TITLE: Photonic Synthesis of Continuous-Wave Millimeter-Wave Signals Using a Passively Mode-Locked Laser Diode and Selective Optical Filtering

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ABSTRACT: We report a photonic synthesis scheme for CW mm-wave signal generation using a single Passively Mode-Locked Laser Diode (PMLLD), optical filtering and photomixing in a fast photodiode. The phase noise of the photonically synthesized signals is evaluated and inherits the characteristics of the PMLLD electrical power spectrum.

I. INTRODUCTION

The lack of suitable generation and detection technology above 120 GHz, and most notably in the THz band is lagging the widespread use of signals in this frequency range within important fields of application such as security, biology, medicine [**1**] and wireless communications [**2**]. The development of such sources and detectors has motivated huge research efforts in this field over the last years, and now several techniques for Continuous Wave (CW) mm-wave and THz generation are available [**3**]. Among these, photonic techniques are potentially advantageous for producing low cost, compact and room temperature operation components given the recent advances in Photonic Integrated Circuits (PIC) [**4**].

The most promising photonic mm-wave and THz generation technique is based on the combination (mixing) of two input wavelengths, producing a signal with a frequency equal to the difference between them. The mixing takes place either in a nonlinear media (i.e. Difference Frequency Generation) or in a photomixing device (i.e. Optical Heterodyne Photomixing), such as a photoconductive antenna or a photodiode [**3**].

The usual schemes for Optical Heterodyne Photomixing (OHP) employ either two optical frequencies from different laser sources, achieving a great frequency range and continuous tunability at the expense of complex Optical Phase Locked Loops (OPLL) schemes [**5**]; or two modes filtered from an Optical Frequency Comb Generator (OFCG), where additional devices such as phase modulators, RF synthesizers, nonlinear optical fiber and complex optical filters are usually needed to implement the OFCG, generate the electrical signal, and maintain the continuous tunability [**6**].

In this paper, we present a straightforward OHP setup for mm-wave and sub-THz signal generation based on three key elements: a single Passively Mode-Locked Laser Diode (PMLLD) acting as OFCG, two high selectivity Fabry Perot fiber filters to select two of the optical modes from the OFCG, and a fast photodiode as the photomixing element. These elements present a great integration potential, then the presented OHP scheme could be translated into a Photonic Integrated Circuit. The use of a PMLLD allows not only the implementation of a monolithic OFCG based on a single device but also takes advantage of the low phase noise performance demonstrated by this kind of devices without the use of an OPLL or external RF references [**7**]. The frequency range of the electrical signal that can be synthesized with this setup is only limited by the optical bandwidth of the optical comb generated by the PMLDD (640 GHz in our case) and the bandwidth of the photodiode device, that can be close to 1THz, as it is the case of the Travelling-Wave Uni-Travelling Carrier Photodiode (TW-UTC-PD) technology [**8**].

II. PASSIVELY MODE-LOCKED LASER DIODE AS MONOLITHIC OPTICAL FREQUENCY COMB GENERATOR

The PMLLD used in this study has a two contact structure comprised of a saturable absorber and a gain section, of 85 µm and 3915 µm length respectively [**9**]. The active region contains one InGaAsP/AlGaInAs QW emitting at a central wavelength of 1527 nm. Longitudinal confinement of the optical field is achieved by the formation of a 2 µm width ridge waveguide structure. The facet at the absorber end is HR coated (95% reflection) and the output facet is as cleaved.

Passive mode-locking regime is achieved with a reverse DC voltage on the saturable absorber. Figure 1 shows the optical spectrum of the laser in this regime when the reverse bias applied to the saturable absorber is -2.7 V and the drive current is 55 mA. The main trace shows the complete spectrum on a 40 nm span. The inset presents the modes around 1527 nm, where the spacing between modes corresponds to the repetition rate of the PMLLD (f_{ml} = 9.92 GHz).

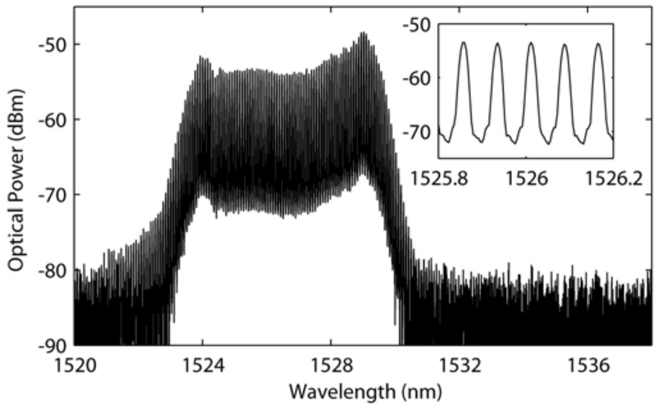

Figure 1. Optical Spectrum of the QW PMLLD (40 nm span, A in Figure 2). Inset: detailed span (0.4 nm).

III. CW MM-WAVE AND SUB-THZ PHOTONIC SYNTHESIS SYSTEM DESCRIPTION

The experimental setup of the mm-wave and sub-THz signal photonic generation scheme presented in this work is shown in Figure 2. The PMLLD chip is on a thermoelectric controlled stage and the light at the output facet is coupled to a single mode fiber. An optical isolator is included at this point to avoid back reflections from the following elements of the set-up, such as the 90:10 split ratio directional coupler placed to monitor the optical output power.

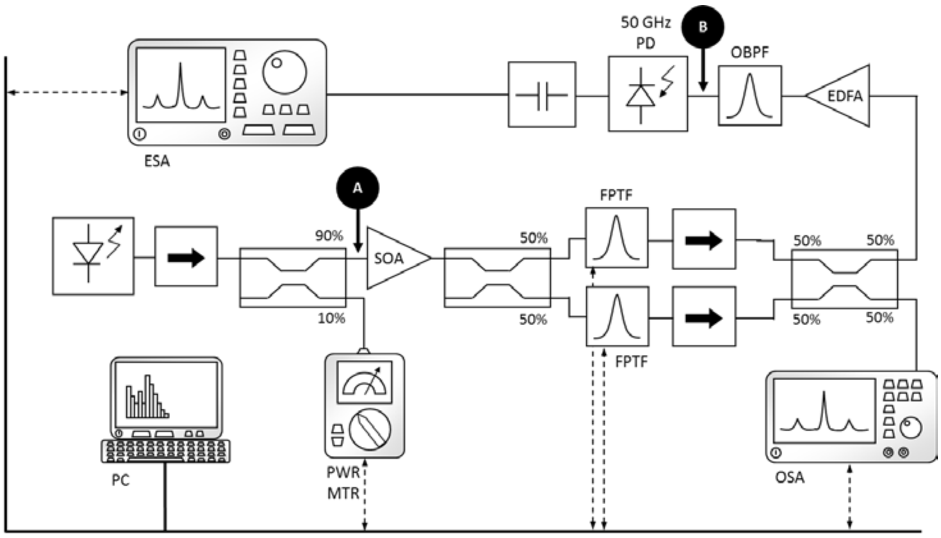

Figure 2. Experimental setup for CW mm-Wave and SubTHz Photonic Synthesis.

The 90% output of this splitter is then amplified using an Erbium Doped Fiber Amplifier (EDFA) and divided in two branches, each with a Fabry Perot Tunable Filter (FPTF). These filters have a very high selectivity (Finesse = 3000, i.e. 3dB-Bandwidth = 50 pm) that corresponds to a 3dB bandwidth of 6.43 GHz at 1527 nm and allow us to filter one mode from the complete optical spectrum (Figure 1) independently on each branch. The filters are followed by another optical isolator to prevent reflections. The two filtered wavelengths that exhibit the desired frequency difference are then recombined in a 50:50 optical directional coupler to obtain an optical signal comprising the two selected modes. One of the outputs of the 50:50 coupler is directly connected to an Optical Spectrum Analyzer (OSA) to track the spectrum and the mode spacing. Figure 3 shows the spectrum of the optical signal after filtering and recombination. Also in this figure, the detailed optical spectrum of one of the filtered modes is shown, demonstrating a side mode suppression ratio of 12 dB. It is important to note that the high selectivity of these filters requires a fine control and stabilization of their control voltages, as small drifts or voltage amplitude noise would translate into associated amplitude variations in the final synthesized signal

The other coupler output is sent to another amplification stage with a linear Semiconductor Optical Amplifier (SOA QPhotonics QSOA-1550). This stage is needed to increase the optical power and make it possible to clearly detect the beat note signal at the photodetector output. The SOA output is then sent to an Optical Band-Pass Filter (OBPF) to reduce the Amplified Spontaneous Emission (ASE) of the spectrum outside the bandwidth of interest, hence increasing the Signal-to-Noise Ratio (SNR). The filtered modes beat on a fast photodiode (u2t XPDV2020R), used as photomixing element, which offers a 3-dB bandwidth of 50 GHz. The generated electrical signal, with a frequency given by the frequency difference between the optical modes is observed on an Electrical Spectrum Analyzer (ESA).

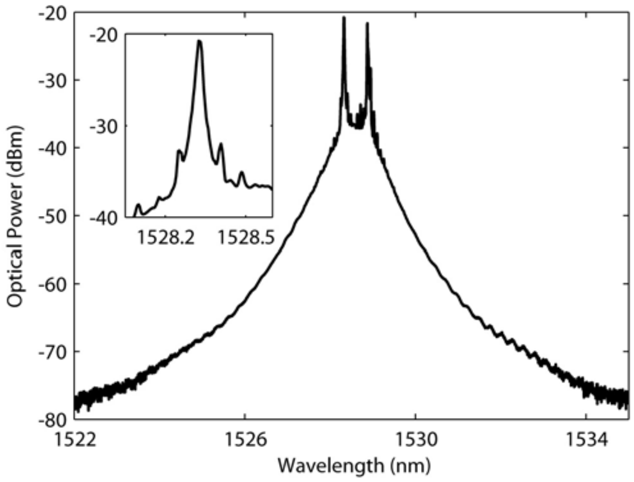

Figure 3. Processed optical signal prior to photomixing stage (B in Figure 2). Inset, detail of one of the modes.

It is worth to mention that the tunability of the presented photonic synthesis covers the mm-wave to sub-THz signals ranges by tuning of one of the filters to the peak wavelength of one mode and subsequent application of a variable voltage to the other filter to select the desired second mode, spaced from the first one a frequency equal to the desired synthesized electrical signal. The frequency step is 9.92 GHz, determined by the repetition rate of the PMLLD (f_{ml}).

IV. EXPERIMENTAL RESULTS

The study of the CW mm-wave synthesized signal is carried out by evaluating its electronic spectral characteristics after the mixing of the selected optical modes in the fast photodiode, separated by a frequency equal to $4 \cdot f_{ml}$. The experimental study has been centered to this frequency range ($4 \cdot f_{ml}$ = 39.73 GHz) to guarantees a negligible contribution of the sum of the side residual optical modes after filtering (inset of Figure 3) while maintaining the frequency within the detection limits (limited only by the photodiode and the ESA).

The phase noise performance, important for applications such as wireless communications, is evaluated measuring the Single Side Band (SSB) noise and the Full Width at Half Maximum (FWHM) of the electrical spectrum. To understand its characteristics, these results are compared with those found studying the electrical signal directly obtained from the PMLLD by harmonic generation (i.e. optical to electrical conversion of the PMLLD output (Figure 1) in the fast photodiode without mode filtering). In this case, the two filtering branches are replaced by a tunable optical attenuator to have the same noise and spectral contribution of the optical amplification stages and properly compare the spectra.

Figure 4 shows the SSB noise-to-carrier power ratio (L(f)) of the signals under study. The analysis of the phase noise of the signal obtained by harmonic generation from the PMLDD shows a difference between the fundamental and the fourth harmonic of ≈12 dB that is in well agreement with the increment associated to frequency multiplication, given by 20·log(N), where N is the harmonic number. The SSB noise of the photonically synthesized signal at $4 \cdot f_{ml}$ is similar to that of the corresponding harmonic of the PMLLD signal. Nevertheless, the SSB noise of the synthesized signal exhibits a set of frequency peaks present in the fundamental harmonic that are not observed at the fourth harmonic of the source signal. This demonstrates that the SSB noise of the synthesized signal, although having a general behavior similar to that associated to the harmonic at the same frequency, inherits phase noise characteristics directly from the fundamental harmonic associated with the repetition rate of the PMLLD. This implies a clear advantage of the synthesized signal over the PMLDD direct harmonic generation signal when maximum deliverable power is a concern. The maximum electrical power offered by a photodiode is limited by its maximum input optical power. Generating an electrical signal using only two modes (synthesized signal) instead of all modes (PMLLD harmonic signal) means that only the optical power at the required frequency is mixed in the photodiode, maximizing its electrical power with no degradation of the phase noise, only at the expense of further optical amplification of the selected longitudinal modes.

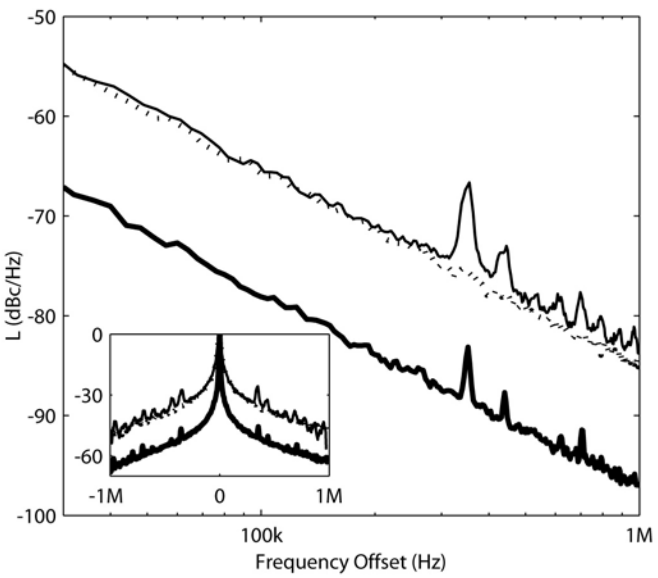

Figure 4. SSB noise-to-carrier power ratio (L(f)) vs frequency offset. Thick black line, fundamental harmonic (f_{ml} = 9.92 GHz); dotted black line, fourth harmonic ($4\cdot f_{ml}$ = 39.73 GHz); thin black line, photonically synthesized signal ($4\cdot f_{ml}$ = 39.73 GHz). Inset, power normalized spectra.

The normalized spectra of the generated signals are represented in the inset of Figure 4. Considering the electrical spectra of the PMLLD signal, the measured FWHM of the fundamental harmonic is 8.77 kHz, while the value for the fourth harmonic is 24.58 kHz. Using the fundamental harmonic FWHM as reference, the values have an almost linear dependence with the frequency, as it has been described for these optical sources [**11**]. Observing the synthesized signal, we obtain a FWHM of 27.42 kHz. As this measure is similar to that obtained for the fourth harmonic of the PMLLD signal and also matches the linear dependence described above, this would allow us to predict the FWHM for signals synthesized at higher frequencies [**11**].

It is important to note that the eventual contribution to the SSB noise given by amplitude jitter associated to possible drifts of the central frequency of the FPTFs will be negligible compared to the contribution of the timing jitter to the SSB noise as demonstrated in [**11**]. That is another advantage of our setup over more complex systems that rely on OPLL for sub-THz signal generation where phase instabilities in the loop are directly translated to timing jitter and therefore to SSB noise.

V. CONCLUSIONS

In this work we have presented a compact and straightforward system for photonic synthesis of CW mm-wave and sub-THz signals using a QW PMLLD, tunable Fabry Perot fiber filters and photomixing in a fast photodiode. The use of a single QW PMLLD to serve as OFCG presents a great integration potential for the system while offering very low phase noise performance inherent to this kind of devices. Other advantages of the system include a negligible phase noise degradation related to eventual drifts at the Fabry Perot filters, and a higher deliverable electrical power since only optical power at the required frequency difference is mixed (synthesized signal, two modes) and not at other non-desired frequencies (direct harmonic generation, all modes).

With this setup, mm-wave and sub-THz signals at integer multiples of that associated to the repetition rate of the PMLLD (9.92 GHz in this case) can be obtained through selective filtering of the optical spectrum emitted by the laser and photomixing in a fast photodiode, with a highest frequency to be synthesized only limited by the optical spectrum of the OFCG and the photodiode bandwidth.

A photonically synthesized signal at 39.73 GHz has been generated with this setup and analyzed, reporting performance for both SSB noise and FWHM similar to that of the corresponding harmonic at the same frequency of the QW PMLLD. Moreover, some spectral characteristics (i.e. frequency peaks in the SSB noise) from the fundamental harmonic that are not observed at the fourth harmonic are directly inherited to the synthesized signal at 39.73 GHz, offering a system that translates to the generated mm-wave signal the noise characteristics of the OFCG employed.

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