Serrano, A.R.C.; de Dios Fernandez, C.; Cano, E.P.; Ortsiefer, M.; Meissner, P.; Acedo, P., "VCSEL-Based Optical Frequency Combs: Toward Efficient Single-Device Comb Generation", *IEEe Photonics Technology Letters, (2013), 25(20),* 1981,1984.
DOI: http://dx.doi.org/10.1109/LPT.2013.2280700

VCSEL based Optical Frequency Combs: towards efficient single-device comb generation

A. R. Criado, C. de Dios, E. Prior, M. Ortsiefer, P. Meissner, and P. Acedo

***Abstract*— Optical Frequency Combs Generators (OFCGs) have demonstrated to be extremely useful tools in a wide variety of applications. The current research trends look towards compact devices able to offer high phase correlation between optical lines, and in this sense, Mode-Locked Laser diodes (MLLDs), with repetition frequencies in the few GHz range; and especially microresonators, with repetition frequencies of hundreds of GHz, are the most promising devices fulfilling these requirements. Nevertheless, focusing in the few GHz frequency rate, MLLDs cannot provide continuous tunability and require special devices that are still far from offering reliability and repeatability for commercial use. In this work we demonstrate for the first time the generation of a flat OFCG based on a single commercial Vertical Cavity Surface Emitting Laser (VCSEL) under Gain-Switching regime with 20 optical lines (spaced by 4.2GHz) in a 3-dB bandwidth, offering wide tunability range and very high phase correlation between optical modes. This OFCG does not need any external modulator and it is the most energy-efficient OFCG reported to date.**

***Index Terms*—Optical Frequency Comb, VCSEL, Gain Switching, energy efficiency.**

I. INTRODUCTION

OPTICAL Frequency Comb Generators (OFCGs) are versatile and powerful tools for a range of applications including metrology [1], spectroscopy [2], optical communications [3], THz generation [4], optical arbitrary waveform generation [5] or microwave photonic filters [6]. The desirable characteristics of an OFCG vary from one application to another, but compactness and high correlation between optical modes are becoming common place for most of them in the last years [7], [8]. In order to expand the fields of application for such a powerful optical tool, compact systems are needed to replace the typical bench top schemes. In this sense, implementation of OFCGs in a single device is desirable. This can be achieved from a pulsed optical source such as Mode-Locking Laser Diodes (MLLD) [7] or microresonators [8]. These devices can be divided according to their repetition frequency, being MLLDs in the order of several GHz, and microresonators in the order of few hundreds of GHz. Microresonators are recent and very promising devices able to generate extremely wide OFCGs, but their high repetition frequencies make them unsuitable for a significant number of applications[8]. On the other hand, MLLDs have been widely used during the last decades, but they still present important drawbacks, like the absence of continuous tunability of the repetition frequency and the need of specially designed structures that nowadays are still far from offering reliability and repeatability in the manufacturing processes for commercial purposes.

In this sense, some recent works have recovered a well-known technique for inducing pulsed operation in a semiconductor laser, Gain-Switching (GS), in order to implement multi-GHz OFCGs that are to overcome some of these drawbacks associated with MLLDs [4], [9]. Although they offer much less optical span than MLLDs, GS-based OFCGs offer wide tunability range, high correlation between optical modes, and low-cost; as they can be implemented using commercial semiconductor lasers. Nevertheless, if standard edge-emitting lasers are used, the amount of direct modulation power needed for an OFCG featuring 8-10 lines is about 0.5-1 W, which makes necessary the use of Radiofrequency (RF) power amplifiers [4], [10]. Moreover, the generated optical spectra are not flat, and additional stages based on nonlinear techniques and comprising several external components are usually needed to obtain flat-topped pulses, such as cascaded Intensity or Phase Electro-Optical Modulators (EOMs) [11–13] and Four Wave Mixing (FWM) [14].

For this reason, different types of semiconductor lasers have been used under GS regime in the search of compact, commercial devices based pulsed sources, and, Vertical Cavity Surface Emitting Lasers (VCSELs) are promising candidates [15–19]. VCSELs need very few current to operate (under 10 mA), and their integration capabilities as well as the capacity for on-chip testing allow for low cost optical subsystems with an excellent energy efficiency. Moreover, they have demonstrated wide wavelength tuning capabilities (in excess of 100 nm) with direct control of the cavity length using membranes [20]. In this sense, VCSELs would lead to the possibility of low-cost, widely wavelength-tunable and high power efficiency OFCGs.

Manuscript received May 30, 2013. The work by A. R. Criado has been supported by the Spanish Ministry of Science and Technology under the FPI Program, Grant# BES2010-030290.

Á. R. Criado, C. de Dios, E. Prior, and P. Acedo are with the Electronics Technology Department, Universidad Carlos III de Madrid of Leganes, Madrid 28911, Spain. (e-mail: acriado@ing.uc3m.es).

M. Ortsiefer is with Vertilas GmbH. Garching, Germany.

P. Meissner is with the Technische Universität Darmstadt. Darmstadt, Germany. During this work, he has been under the Chair of Excellence Programme, Electronics Technology Department, Universidad Carlos III de Madrid. Madrid, Spain.

In this work we demonstrate the ability of a single commercial VCSEL to implement a multi-GHz OFCG with a significant number of optical lines and with excellent flatness (20 optical lines in a 3 dB bandwidth) directly in a one stage scheme, without the necessity of other external components. It is also highly energy-efficient, as the bias current requirements are below 10 mA and the needed RF modulation power is around 15 dBm, well below the standard requirements for edge emitting lasers based systems using either GS or external EOMs, where modulation powers more than one order of magnitude are required[4]. Through the use of GS, the repetition frequency is widely tunable and the phase correlation between optical lines is very high, with a photodetected beat signal linewidth in the Hz-range[4]. Moreover, this OFCG has the potential for wide wavelength tunability exceeding 100 nm [20].

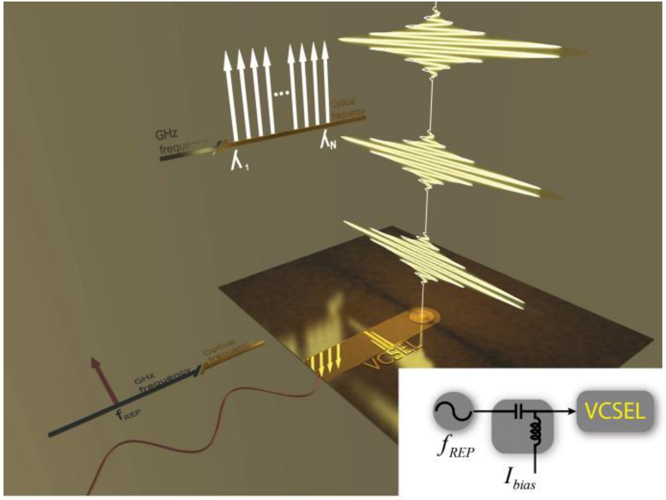

Fig. 1. A VCSEL is modulated in GS regime with a CW RF synthesizer. The optical output is directly an Optical Frequency Comb. Inset: Experimental setup.

II. EXPERIMENTAL RESULTS

In Fig. 1 we show the experimental setup employed. The OFCG encompasses only a commercial VCSEL (VERTILAS VL-1550-8G-P2-H4) modulated with a Continuous-Wave (CW) RF synthesizer and stabilized in current and temperature with a laser diode controller. The repetition frequency is 4.2 GHz, which corresponds to the resonant frequency of the passive matching network circuit implemented to modulate the VCSEL. The experimental characterization of the resulting OFCG is based on three steps. First, the number of optical lines generated and their flatness are measured as a function of the two control parameters of GS regime (bias current and modulation power). Second, the phase correlation between optical modes is evaluated. Third, the temporal pulse width is analyzed, as well as its quality in terms of Time-Bandwidth Product (TBP).

Fig. 2 shows the measured operational maps of the VCSEL under GS operation as a function of the bias current and the modulation power. In this figure the number of optical modes within a 3 dB (top) and 30 dB (bottom) bandwidths are shown. A record number of 20 lines for 3 dB bandwidth with only 9 mA bias current and 15 dBm RF input is achieved. This optical spectrum is shown in Fig. 3, where it can be noticed a minor asymmetry which is in well agreement with the expected behavior under this modulation regime [21]. It must be noted that the effective OSA resolution is about 2.12 GHz at 1550 nm, which is a value close to the repetition frequency employed. Because of this, the measured values of extinction ratio and flatness are not conclusive, and the actual values could be better and worse, respectively. The key advantages of this OFCG is that no external EOMs [11] or further components are needed to obtain such a flat spectrum [11–14]; and that the amount of power needed is more than one order of magnitude lower than typical OFCG implementations [12], [22]. Furthermore, and unlike MLLDs, the frequency spacing between lines can be easily changed using the external CW RF synthesizer in a continuous way and with high frequency resolution, as it is also the case when EOMs are used.

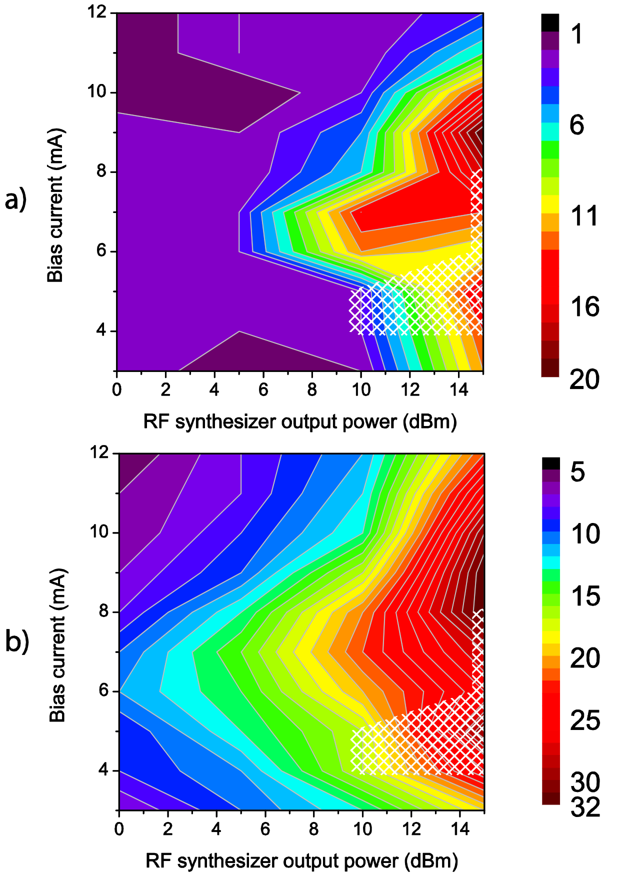

Fig. 2. Number of optical lines of the VCSEL-based OFCG: a) bandwidth of 3 dB; b) bandwidth of 30 dB. Overlay represent double-period region.

At this point, it is worth comparing our results with the most energy-efficient OFCG reported up to date [23]. Although a direct comparison is not completely fair as slightly different repetition frequencies are employed (4.2 GHz vs. 6.25 GHz), they are close enough to generalize our results to that repetition frequency (6.25 GHz) with the use of a matching network circuit adapted to this frequency together with our VCSEL (the 3-dB bandwidth of our VCSEL is around 8 GHz as per manufacturer specifications [24]). First, we only use a laser and a CW synthesizer, while Mishra et al. add to this component count also a Dual-Driven Mach-Zender modulator (DD-MZM, with bias requirements), a phase shifter, an RF amplifier and a frequency doubler. Second, both OFCGs generate 9 comb lines in a 1-dB bandwidth approximately. Our OFCG needs just 15 dBm of modulation power, while the one reported by Mishra et al. needs a simultaneous modulation of about 19 dBm (at 6.25 GHz) and 15 dBm (at 12.5 GHz), i.e. a total modulation power of 20.6 dBm. On the other hand, our extinction ratio seems to be worse. Third, our VCSEL consumes just 9 mA. In the compared OFCG it is not specified the laser employed, but if a regular edge-emitting laser is used, the energy consumption would be around one order of magnitude higher. As a drawback of our approach, it must be said that direct multiple comb feeding from a same laser is not possible because of the direct generation approach.

Also in Fig. 2, a dashed area is shown where Double Period (DP) behavior of the VCSEL is identified (lines at $f_{MOD}/2$ and its harmonics). This effect has already been reported several times for edge emitting lasers under direct modulation [25], and it is reported here for completeness. It is worth noticing that the optimum bias current points for GS operation (i.e. maximum number of optical lines) are outside the DP region, thus the optimum points for OFCG operation will not include DP behavior in any case.

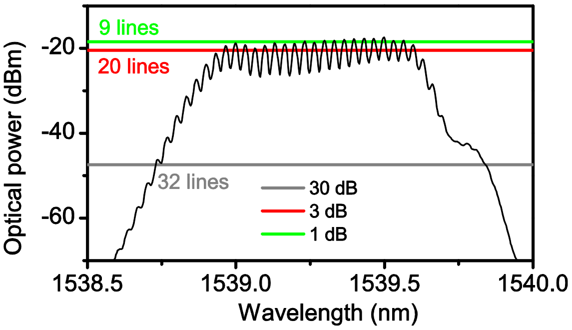

Fig. 3. Flat optical comb generation with 9 lines in a 1-dB bandwidth, 20 lines in a 3-dB bandwidth and 32 lines in a 30-dB bandwidth.

As a second step of this characterization, the coherence between the different optical lines generated is evaluated. Fig. 4a shows the electrical spectra recovered after direct detection of the OFCG optical output under both optimum GS (i.e. optimum OFCG operation, I_{BIAS} =9 mA and P_{RF} =15 dBm) and DP (I_{BIAS} =5 mA and P_{RF} =15 dBm) regimes. It is clear from these spectra how DP regime significantly degrades the noise floor of the beat signal, especially below 10 GHz. A more detailed analysis of these beat signals at the fundamental frequency is shown in Fig. 4b, where the Single Side Band (SSB) noise of the previously analyzed cases (optimum point for GS-OFCG operation and DP regime) and that of the RF modulation signal are depicted. It can be seen how for the optimum OFCG operation point (i.e. GS regime), the SSB noise is similar to that of the reference signal below 1 MHz, and only the noise floor is increased by 15 dB. As expected, when the reference is compared with the signal under DP regime, the SSB noise is highly degraded, both at lower and higher frequency offsets. This result confirms the high phase correlation between the different lines for OFCG operation under GS regime, especially at lower offset frequencies.

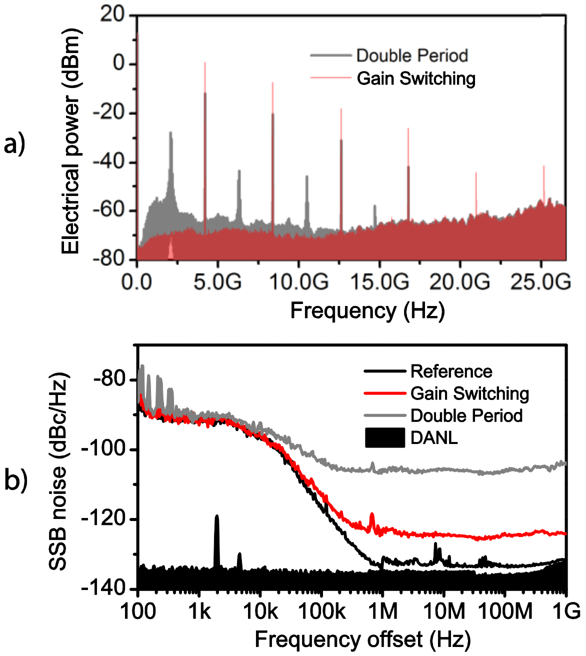

Fig. 4. a) Electrical Spectrum of the photodetected OFCG: red trace (GS regime); grey trace (DP regime). b) Single Side Band phase noise measurements: black trace (modulation reference signal); red trace (photodetected OFCG in GS regime); grey trace (photodetected OFCG in DP regime); black region (DANL, Displayed Averaged Noise Level).

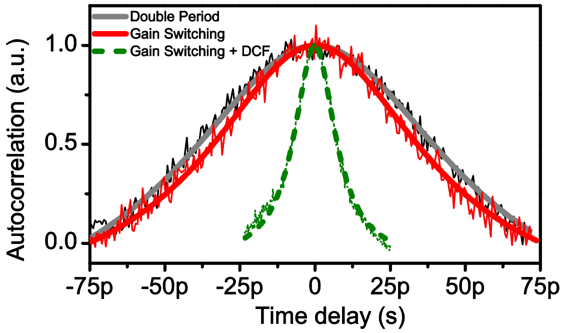

Fig. 5. Autocorrelation function of the output optical pulse of the OFCG: optimum OFCG operation-GS regime (red solid trace); optimum OFCG operation-GS regime with 1100 m of DCF (green dashed trace); and OFCG under DP regime (grey solid trace). All traces show an optimum fit to a Lorentzian function.

The final characterization step involves the measurement of the quality of the optical output in terms of temporal pulse width. For this reason, Fig. 5 shows the autocorrelation function of the output optical pulse of the OFCG in the two analyzed cases (optimum OFCG operation and DP regime). The temporal pulse widths are around 44 and 55 ps for GS

This is the author's version of an article that has been published in this journal. Changes were made to this version by the publisher prior to publication.
The final version of record is available at http://dx.doi.org/10.1109/LPT.2013.2280700

and DP regimes, respectively, giving TBP values around 3.5 for both cases as the optical bandwidth is different. This result confirms that the pulse presents a chirped behavior that has to be compensated if further comb expansion stages are required [11], [22]. Fig. 5 shows the autocorrelation function for GS regime after 1100 m of Dispersion Compensation Fiber (DFC). The new time-bandwidth product of 0.67 (temporal pulse of 8 ps) is enough for further expansion by the use of both Highly Nonlinear Fibers (HNLF) and EOMs to achieve much higher optical bandwidths exceeding 1 THz [11], [22]. In this sense, this OFCG can be used as a very efficient optical seed.

III. CONCLUSIONS

In conclusion, we have reported on the achievement of the most compact, power-efficient multi-GHz OFCG to date based on a commercial VCSEL under GS operation, without the need of any other external component. Up to 20 optical lines in a 3-dB bandwidth are directly generated with a frequency spacing of 4.2 GHz, showing a high phase correlation between them (photodetected beat signal with a phase noise similar to the modulation signal, especially in the low frequency offset). Since there is no fundamental difference with membrane-based tunable VCSELS as those reported in [20], this work opens the path to very low-cost, compact, low power consumption and tunable (both wavelength and repetition frequency) optical frequency comb sources of direct application in gas spectroscopy, metrology, communications and THz generation.

REFERENCES

[1] T. Udem, R. Holzwarth, and T. W. Hänsch, “Optical frequency metrology.,” *Nature*, vol. 416, no. 6877, pp. 233–7, Mar. 2002.

[2] F. Zhu, T. Mohamed, J. Strohaber, A. A. Kolomenskii, T. Udem, and H. A. Schuessler, “Real-time dual frequency comb spectroscopy in the near infrared,” *Applied Physics Letters*, vol. 102, no. 12, p. 121116, 2013.

[3] P. J. Delfyett, S. Gee, M.-T. Choi, H. Izadpanah, W. Lee, S. Ozharar, F. Quinlan, and T. Yilmaz, “Optical Frequency Combs From Semiconductor Lasers and Applications in Ultrawideband Signal Processing and Communications,” *Journal of Lightwave Technology*, vol. 24, no. 7, p. 2701–, Jul. 2006.

[4] A. R. Criado, C. de Dios, G. H. Döhler, S. Preu, S. Malzer, S. Bauerschmidt, H. Lu, A. C. Gossard, and P. Acedo, “Ultra narrow linewidth CW sub-THz generation using GS based OFCG and n-i-pn-i-p superlattice photomixers,” *Electronics Letters*, vol. 48, no. 22, pp. 1425–1426, 2012.

[5] S. T. Cundiff and A. M. Weiner, “Optical arbitrary waveform generation,” *Nature Photonics*, vol. 4, no. 11, pp. 760–766, Oct. 2010.

[6] R. Wu, C. M. Long, D. E. Leaird, and A. M. Weiner, “Directly Generated Gaussian-Shaped Optical Frequency Comb for Microwave Photonic Filtering and Picosecond Pulse Generation,” *IEEE Photonics Technology Letters*, vol. 24, no. 17, pp. 1484–1486, Sep. 2012.

[7] A. R. Criado, C. de Dios, P. Acedo, G. Carpintero, and K. Yvind, “Comparison of Monolithic Optical Frequency Comb Generators based on Passively Mode-Locked Lasers for Continuous Wave mm-Wave and sub-THz generation,” *Journal of Lightwave Technology*, vol. 30, no. 19, pp. 3133–3141, Jan. 2012.

[8] T. J. Kippenberg, R. Holzwarth, and S. A. Diddams, “Microresonator-Based Optical Frequency Combs ,” *Science* , vol. 332 , no. 6029 , pp. 555–559, Apr. 2011.

[9] R. Zhou, S. Latkowski, J. O’Carroll, R. Phelan, L. P. Barry, and P. M. Anandarajah, “40nm wavelength tunable gain-switched optical comb source,” *Optics Express*, vol. 19, no. 26, pp. B415–20, Dec. 2011.

[10] P. M. Anandarajah, R. Maher, Y. Q. Xu, S. Latkowski, J. O’Carroll, S. G. Murdoch, R. Phelan, J. O’Gorman, and L. P. Barry, “Generation of Coherent Multicarrier Signals by Gain Switching of Discrete Mode Lasers,” *IEEE Photonics Journal*, vol. 3, no. 1, pp. 112–122, Feb. 2011.

[11] R. Wu, V. Torres-Company, D. E. Leaird, and A. M. Weiner, “Supercontinuum-based 10-GHz flat-topped optical frequency comb generation,” *Optics Express*, vol. 21, no. 5, p. 6045, Mar. 2013.

[12] J. Zhang, J. Yu, N. Chi, Z. Dong, X. Li, Y. Shao, J. Yu, and L. Tao, “Flattened comb generation using only phase modulators driven by fundamental frequency sinusoidal sources with small frequency offset,” *Optics Letters*, vol. 38, no. 4, p. 552, Feb. 2013.

[13] V. Torres-Company, J. Lancis, and P. Andrés, “Lossless equalization of frequency combs,” *Optics Letters*, vol. 33, no. 16, p. 1822, Aug. 2008.

[14] V. R. Supradeepa and A. M. Weiner, “Bandwidth scaling and spectral flatness enhancement of optical frequency combs from phase-modulated continuous-wave lasers using cascaded four-wave mixing,” *Optics Letters*, vol. 37, no. 15, pp. 3066–3068, Aug. 2012.

[15] B. Zhu, I. H. White, K. A. Williams, M. R. T. Tan, R. P. Schneider, S. W. Corzine, and S. Y. Wang, “Ultralow timing jitter picosecond pulse generation from electrically gain-switched oxidized vertical-cavity surface-emitting lasers,” *IEEE Photonics Technology Letters*, vol. 9, no. 10, pp. 1307–1309, Oct. 1997.

[16] A. Consoli, I. Esquivias, F. J. L. Hernandez, J. Mulet, and S. Balle, “Characterization of Gain-Switched Pulses From 1.55-<formula formulatype=‘inline’><tex Notation=‘TeX’>μ</tex></formula>m VCSEL,” *IEEE Photonics Technology Letters*, vol. 22, no. 11, pp. 772–774, Jun. 2010.

[17] J. M. Wiesenfeld, G. Hasnain, J. S. Perino, J. D. Wynn, R. E. Leibenguth, Y.-H. Wang, and A. Y. Cho, “Gain-switched GaAs vertical-cavity surface-emitting lasers,” *IEEE Journal of Quantum Electronics*, vol. 29, no. 6, pp. 1996–2005, Jun. 1993.

[18] K. Koizumi, M. Yoshida, and M. Nakazawa, “10-GHz 11.5-ps Pulse Generation From a Single-Mode Gain-Switched InGaAs VCSEL at 1.1 <formula formulatype=‘inline’> <tex Notation=‘TeX’>μ</tex></formula>m,” *IEEE Photonics Technology Letters*, vol. 21, no. 22, pp. 1704–1706, Nov. 2009.

[19] J. Lin, J. K. Gamelin, S. Wang, M. Hong, and J. P. Mannaerts, “Short pulse generation by electrical gain switching of vertical cavity surface emitting laser,” *Electronics Letters*, vol. 27, no. 21, p. 1956, 1991.

[20] C. Gierl, T. Gruendl, P. Debernardi, K. Zogal, C. Grasse, H. A. Davani, G. Böhm, S. Jatta, F. Küppers, P. Meißner, and M.-C. Amann, “Surface micromachined tunable 1.55 µm-VCSEL with 102 nm continuous single-mode tuning,” *Optics Express*, vol. 19, no. 18, p. 17336, Aug. 2011.

[21] C. de Dios and H. Lamela, “Improvements to Long-Duration Low-Power Gain-Switching Diode Laser Pulses Using a Highly Nonlinear Optical Loop Mirror: Theory and Experiment,” *Journal of Lightwave Technology*, vol. 29, no. 5, pp. 700–707, Mar. 2011.

[22] T. Yang, J. Dong, S. Liao, D. Huang, and X. Zhang, “Comparison analysis of optical frequency comb generation with nonlinear effects in highly nonlinear fibers,” *Optics Express*, vol. 21, no. 7, p. 8508, Apr. 2013.

[23] A. K. Mishra, R. Schmogrow, I. Tomkos, D. Hillerkuss, C. Koos, W. Freude, and J. Leuthold, “Flexible RF-Based Comb Generator,” *IEEE Photonics Technology Letters*, vol. 25, no. 7, pp. 701–704, Apr. 2013.

[24] Vertilas GmbH, “Vertilas GmbH,” 2013. [Online]. Available: www.vertilas.com. [Accessed: 06-Feb-2013].

[25] Y. C. Chen, H. G. Winful, and J. M. Liu, “Subharmonic bifurcations and irregular pulsing behavior of modulated semiconductor lasers,” *Applied Physics Letters*, vol. 47, no. 3, p. 208, Aug. 1985.