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Expansion of VCSEL-based optical frequency combs in the sub-THz span: comparison of non-linear techniques

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***Abstract*—In this work we detail our experimental study on the expansion of Vertical-Cavity Surface-Emitting Laser (VCSEL) Optical Frequency Combs (OFCs) with different non-linear techniques. For this purpose, we modulate a VCSEL device under Gain Switching (GS) regime to obtain an initial seed comb record in terms of energy efficiency and mode coherence. This seed OFC will be improved adding a non-linear stage to expand this primary signal. The non-linear techniques here presented are High Non Linear Fibers (HNLF), Non Linear Optical Loop Mirrors (NOLM) and Electro optical (EO) Phase Modulators (PM). In this work, we show the different extended OFCs that these techniques offer and we present a detailed comparison of their characteristics, evaluating the advantages and disadvantages of each technique. We have observed that the obtained OFCs maintain the high coherence offered by the seed VCSEL-OFC. Nevertheless, the optical span, flatness, frequency tunability, dynamic range, energy and cost efficiency or compactness of each expanded OFC significantly vary, depending on the expansion technique used. Our careful evaluation will serve as a reference to evaluate the suitability of each expansion technique depending on the needs or the application.**

***Index Terms*— Gain Switching, Laser Diodes, Optical Frequency Comb, Vertical-Cavity Surface-Emitting Laser, Energy Efficiency, Non Linear Optical Loop Mirror, Highly Non Linear Fiber, Electro-Optical Components, Phase Modulator**

I. INTRODUCTION

Optical Frequency Combs (OFC) are very attractive and versatile systems that have recently found application in a large variety of disciplines like THz generation, spectroscopy, optical communications, metrology or microwave photonics [1]–[6]. Femtosecond mode-locking lasers or fiber lasers are typical bench-top schemes used to generate high quality wide span optical combs [7]. However, compact systems would be desirable to reduce the complexity, the cost and the energy consumption. An OFC source with these characteristics would widen even further the range of applications and would surely help to bring technologies such as THz generation, dual-comb spectroscopy [4] or optical processing [8] out of the laboratory. In this sense, the implementation of OFC in a single device using Mode-Locking Laser Diodes (MLLD) is one of the possibilities. MLLD have been extensively studied during the last decades [9]. However, they require specially designed structures that still today do not offer repeatability in the manufacturing processes. Another approach is the use of microresonators [10]. These promising devices are able to generate extremely wide OFCs with high repetition frequencies, but are still very new and the excitation of their resonant cavity requires high power and set-ups with several stages.

A straightforward alternative arises here, Gain Switching (GS). Some recent works have recovered this well-known technique to implement multi-GHz OFC for various applications [11] [3]. GS is based on the deep modulation of the gain medium of a semiconductor laser to induce a pulsed regime of operation. Although the resulting OFCs achieve much less optical span than MLLDs or microresonators, GS OFCs offer wide frequency tunability range, high correlation between optical modes, compactness and low-cost, as they can be implemented using any commercial semiconductor laser diode (LD) technology.

One of the LD technologies most appealing for this comb generation are Vertical-Cavity Surface-Emitting Lasers (VCSELs) [12]–[14]. High quality OFCs with record optical span and cost and energy efficiency [10] have been reported using such laser technology and Gain Switching (GS) modulation. However, further research efforts have to be taken in the study of combs based on VCSELs under GS (VCSEL-OFCs), especially on the improvement of their optical span while maintaining the mode coherence and the low power consumption of the system. Such combs will find application in

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fields like THz generation or green optical communications [15], [17].

In this work, we present new results on our study of VCSEL-based GS-OFCs focused on the expansion of the optical span they can offer. We implement and compare different comb expansion schemes based on non-linear elements: Highly Non Linear Optical Fibers (HNLF), Non-linear Optical Loop Mirrors (NOLM) and Electro-optical (EO) Phase Modulators (PM). All these components exploit non-linear optic effects to accomplish the improvement of the initial VCSEL-OFC. HNLF are optical fibers that exhibit a high nonlinear refractive index and help generate new frequencies mainly due to Self Phase Modulation (SPM) and Four Wave Mixing (FWM) when the optical power is high enough [18]. On the other hand NOLMs are optical loops based on fiber Sagnac interferometers. Inside the loop, the optical signals travelling clockwise and counter clockwise suffer differently the nonlinear effects and both signals interfere with different phases [19]. HNLF and NOLM are often used as building blocks of larger comb generation schemes known as parametric mixers. Parametric mixers have demonstrated ultra-wide optical combs (above 10THz) [20]. They are based on the concatenation of numerous nonlinear optical stages to optimize the generation of new frequencies from an initial dual optical source. Finally, the use of EO modulators in cascade configuration is one of the most commonly used technique for comb generation and/or expansion [21], [6], especially for high repetition rates above the modulation bandwidth of the laser source under use. Optical combs that cover above 3THz have been reported with EO modulators. Based on these approaches, we have designed three different schemes to increase the span of an initial VCSEL-OFC while maintaining the coherence between the comb lines. In order to undergo a fair comparison, all of them offer expansion ratios close to 3 times.

In section II, we present each of these expansion techniques and the OFCs experimentally obtained with them. Then, in section III, we present a detailed comparison and the features of the different resulting combs showing the main advantages and disadvantages of each expansion scheme.

II. EXPERIMENTAL STUDY ON OPTICAL FREQUENCY COMB EXPANSION

In Fig. 1 we can see the initial comb to be expanded using several techniques. This seed comb is the Vertical-Cavity Surface-Emitting Laser (VCSEL) output spectrum under Gain Switching regime. This laser diode is a state of the technology fiber coupled 1550nm manufactured by VCSEL (VERTILAS VL-1550-8G-P2-H4) that is stabilized at 20ºC and biased at Ibias/Ith = 1.04. The VCSEL is modulated at 5.2 GHz with a 16 dBm RF signal (modulation depth of $I_{RF}/I_{bias} = 2.5$). Under these conditions we generate the broadest Optical Frequency Comb (OFC) [10] with 27 teeth in the 20dB span, which corresponds to 135GHz total bandwidth. An optical isolator is placed at the output of the VCSEL to avoid any optical feedback. We have given more details in this VCSEL device and its Continuous Wave (CW) and GS operation [15].

In the following sections we study and compare different expansion techniques taking several measurements of the resulting OFCs: the optical spectra, the RF beating of the OFC and the temporal autocorrelation traces (ACT). It is worth mentioning that an Erbium Dopped Fiber Amplifier (EDFA) is introduced for some RF beating measurements in order to equalize the received electrical power. Regarding the AC traces, as they exhibit a complex structure, typical of the GS technique, they have been analysed using time retrieval algorithms and root-mean square time-bandwidth metrics[22].

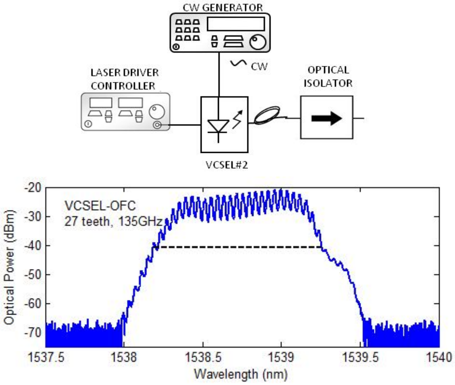

Fig. 1 Top: Setup used for the VCSEL-OFC and the resulting seed comb. Bottom: VCSEL output under Gain Switching obtained at 20 ºC, Ibias/Ith = 1.04, 5GHz, 16dBm. The VCSEL-OFC has 27 teeth in the 20dB span which corresponds to 135GHz. See text for more details.

In the following sections A, B and C, we present the three different schemes to expand this VCSEL-OFC. In order to offer a fair comparison among the techniques under study, we have considered implementations that offer similar output optical 20dB spans. Each expansion stage is formed by all the optical elements found after the output of the initial VCSEL-OFC. For the HNLF and the NOLM configurations, basic initial simulations based on rate equations and nonlinear Schrodinger equation (NLSE) [22] were carried out. This gave an estimation of the linear compression and amplification needs, as well as the configuration of the nonlinear elements to achieve an expansion ratio close to 3. Then, further experimental adjustments led to the final implementations presented here.

A. Comb expansion with non-linear fiber: HNLF-OFC

The first method described in this work to expand the VCSEL-OFC consists in the use of a Highly Non-Linear Fiber (HNLF). This scheme mainly exploits the enhanced Self Phase Modulation Effect (SPM) [23] exhibited by HNLF fibers and has been commonly used for comb expansion and broadband signal generation [6], [24], [25]. The expansion scheme is formed by two sub-stages. Prior to the nonlinear expansion itself, we find the first sub-stage where we condition the optical signal including a Dispersion Compensating Fiber (DCF) and an EDFA. With the DCF we linearly compress the pulses from the VCSEL-OFC as they are chirped because of the GS regime

[26]. This DCF fiber has a dispersion of -1318ps/nm, and a length of 1100m. Then the EDFA increases the optical power up to 22dBm (mean power) before the HNLF which is an optimum trade-off output power vs. noise floor. This sub-stage experimentally reduces the optical pulse duration (Full Width Half Maximum, FWHM) from 14.4ps to 6.07ps but does not influence the optical spectra. Finally, the HNLF is a 200m patch with a non-linear coefficient of $\gamma = 11$ $(W{\cdot}km)^{-1}$. The broadest comb has been obtained with the VCSEL biased at $I_{bias}/I_{th} = 1.2$, while the rest of the parameters are the values previously mentioned. This expansion scheme is shown in Fig. 2.

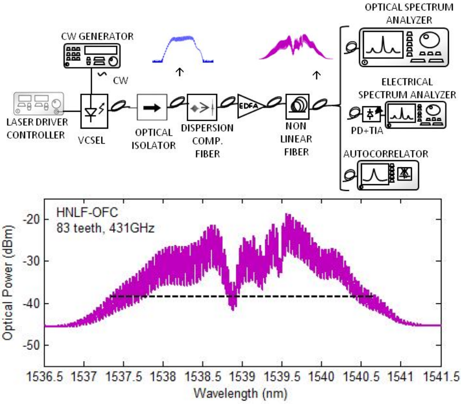

Fig. 2 Top: Setup used for the HNLF-OFC and the resulting comb. In the picture we can see the VCSEL which is first compressed with a DCF, secondly amplified with an EDFA and then broadened with a HNLF. The HNLF-OFC (pink trace), has 83 teeth in the 20dB span which corresponds to 431GHz. See text for more details.

This technique expands the VCSEL-OFC from 27 to 83 teeth, which corresponds to an expansion factor of 3.07 and 431GHz (20dB span). The resulting HNLF-OFC is not flat, especially in the area between 1538.5nm and 1539.5nm with a flatness factor is 0.12 (more details in Section III). The optical noise level has now increased to -45dBm having a dynamic range of 25.3dB. We believe that this degradation is likely to be related to the amplified spontaneous emission noise (ASE) of the EDFA amplifier. We experimentally found that any further increase in the optical gain of the EDFA would cause a dramatic growth of the noise floor without any further expansion of the OFC. However, this is a simple way to obtain broad combs with moderate energy consumption.

B. *Comb expansion with NOLM: NOLM-OFC*

Non-linear Optical Loop Mirrors (NOLM) are commonly used for pulse compression and reshaping, comb filtering, switching or multiplexing optical signals [22], [27], [28]. In this section, we propose this technique to expand the comb, therefore focusing on the spectral broadening achieved. These systems are basically nonlinear fiber Sagnac interferometers based on SPM [19]. Several set-ups have been tested for this work and our final loop includes a Semiconductor Optical Amplifier (SOA) as non-linear element inserted into the loop [22]. These systems are also called Non-linear Amplifier Loop Mirrors (NALM) [29]. SOAs devices are interesting here due to their strong non-linear operation, low power consumption and small size [18], [30].

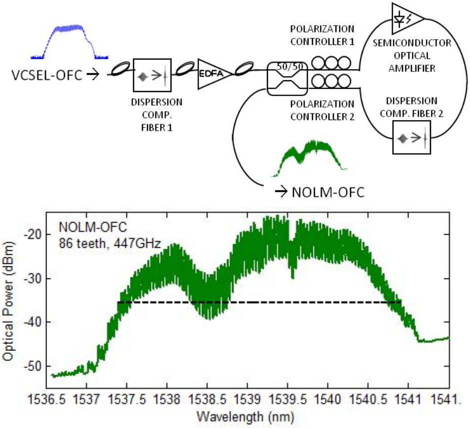

Fig. 3 Top: Setup used for the NOLM-OFC and the resulting comb. The VCSEL-OFC is first compressed and then amplified with a DCF and an EDFA. The NOLM "door" is a 50/50 coupler and it has inside a SOA another DCF and two polarization controllers. Bottom: The NOLM-OFC (green trace), has 86 teeth in the 20dB span which corresponds to 447GHz. See text for more details

The set-up used for this comb expansion based on a NOLM is depicted in Fig. 3. In order to maximize its performance, we included a sub-stage before the 50/50 coupler, at the entrance of the loop. At this sub-stage, the light signal is conformed using a DCF and an EDFA. The DCF is 600m long and it compresses the light pulse right before the EDFA (14.4ps to 6.07ps FWHM) so the peak power at the EDFA output is optimized. The output power of the EDFA in this set-up is 32dBm. Higher powers cannot be applied because of operational limits for the SOA. Another DCF fiber with the same characteristics is placed inside the loop with the SOA (QPhotonics QSOA-1550), and the best result has been obtained when this DCF has a length of 500m and the SOA is biased with 396mA. The set-up also includes two polarization controllers to match the clockwise and counter clockwise pulses making them interact in the way that we obtain the highest pulse compression and therefore, the comb broadening is optimized. In order to improve the NOLM-OFC, the bias current of the VCSEL has been changed to $I_{bias}/I_{th} = 1.2$ and the RF frequency is 5.2GHz.

The output comb has a 20dB span of 447GHz which corresponds to 86 teeth and an expansion factor of 3.18. We can see that the noise floor has been increased to -45dBm so the dynamic range at this point is 32dB and the flatness has been worsened too, presenting a flatness factor of 0.28. However, a significant amount of power is needed from the EDFA to achieve an expansion factor close to 3.

C. Comb expansion with EO Modulators: EO-OFC

Apart from direct comb generation, like GS regime, in which the comb is generated inside the laser cavity, there exist indirect techniques in which the comb is generated with the laser working in CW operation and using external non-linear elements, typically Electro Optical (EO) modulators. This is the most common technique for comb generation and expansion, and has been deeply studied in previous works, using different amount of both Intensity Modulators (IM) and Phase Modulators (PM) [6], [21], [25]. EO modulators allow comb generation with high and tunable teeth spacing independently of the laser source used. Several of these modulators can be cascaded to broaden the comb about two times per modulator. These schemes generate very flat and tunable combs but, at the same time, the set-up is relatively complex to adjust specially the RF part. This fact together with the high cost and the energy consumption of the modulators are the main drawbacks of this technique.

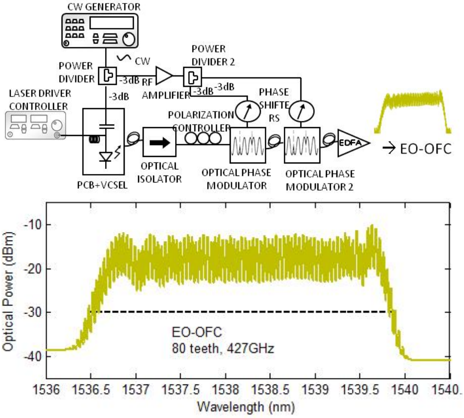

Fig. 4 Top: set-up used for the EO-OFC and the resulting comb. The VCSEL-OFC is broadened with two phase modulators in cascade. The RF signal is amplified and matched with the use of one amplifier and two phase shifters. Bottom: the EO-OFC (yellow trace), has 80 teeth in the 20dB span which corresponds to 427GHz. The VCSEL supply parameters are 20 ºC, 11.4mA, 5.3GHz, 16dBm. The RF injected into the modulators is 35dBm and the EDFA has an output power of 12.5dBm.

In one of our previous works [31], we have combined both the direct GS modulation to generate the comb and the indirect EO modulators (two PMs in cascade) to expand it afterwards obtaining a comb of 272GHz (53 teeth) in the 20dB span. Now we are using a similar set-up with modulators showing higher performance. They have ultra-low V_{pi} and wider modulation bandwidth. The output of the laser under GS (VCSEL-OFC in Fig. 1) enters two PMs with V_{pi} <3.3V placed in cascade configuration. The RF signals driving them are first amplified and after that, phase matched using Phase Shifters (PS) so the expansion is optimized. Finally, the output signal is amplified in the EDFA to increase the signal level to 12.5dBm. It is important to notice that this EDFA is not necessary in the set-up to expand the comb like in the previous schemes, but to increase the signal to a similar power level compared to the previous optical combs. This set-up is shown in Fig. 4. EO schemes typically include intensity modulators (IM) to improve the flatness of the resulting comb. However, when the GS technique is used, the flatness is optimum and no extra modulator is needed, reducing the cost and size of the OFC.

With this technique that combines GS and high performance EO modulators we have expanded the comb a factor 2.96 which means 80 teeth in the 20dB span, so 427GHz broad taking into account that the RF signal is set at 5.3GHz. This comb exhibits a high flatness factor of 0.87; and a dynamic range of 28.8dB. This value was measured after the levelling EDFA. Without it, the dynamic range slightly increases to 31dB. On the other hand, this set-up is the costliest of the ones presented here and requires more complicated adjustments (more details in Section III).

III. OPTICAL FREQUENCY COMBS COMPARISON

In the previous sections we have presented different configurations for comb expansion based on different non-linear processing techniques. All of them allow us to increase the comb span about three times compared to the bandwidth obtained with the sole VCSEL under GS regime. However, each of these schemes has different potentials and weaknesses and this might determine their use in certain applications. In this section we are comparing different features of the resulting combs and each set-up, analyzing their advantages and disadvantage. The factors here analyzed are summarized in TABLE I. In Fig. 5 we can see a comparison of the different combs with the same ranges of wavelengths and optical powers.

Comb expansion factor: Along this work we use the 20dB span to measure the broadness of the comb, as we have done in our previous works because it is the useful span in applications like photonic THz generation [3]. NOLM-OFC provides the broadest comb. In this work we have defined the expansion factor as the coefficient between the comb teeth in the output comb and the comb teeth in the VCSEL-OFC. This factor is, as we see in TABLE I 3.00, 3.07 and 3.18 for the EO-OFC (the narrowest), the HNLF-OFC and the NOLM-OFC (the broadest) respectively.

Flatness: The flatness is an important parameter for many applications. In this work we have defined the flatness factor as the coefficient between the comb teeth in the 3dB and the 20dB spans. The flatness in VCSEL-OFC is 0.77 which is quite good but is even improved with the EO-OFC set-up with a flatness factor of 0.87. This EO-OFC provides much flatter combs in comparison to the other methodologies. On the other hand, NOLM-OFC has a flatness factor of 0.28 and HNLF-OFC presents the lowest flatness, with a factor of 0.12.

Pulse quality: We have also evaluated the properties of the temporal pulses associated to each expansion configuration measuring their background-free autocorrelation traces (ACT). The resulting traces (Fig. 6) are complex and exhibit different shapes with pedestals. This is typical of the GS technique and such traces have to be analysed using time retrieval algorithms

[22] and evaluated using metrics such as the root mean square (*rms*) Time Bandwidth Product: $TBP_{rms} = \omega_{rms} \cdot \tau_{rms}$, where ω_{rms} is the *rms* width of the optical spectra and τ_{rms} is the *rms* pulse width. Regardless of the pulse shape or spectral structure, the fundamental limit of TBP_{rms} is 0.5 [32]. The use of the *rms* metric permits the comparison among pulses and spectra that do not exhibit the same profile. The results are shown in TABLE I and summarized in figure 6. The EO-OFC configuration is the one offering pulses with slightly better characteristics ($TBP_{rms} = 7.2$). However, all the configurations behave in a similar way and significantly increase the dispersion of the initial optical pulses. These dispersed pulses could be further compressed to their TBP_{rms} limit using linear compression techniques.

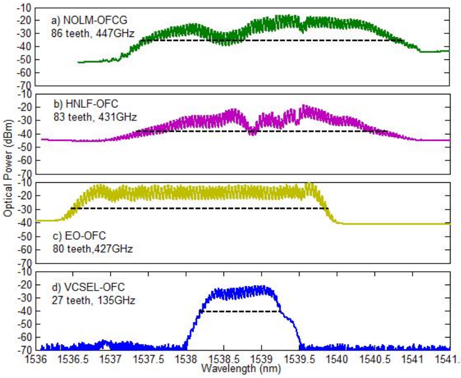

Fig. 5 Optical Spectra comparison. a)NOLM-OFC (green trace) with 86 teeth/447GHz. b)HNLF-OFC (pink trace) with 83 teeth/431GHz. c) EO-OFC (yellow trace) with 80 teeth/427GHz. d) VCSEL-OFC (blue line) with 27 teeth/135GHz. All these OFCs are presented with the same optical power and wavelenght ranges for an easier comparison. The 20dB span is marked with a dotted black line.

Frequency spacing tunability: All these expansion techniques admit the tuning of the spacing between comb teeth. For this purpose, we first need to adjust to its new value the RF frequency that modulates the VCSEL. After this, some adjustments of the set-up are needed depending on the scheme used for the comb expansion. For the HNLF-OFC, no extra adjustment is needed. This is the most direct set-up to change the distance between comb teeth. The NOLM-OFC needs some equalization of the optical paths inside the loop and therefore the Polarization Controllers (PC) in order to maintain the optical span as high as possible. The most complicated set-up to change the comb spacing is the EO-OFC: it needs optical adjustment of the polarization in the PC placed before the first PM but also RF readjustment in both Phase Shifters. Regarding the VCSEL-OFC, a change in the frequency spacing slightly affects the optical span and the flatness as long as it remains within the VCSEL electronic modulation bandwidth (more details in [33]).

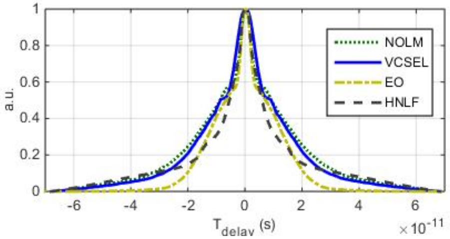

Fig. 6 Autocorrelation traces (ACTs). Solid: VCSEL-OFC ACT with TBPrms = 3. Slash: HNLF-OFC ACT with TBPrms = 10. Dot: NOLM-OFC ACT with TBPrms = 8.8. Slash/Dot: EO-OFC trace with TBPrms = 7.2

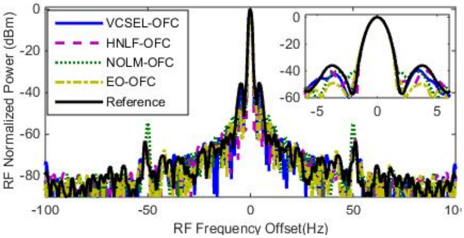

Fig. 7 RF Linewidth for the different combs in Fig. 5: VCSEL-OFC (blue line), HNLF-OFC (pink line), NOLM-OFC (green line), EO-OFC (yellow line) and Reference: linewidth of the RF CW signal used to induce GS (black line). In the inset we plot a zoom obtained with the lower Resolution Bandwidth available in the ESA used. Resolution bandwidth and video bandwidth were set to 1Hz. These measurements are limited by the equipment capabilities. See text for more details. Side-peaks at 50Hz are spurious coming from the Reference.

Optical dynamic range (DR): The inclusion of new elements along the path implies some losses in the DR, which has been measured in this work as the difference between the peak power in the highest comb tooth and the noise level. In our set-ups the DR is reduced from 50dB in the VCSEL-OFC to 25.3, 28.8 and 32dB for the HNLF-OFC, EO-OFC and NOLM-OFC respectively. NOLM-OFC is therefore, the most resistant scheme to the noise. This is consistent with the nonlinear interferometric nature of the NOLM, that filters out low power signal components and hence, reduces noise [34].

Electrical linewidth: The electrical beat tone signal at f_{RF} allows us to evaluate the phase coherence between comb teeth. In this work, we measure the 3dB linewidth of that signal at f_{RF} after the detection of the whole comb in a fast photodiode and compare it to the linewidth of the reference, which is the RF source that modulates the VCSEL-OFC under GS. The measurements were performed using a resolution bandwidth of 1Hz, the minimum offered by the ESA. In Fig. 7, we see that all the comb expansion schemes present an electrical beat tone with a linewidth equal to 1Hz, the resolution limit of the equipment. This implies that every set-up provides a comb with an extremely high coherence between teeth, inherited from the VCSEL-OFC due to GS modulation.

Installation and start sequence: Another important aspect to consider when selecting the expansion scheme is the complexity when installing the set-up and the need of readjustments after operation. HNLF-OFC is the simplest scheme and the only parameter to be adjusted during turn-on is the output power in the EDFA. NOLM-OFC needs some other adjustments besides the EDFA output power: the polarization needs to be adjusted with the PCs inside the loop. This optical path needs some fine-tuning also each time the set-up is ignited. Lastly, EO-OFC is the most complex set-up to be installed as both, optical and electrical components, need to be tuned: the optical polarization at the entrance of the PM is optimized with the PC but also the RF phase shifters need a careful fine-tuning during installation and switching-on.

TABLE I
OPTICAL FREQUENCY COMBS MAIN FEATURES

	VCSEL-OFC	HNLF-OFC	NOLM-OFC	EO-OFC
Optical span @20dB	135GHz /27 teeth	431 GHz / 83 teeth	447GHz / 86 teeth	427 GHz / 80 teeth
Optical span @10dB	125GHz /24 teeth	296GHz /57 teeth	333GHz /64 teeth	403GHz /76 teeth
Optical span @3dB	105GHz /21 teeth	52GHz /10 teeth	125GHz /24 teeth	371GHz /70 teeth
Optical span @20dB (nm)	1.1	3.33	3.5	3.41
Expansion factor	1	3.07	3.18	2.96
TBPrms	3	10	8.8	7.2
Flatness factor	0.77	0.12	0.28	0.87
Dynamic range (dB)	50	25.3	37	28.8
Linewidth RF (3dB)	<1Hz	<1Hz	<1Hz	<1Hz
Energy consumption (W)	-	1.99W	8.12W	2.39W

Energy consumption: We have made an estimation of the energy consumption of each expansion technique by calculating the electrical power needed in the active elements that are included after the VCSEL-OFC. This is an important parameter when working in fields like green optical communications [17] or incorporating such schemes in actual systems. These elements are the EDFA in all the set-ups, the SOA in the NOLM-OFC and both PMs in the EO-OFC. The power in the EDFA has been computed with the laser current set in the device for each set-up and assuming a typical 980nm pump LD with a diode operating voltage of 1.7V [35]. The results are shown in TABLE I where we see that the NOLM-OFC consumes much more power than the other set-ups. This is mainly due to the high optical power needed at the output of the EDFA (32dBm) to achieve maximum expansion in the loop as this component consumes 7.47W by itself and the SOA needs 0.65W in this configuration. The EO-OFC consumes 1.13W in the EDFA and 1.26W in the two PMs, so this set-up has lower energy needs compared to the previous one. Finally the HNLF-OFC, in which the EDFA is the only active component, has the lowest energy needs, with 1.99W.

Component count and cost: HNLF-OFC is the set-up that needs lower number of components in the expansion stage, two fibers (one DCF and one HNLF) and the EDFA. NOLM-OFC is the one with larger (optical) component count as it includes, apart from all these components, another DCF, the coupler, one SOA and two PCs. However, the costliest set-up is EO-OFC as the electro-optical modulators are very specific and expensive components.

IV. CONCLUSIONS

In this work, we have presented out latest results in Optical Frequency Combs (OFCs) based on Vertical-Cavity Surface-Emitting Lasers (VCSELs) under Gain Switching (GS) regime. We have shown different expansion techniques that produce results of combs around 430GHz in the 20dB span, and them all maintain the high coherence offered by the seed VCSEL-OFC. All our set-ups have been implemented with off the shelf components and Laser Diodes (LDs) which allow us to obtain effective, efficient in cost and energy, and compact OFC systems. The use of VCSELs enhanced these factors and provides even wider combs while GS modulation allows us to tune the comb easily with no need of extra components obtaining a system that can be tailored for different applications. For all this reasons we find our VCSEL-based OFCs of significance, and that is why we focus our efforts in improving their capabilities.

Besides, in this work we have presented a thorough comparison of different expansion techniques applied to VCSEL-based OFCs showing that they stand out in different aspects. Therefore, we conclude that the expansion scheme needs to be tailored depending on each particular comb application if we want to optimize the result. For instance, the EO-OFC is the one that provides the flattest but the most complex and costliest scheme. On the other hand, the HNLF-OFC is the simplest, most energy efficient and cheapest comb but it depends on the laser source and the GS regime and the flatness is low. NOLM-OFC is a balanced option, with a high noise rejection and the broadest comb but depends on the source, exhibits low flatness and has a higher energy consumption. These differences will make each of these set-ups more or less interesting depending on each specific application, so the appropriate selection of the expansion technique will maximize the performance of a system that includes an OFC generation stage in it.

Our efforts continue in order to improve the broadness of the resulting combs and reach the 1THz 20dB span while maintaining the simplicity, compactness and energy consumption VCSEL-based combs offer.

V. ACKNOWLEDGMENTS

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