Highly spectrally pure 90 GHz signal synthesis using a coupled optoelectronic oscillator

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Aliou Ly, Vincent Auroux, Ramin Khayatzadeh, Napoleon Gutierrez,

Arnaud Fernandez, Olivier Llopis, Member, IEEE

Abstract— **A 90 GHz frequency reference is synthesized through harmonic generation from a 30 GHz coupled optoelectronic oscillator. The 30 GHz signal and its third harmonic feature an average power level of −5.6 dBm and −15.8 dBm respectively at the photodiode output. Phase noise measurements at 30 GHz and 90 GHz have been performed and phase noise levels as low as −114.4 dBc/Hz at 1 kHz offset for the fundamental and −104 dBc/Hz at 1 kHz offset frequency for the 90 GHz signal have been obtained.**

Index Terms— **Optoelectronic oscillator; COEO; microwave photonics; harmonic generation; millimeter wave; phase noise.**

I. INTRODUCTION

High frequency (millimeter-wave), spectrally pure and high power (milliwatt range) RF signals are of great interest for applications in high speed signal processing [1], advanced radar systems [2], wireless communications, fiber-radio systems and so on. Conventional techniques for generating such signals are based on the multiplication of lower frequency RF sources, which generally results in an important increase of the phase noise and particularly the phase noise floor (far from carrier phase noise). Optical approaches are thus an interesting alternative to improve the phase noise or the tunability of such sources. As an example, heterodyne mixing of two laser modes results in a large tunability and a very operation frequency, but also in poor phase noise. Conversely, state of the art phase noise is obtained from coherent optical frequency division of a stabilized frequency comb [3, 4]. However this technique remains bulky and difficult to set up. Compared to these approaches, the optoelectronic oscillator (OEO) is a good alternative featuring relatively small size and complexity and low phase noise. Indeed, a simple OEO loop consists of a light source, an optical modulator, a fiber delay line, a photodiode, an amplifier and a filter (electronic or photonic) [5, 6]. Thus, the different components of the loop can be freely chosen to meet the objectives of the application to which the OEO is dedicated. Oscillation at any high frequency in the millimeter-wave (mm-wave) range is theoretically possible [7] provided that high bandwidth modulators and high speed photodiodes are available.

However, expansion in frequency range somehow results in an increase of cost accordingly since low noise and high bandwidth RF components are nowadays certainly available but expensive. Consequently, the cost effective generation of pure RF signals in the V, E or W bands remains a challenge. As a trade-off to producing signals in the former bands from lower bandwidth RF components, frequency multiplication turned out to be a good alternative. As an example, it is possible to generate 60 GHz to 100 GHz signals by simply exploiting the nonlinearity of a Mach Zehnder modulator (MZM) [8, 9]. A tunable (95-115 GHz) low noise mm-wave source has also been demonstrated by combining nonlinearities in a MZM and four waves mixing in an optical amplifier [10]. The mode-locked laser is also highly attractive for optical multiplication since this device is highly nonlinear and generates a frequency comb with a sufficient span. Thus, Fukushima et *al.* reported a 10-110 GHz mm-wave signals synthesis by optical injection locking of two lines of an optical frequency comb generator [11]. Fortier et *al.* generated a 100 GHz signal by using an electro-optic modulator driven at 10 GHz and an optical etalon to filter two 100 GHz spaced sidebands [12]. By using an ultra-high finesse etalon as a photonic filter in an OEO, Bagnell et *al.* produced a 6-60 GHz signal which corresponds to the harmonics of the 1.5 GHz etalon free spectral range [13]. It turns out, in most of the experiments described above, that the generation of signals in the W band is either efficient in terms of spectral purity but requires large equipment or is simple but not efficient enough in terms of RF output power and spectral purity. To the best of our knowledge, there is to date no reported work on the synthesis of a mm-wave in the W band from a coupled optoelectronic oscillator (COEO). The COEO is a special case of a mode locked laser. It is actually the coupling of an electronic oscillator and an optical oscillator, both sharing the same active resonator. The COEO is thus the ideal candidate for millimeter wave generation with optics, because of this unique interplay between the extremely high Q of the active optical loop and the RF feedback loop. Harmonic generation from such system is particularly interesting since it benefits from the high spectral purity of the fundamental frequency and of the efficient multiplication factor due to the optical comb generation.

The aim of the present paper is to demonstrate that a 30 GHz COEO is a good candidate for frequency generation at W band. Firstly, the COEO at 30 GHz is described. Then, its performances in terms of RF power at 30 GHz and 90 GHz as well as the corresponding spectral purity (phase noise) are presented

II. DESCRIPTION OF THE 30 GHz COEO

The 30 GHz COEO architecture is depicted in Fig. 1. It is based on two coupled loops: an optical loop (black) and an opto-electrical loop (black and purple). The optical loop consists of a semiconductor optical amplifier (SOA) acting both as an active medium and a source of light. It features an output saturation power of 16 dBm and a 30 dB small signal gain. Light from the SOA successively travels an optical isolator (OI) to protect the SOA from reflection, a 50:50 optical coupler (OC1) and a 90:10 optical coupler (OC2) which 90 % output port is connected to a 400 m standard single mode fiber spool. This latter acts as a delay line and an energy storage device with a chromatic dispersion of the order of +6.8 ps/nm. Intra-cavity dispersion management is however of paramount importance to control the optical frequency comb coherence and to prevent from RF power fading effects. Thus, a chirped fiber Bragg grating (CFBG) with a chromatic dispersion of -7 ps/nm, used in reflection, was inserted into the loop for the group velocity dispersion compensation [14]. The output of the CFBG is next sent to a 40 GHz bandwidth MZM and a polarization controller (PC) is used to control its losses. Last, a second fiber delay (200 m SMF) is used to direct the light from the optical loop to the electrical loop.
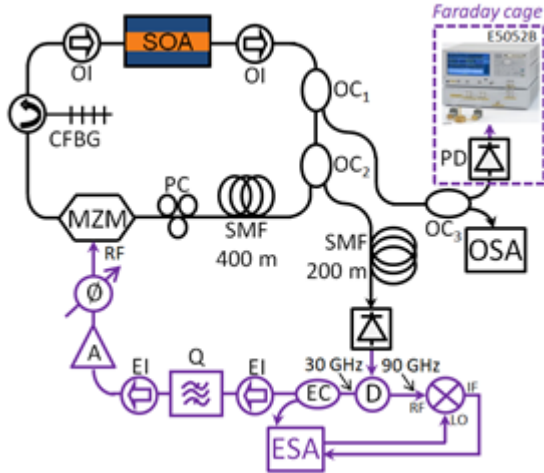

Fig. 1: Schematic of the experimental setup. MZM: Mach Zehnder Modulator, SOA: Semiconductor Optical Amplifier, PC: Polarization Controller, ESA: Electrical Spectrum Analyzer. OSA: Optical Spectrum Analyzer. E5052B: phase noise analyzer. SMF: Single Mode Fiber. CFBG: Chirped Fiber Bragg Grating. OI: Optical Isolator. EI: Electrical Isolator. OC: Optical Coupler. EC: Electrical Coupler. D: Duplexer. A: RF amplifier.

The electrical loop consists of a 75 GHz bandwidth U2T photodiode which output is immediately connected to a duplexer (a W band waveguide thanks to a V-W transition). Both RF frequencies (fundamental and third harmonic) are next generated and, a 10 dB RF coupler (EC) directs 90 % of the power at 30 GHz to a RF filter. This latter is a home built dielectric resonator centered at 30.1 GHz, featuring a loaded quality factor Q of 430 (69 MHz at 3 dB bandwidth) and 5.7 dB transmission losses. This filter is placed between two electrical isolators (ECs) because the resonator is not perfectly 50 Ω matched. Finally, the filtered signal at 30 GHz is successively

sent to a RF amplifier with a saturation power of 21 dBm and a gain of 30 dB, then to a RF phase shifter and back to the MZM. Let's see now how our system performs in term of RF power at 30 GHz and 90 GHz as well as the corresponding phase noise.

III. COEO PERFORMANCES

A. Optical frequency comb of the 30 GHz COEO

Observation of the spectrum of the optical frequency comb generated from the COEO is primary since it gives clear information on the phase matching between all modes that can oscillate. More precisely, a wide span frequency comb with intense lines will result in ultra-short and low jitter optical pulses [15, 16] and thus in a low phase noise for the corresponding RF signal accordingly. To this aim, the 10% output port of the 90:10 optical coupler (OC3, Fig. 1) is connected to an optical spectrum analyzer (OSA HP86142A). We set the bias voltage of the MZM (V_π around 5V) to V_{bias}= 4.02 V and optimized the COEO to get the spectrum displayed in Fig. 2. The optimization consisted of acting on the PC and on the RF phase shifter so as to get a large spectrum with lines with a good contrast.
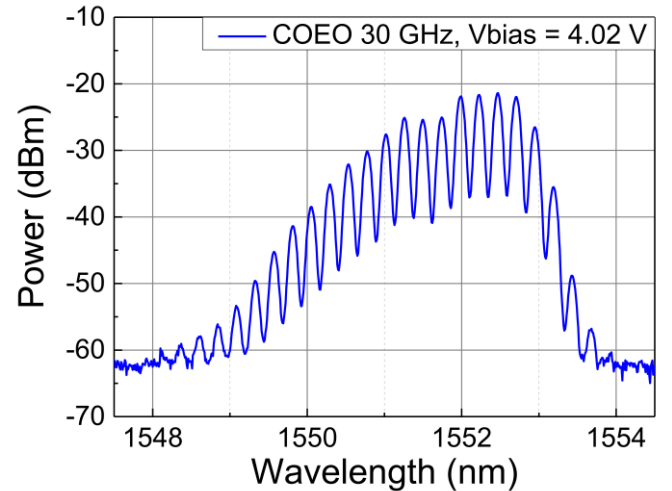

Fig. 2: Optical frequency comb of the 30 GHz COEO obtained at a 4.0 V bias voltage of the MZM.

B. RF power at 30 GHz and at 90 GHz

The evolution of the RF power at the fundamental frequency and its third harmonic versus the MZM bias voltage is studied in this section. The power was measured using an Agilent E4448A electrical spectrum analyzer (ESA, Fig. 1). For the RF signal at 30 GHz, the 10% output port of a 90:10 electrical coupler (EC) is connected to the ESA thanks to a K cable. We have assumed this cable induces an attenuation of 2 dB, then measurements to the ESA are accordingly corrected. For the third harmonic at 90 GHz, it has to be down converted since the ESA features only a maximum input frequency of 50 GHz. The harmonic mixer, which is driven by an internal source of the ESA, is calibrated by the manufacturer (Agilent) and a correction factor is directly applied to the ESA to get the effective power at 90 GHz at the mixer input.

Fig. 3 displays the RF powers for both signals (fundamental and third harmonic) at the duplexer output. As it can be seen, the RF power at 30 GHz remains nearly constant with an average value of -5.6 dBm. Indeed, losses increase with the bias voltage but they are compensated, to a certain limit by the RF amplifier in the electrical loop.
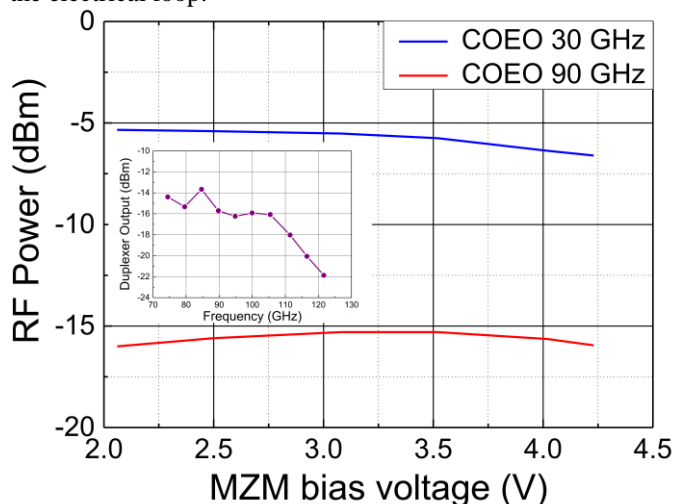

Fig. 3: RF powers at the level of the duplexer for the fundamental frequency (30 GHz) and its third harmonic (90 GHz) versus the MZM bias voltage. Inset, frequency response of the photodiode measured at the duplexer output.

The RF power of the 90 GHz signal features the same evolution as the fundamental with a mean value of -15.8 dBm. These results have to be compared to the -10 dBm obtained at 110 GHz by Fukushima et *al.* and to the -37 dBm obtained at 50 GHz by Llopis et *al.* In the former case an EDFA was placed before the photodiode in order to generate such RF output power. The photodiode response (inset of Fig. 3) has been measured using the beat signal between two identical DFB lasers independtly controlled in temperature. Considering its almost flat response up to 105 GHz, our compact system is able to generate appreciable RF power at mm-wave in the W band.

C. Spectral purity at 30 GHz and at 90 GHz

A last but not least study is the level of phase noise associated to our 90 GHz mm-wave synthesis. The harmonic generation should introduce a degradation of 9.5 dB compared to the phase noise spectrum at 30 GHz due to the frequency multiplication. Thus, the lower the phase noise at 30 GHz, the better the spectral purity of the RF signal at 90 GHz. The phase noise measurements are performed at 30 GHz and 90 GHz using an Agilent E5052B signal source analyzer combined with a microwave down converter E5053A and external millimeter wave mixers. Two identical mixers are used, in order to perform the correlation technique which allows an improvement of the phase noise floor of about 12 dB (correlation factor of 300). These mixers feature a loss of about 46 dB on the 75 GHz/110 GHz frequency band, which is partially compensated by a 30 dB low noise W band amplifier.

Since theses apparatus are placed into a Faraday cage located in another room, a 20 m fiber has been used to direct the optical signal from the 90% output port of the 90:10 optical coupler (OC3, Fig. 1) to the photodiode (the same as that one in Fig. 1).

The bias of the MZM is fixed at 4.02 V, which corresponds to the optical spectrum in Fig. 2. Phase noise measurements at 30 GHz and at 90 GHz are plotted in Fig. 4 for a correlation factor of 300. Phase noise level at 10 Hz offset frequency as low as -45 dBc/Hz and -33.2 dBc/Hz can be clearly seen for RF signals at 30 GHz and 90 GHz respectively.
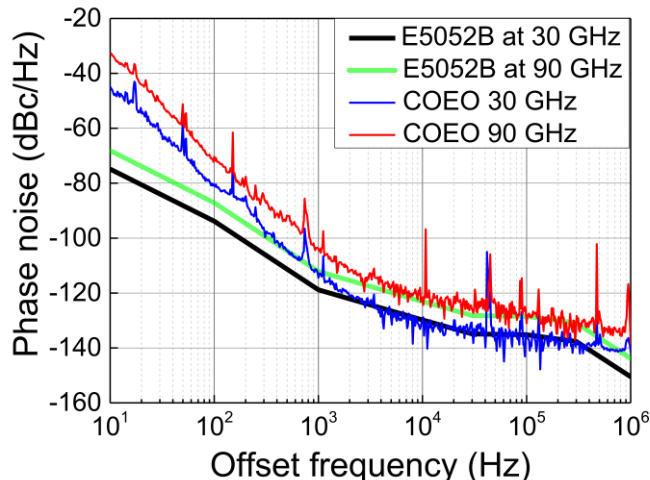

Fig. 4: Phase noise measurements at 30 GHz (blue) and 90 GHz (red) with a cross correlation technique (correlation factor of 300) for a bias voltage of 4.02 V. Dark: phase noise spectrum of the signal source analyzer at 30 GHz. Green: phase noise spectrum of the signal source analyzer at 90 GHz.

Then, the noise decreases with a close to $1/f^4$ slope up to 100 Hz likely due to thermal drifts of the optical resonator and with a close to $1/f^3$ slope between 100 Hz and 2 kHz, which corresponds to flicker frequency noise induced by the 1/f phase noise of the amplifiers (SOA and RF) in the oscillating loops. It reaches -114.4 dBc/Hz at 1 kHz offset frequency for the fundamental and -104.0 dBc/Hz at 1 kHz offset frequency for the third harmonic. Above approximately 3 kHz offset frequency, the noise floor of the E5052B measurement system is reached. Finally, the COEO phase noise performance is effectively transferred to 90 GHz with the only additional noise due to frequency multiplication by 3 (9.5 dB). Such a phase noise level is much lower than the phase noise level available from any frequency multiplication technique and a quartz based synthesizer, as shown in the last paragraph and in Figure 5.

We have compared our phase noise results to recent achievements in the field of low phase noise millimeter-waves synthesis. Figure 5 depicts the phase noise performance at 1 kHz offset of various sources between 50 GHz and 110 GHz. Circular dots represent millimeter wave sources referenced on quartz based microwave synthesizers, using frequency multiplication obtained either through optical or electronic devices. The ellipsoid represents the typical performance which can be obtained with the best microwave synthesizers and this approach. Diamond dots feature sources which are based on optical resonators. The square dot is the special case of a source obtained through optical frequency division. The last case represents the best performance, but it is obtained on a large size and complex system.
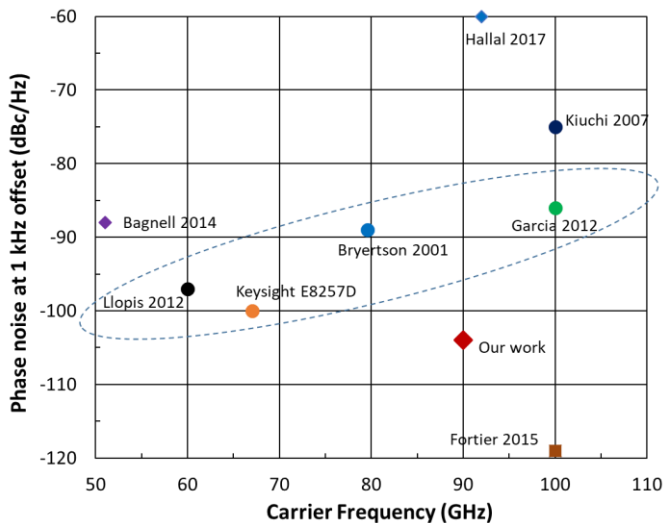
Fig. 5: State of the art of high spectral purity generation in the 50-110 GHz range. Our system features about 10 dB lower noise than the best quartz referenced sources.

IV. CONCLUSION

Harmonic generation from a 30 GHz COEO has been performed to get a high quality frequency reference at 90 GHz. The optical spectrum and the RF power of the fundamental and the third harmonic have been observed for different bias states of the MZM. Available RF powers as high as -5.6 dBm at 30 GHz and -15.8 dBm at 90 GHz have been demonstrated in addition to the low phase noise level obtained. Comparison of our results to those reported in the literature make us to believe that harmonic synthesis using a compact COEO is particularly efficient for ultra-high frequency and high spectral purity mm-wave synthesis. To the best of our knowledge, this is the lowest phase noise level demonstrated at W band using optoelectronic oscillator approach. Future work will address above 100 GHz frequency generation using faster photodiodes, the photodiode being the only frequency limiting device in this system.

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