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Continuous wave sub-THz photonic generation with VCSEL-based optical frequency comb

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A simple and energy-efficient photonic system to generate continuously tunable, low phase noise, sub-THz waves based on COTS components is presented. The optical scheme is based on the use of a commercial vertical cavity surface emitting laser under gain switching modulation that provides a very flat optical frequency comb generator (OFCG) with 23 modes in a 20 dB bandwidth. The laser only needs 15 dBm continuous wave radiofrequency input power and 9 mA of bias current to provide this OFCG. Two optical injection locking stages filter and amplify the two desired modes that are detected in a photodiode to produce the desired sub-THz signal at the frequency difference of these two selected modes. As an example, demonstrated is the generation of a very stable 88.2 GHz tone with lower linewidth than 10 Hz using a reference of 4.2 GHz to generate the OFCG.

Introduction: Photonic generation of high-frequency continuous-wave (CW) signals using difference frequency generation (DFG) is a well-established technique in the mm-wave and sub-THz frequency regions [1, 2]. Moreover, some DFG schemes using optical frequency combs generators (OFCG) have successfully demonstrated similar, or even better performance than the electronic counterparts in terms of frequency resolution and phase noise [2]. These OFCG-based schemes rely either on the use of monolithic components, like mode-locking laser diodes [3] with very low, if any, tunability, or on the use of external phase modulators [4], which need radiofrequency (RF) power in the order of 1 W per modulator and several external components, such as RF electronics, highly nonlinear fibres and compensating fibres for proper operation.

In this Letter, described is a simple and energy-efficient photonic system to generate continuously tunable, low phase noise, sub-THz waves using only COTS components. It is based on an architecture similar to our previous works [2, 5], with a newly designed OFCG that dramatically improves the overall cost, compactness and energy consumption of the system. This OFCG is based on a commercial vertical cavity surface emitting laser (VCSEL) under gain switching (GS) modulation that directly provides a very flat single-stage OFCG with 23 modes in a 20 dB bandwidth. It only needs 15 dBm CW RF modulation input power and 9 mA of bias current. We demonstrate with this system the generation of very stable (in terms of frequency), low linewidth (better than 10 Hz) and continuously tunable sub-THz signals.

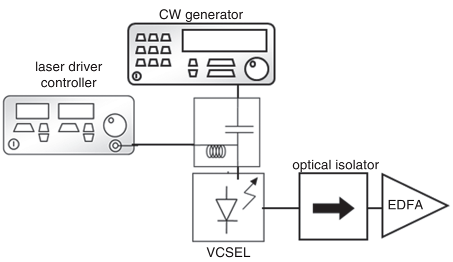

Fig. 1 *VCSEL-based OFCG scheme*

Experimental set-up: In Figs 1 and 2, we can observe the setup that has been used for this experiment. It consists of two different optical subsystems. Fig. 1 shows the OFCG. The core of this first subsystem is a commercial VCSEL (VERTILAS VL-1550-8G-P2-H4) under GS operation using a CW RF generator. The output of this OFCG is shown in Fig. 3 (black trace). A number of 23 lines for 20 dB bandwidth with only 9 mA bias current and 15 dBm RF input (f_{mod} = 4.2 GHz) are achieved. The minor asymmetry in the optical spectrum is in good agreement with the expected behaviour under this modulation regime [6]. As we can see in Fig. 1, no external modulators or further components are needed to obtain such a flat and wide spectrum. A standard OFCG based on standard techniques would need more than one order of magnitude more of modulation power and bias current [4].

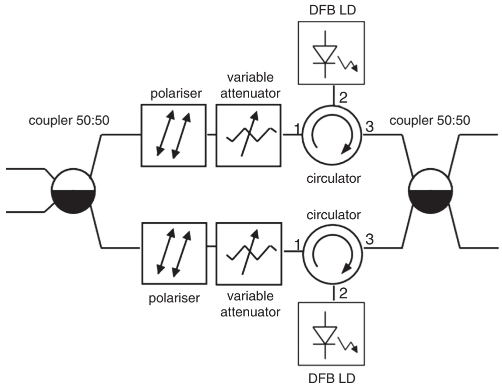

Fig. 2 *Selection of two modes set-up*

Two modes are selected using two-injection locking stages based on COTS DFB lasers

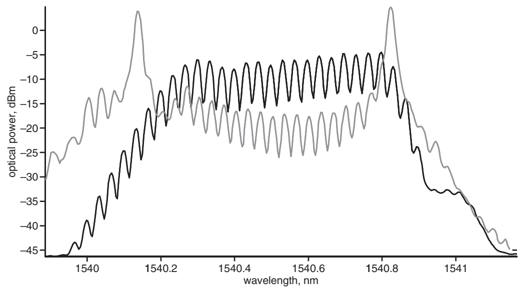

Fig. 3 *Optical spectrum at output of optical frequency comb generator (black trace); and after mode selection stage (grey trace)*

The second optical subsystem, shown in Fig. 2, provides optical mode selection for sub-THz DFG generation. It consists of two identical optical injection locking stages. Two commercial distributed feedback (DFB) lasers are used as slave lasers, in which the OFCG is injected as master signal to select the desired modes. This approach for the optical modes selection allows filtering and amplifying in a single stage and offers much higher performance than selection based on optical filtering [2]. The selection of different lines is achieved by controlling the DFBs' temperatures and bias currents. Continuous tunability of the synthesised frequency is achieved by combining coarse tunability through mode selection and fine tunability through the VCSEL modulation frequency, allowing for continuous coverage of the frequency region covered by the OFCG bandwidth [2].

The output of the mode selection stage after recombination is shown in Fig. 3 (grey trace). In this figure two modes, 21 lines apart, are selected for an 88.2 GHz frequency difference (VCSEL modulation frequency of 4.2 GHz). Besides that, the maximum synthesised frequency can be straightforwardly increased into several hundreds of GHz range using already reported techniques for comb expansion [2].

Experimental result: photonic sub-THz generation: Sub-THz photonic generation in DFG systems is achieved detecting the two optical wavelengths in a photodetector with enough electrical bandwidth. In our case, we have used a commercial photodiode (100 GHz 3-dB bandwidth) directly attached to an electrical spectrum analyser (ESA) that incorporates a subharmonic mixer for the frequency range of interest. The recovered signal is shown in Fig. 4, where we can observe that the expected signal at 88.2 GHz is provided by the system. The tone has a measured 3-dB linewidth in the order of the resolution bandwidth employed (10 Hz, minimum allowed by the ESA). Even though we have 45 dB losses in the subharmonic mixer required for the measurement (these losses have been taken into account to provide the measurement of Fig. 4), the achieved dynamic range is about 40 dB.

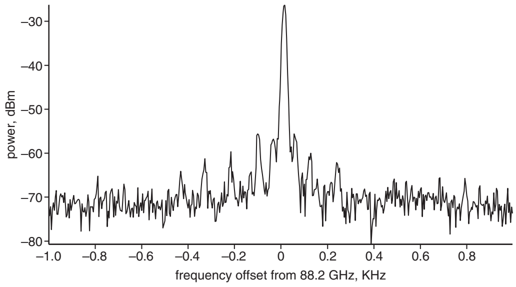

Fig. 4 *Sub-THz generated signal of 88.2 GHz, used span of 2 kHz; x-Axis, frequency offset in Hz (centre frequency 88.2 GHz); y-Axis RF power in dBm*

Finally, we have measured the system's tunability by measuring the sub-THz frequency generated while changing the reference frequency in steps of 1 kHz around 4.2 GHz, i.e. 21 kHz frequency steps in the synthesised sub-THz signal at 88.2 GHz. This characterisation showed an excellent linear behaviour with a coefficient of determination (R^2) to a linear fit of 1.

The signal stability at 88.2 GHz in terms of frequency and amplitude is very high, showing a standard deviation over 1 hour of operation of 25 Hz and 0.9 dB, respectively. It must be noted that the employed resolution bandwidth in this long-term stability analysis is 30 Hz; thus, these standard deviation values are in the measurement instrumentation accuracy and uncertainty limits.

Conclusions: We have developed a system for sub-THz generation using a gain-switched VCSEL-based OFCG. The use of a high-speed VCSEL offers the possibility of low size and high-efficient comb generation systems as we obtain a comb with 23 modes in a 20 dB bandwidth with the GS modulation. No extra components are needed. With this simple scheme, we have synthesised a sub-THz signal at 88.2 GHz with a linewidth lower than 10 Hz and excellent frequency and amplitude long-term stability. Additionally, the frequency tuning characteristic is almost perfectly linear with the reference frequency (f_{REF} is 4.2 GHz in our design). This method is very useful for compact, easy and tunable sub-THz photonic generation systems.

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