International Journal of Microwave and Wireless Technologies, 2011, 3(3), 383–389.
doi:10.1017/S1759078711000262

RESEARCH PAPER

Reconfigurable radar transmitter based on photonic microwave signal generation

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In this paper we propose a photonic technique for a reconfigurable microwave signal generation based on the beating of two laser modes coming from a regenerative fiber mode-locked laser (FMLL) into a photodiode. The excellent performance of this kind of pulsed laser guarantees high stability on the directly generated microwave signal even at ultrahigh frequencies (up to W band). Therefore, by using the proposed architecture, the performance of a reconfigurable full digital coherent radar system can be enhanced for example in terms of moving target indicator (MTI) improvement factor and analog to digital converter maximum signal to noise ratio. Differently from the conventional radar oscillators, whose performance strongly deteriorate with increasing frequencies, the photonic radio frequency (RF) generation always shows an excellent spectral purity. Moreover, thanks to the achievable high repetition rates and the coherence properties of the FMLL, this laser scheme has also been proposed for digitizing, directly at RF, the received signal by electro-optical sampling. Thus the advantage of using just one device for signal generation in both the transmitter and receiver chain, makes the proposed solution a cost-effective architecture for microwave signal generation.

Keywords: Microwave photonics, Radar applications, Radar architectures and systems

Received 14 October 2010; Revised 11 January 2011; first published online 25 March 2011

I. INTRODUCTION

In the last few years the intriguing concept of very-high-performance reconfigurable radar transmitter is becoming feasible, mainly thanks to the introduction in radar application of technological development such as optical signal generation distribution and processing, photonic radio frequency (RF) up/down conversion, optical sampling, and beamforming. Photonics technologies applied to the microwave radar signal generation guarantees a high level of phase coherence and very good potential in terms of tunability and flexibility of the RF generation.

In this scenario, a digital approach could have a lot of advantages with respect to the classical radar architecture in terms of transceiver module size (avoiding the intermediate frequency up/down conversion stage) and cost (using commercial optical and optoelectronic devices), instantaneous pulse bandwidth, software-based capability, low phase noise for coherent radar processing such as moving target indicator (MTI) and moving target detector and finally for multifunctional radar systems.

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In addition, the demand of a new generation of surveillance radar, satellite communications, remote sensing and ground penetrating radar, as well as biomedical imaging, automotive and security systems, has driven the technology development in this direction [1, 2]. For this new kind of radar, the adaptivity of the microwave RF generation according to a variable scenario is one of the most important requirement, together with high operating frequencies, spectral purity, and flexible baseband signal generation.

Therefore, both high-frequency oscillators with very low phase noise for up/down conversion, and direct RF analog to digital converters are required.

In a conventional radar system, the spectral purity of the microwave signal also depends on the frequency stability of a STAble Local Oscillators and COHerent Oscillators. In order to satisfy the microwave regime and to improve the RF signal stability, the combination of different type of oscillators (i.e. acoustic and electrical) is necessary. Some of the weaknesses of this implementation is the usage of low-frequency resonant modes, the necessity of a great number of multiplication stages, and the strongly frequency-dependent performance of microwave signal in terms of amplitude and phase jitter [3].

This instability can induce a large phase noise on the target and clutter echo and can modify the signal spectrum, masking the presence of a small moving target echo. Moreover, it can produce ambiguity on the target radial distance and Doppler frequency estimation, constraining the time delay clutter canceller in the MTI processing and reduce the maximum signal to noise ratio in the data converter [4, 5].

In this paper we propose a photonic technique for realizing a reconfigurable microwave signal generation based on the beating of two laser modes coming from a stable regenerative fiber mode-locked laser (FMLL) and by means of an integrated interferometric structure. Thanks to its excellent stability and high repetition, this architecture has also been proposed as an electro-optical sampler for the received signal [6].

The proposed architecture, based on the use of just one device for both transmitter and receiver chain, also represents a cost-effective solution for microwave signal generation and guarantees the same performance up to ultra-high frequencies.

The aim of the proposed paper is to give an alternative approach for a flexible microwave signal generation suitable for high frequencies and in this direction results are shown for the photonic RF generation to demonstrate the effectiveness of the proposed approach. The results at 10 GHz show excellent spectral purity above 5 kHz if compared to a state of the art Agilent synthesizer even though the timing jitter increases for integration time greater than 10 ms. In order to achieve the same stability performance at both high and low frequencies, a phase locked loop between the laser and a synthesizer could be used.

In this work we extend the results obtained at the X band by evaluating the time jitter at 40 GHz and comparing it to the 10 GHz RF generation. Results show that the time jitter appears to be constant for the frequency detuning and make the proposed photonic microwave generation suitable for the new generation of radar applications exploiting high frequency.

II. RECONFIGURABLE MICROWAVE RADAR TRANSMITTER ARCHITECTURE

The architecture of the reconfigurable full digital radar transmitter is shown in Fig. 1. The generation of the RF carrier frequency is realized by beating two laser modes coming from a fiber mode locked laser into a photodiode. The FMLL is a fiber laser with excellent stability, thanks to the auto-regenerative feedback. It is able to produce very stable narrow optical pulses with repetition rate in the range from 1 to 40 GHz.

The optical spectrum is composed of a number of modes, whose spacing is equal to the pulse repetition rate. All the laser modes are phase locked with each other, thanks to the mode locking condition and the regenerative feedback that keeps the modes well locked [7, 8].

The selection of the two beating modes is realized by splitting the optical signal emitted by the FMLL in two arms by an optical splitter with a 50% splitting ratio. Each replica of the signal is filtered by an optical filter in order to select only one mode from the spectrum. In order to achieve a stable RF signal after the photodiode, the two arms of the scheme should be mechanically stable. The RF up conversion system can be realized by means of an electro-optical modulator (EOM), such as a Mach Zehnder interferometric modulator biased along its quadrature point [9], into one of the two arms.

The EOM is driven by a baseband signal generation block which addresses the digital synthesis of arbitrary waveforms – such as pulse trains, coded waveforms, frequency modulated waveforms such as chirp – with an adaptive bandwidth optimized according to the targets of interest and the environment. For example some of the key features of the baseband signal generation are the frequency, phase and amplitude sweeping capability, the number of bits of the digital to analog convert, and so on.

The two modes, the modulated and the unmodulated ones, are then combined together in a coupler and then sent in a photodiode which realizes the heterodyning, generating the final microwave signal. Finally, the RF amplification stage or a single high power amplifier (HPA) provides the necessary power for transmission [10]. Under this assumption, the concept of reconfigurable transmitter becomes feasible. As a matter of fact, it possible to tune the optical filters changing the operative wavelength by means of an electrical control. We are therefore able to select different laser modes with specified tuning frequency (i.e. a multiple of the laser repetition rate) according to the optical filter bandwidth. Therefore, exploiting a single photodetector, we can easily generate a modulated radar signal at different RF carriers up to W band and achieve frequency flexibility and reconfigurability.

Obviously, in order to make the proposed architecture operatively flexible, we should make use of a wideband direct digital synthesizer able to realize different type of radar signals (such as unmodulated pulses, chirp, and Barker codes). Moreover, an amplification stage composed of RF filters and power amplifiers capable of dealing with wide bandwidth are necessary.

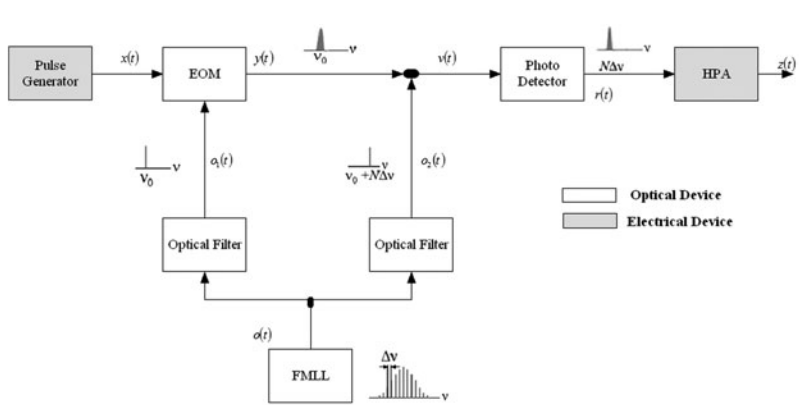

Fig. 1. Reconfigurable radar transmitter architecture.

Referring to Fig. 1, a mathematical expression of the transmitted signal is detailed in the following equations.

Under the assumption of $\omega_o = c/\upsilon_o$, where c is the speed of light, υ_o is the central wavelength, and $\Delta\ \omega = 2\pi\Delta f$. The FML laser signal $o(t)$ can be represented by a superposition of $2N + 1$ sinusoidal functions which represent the different modes propagating in the cavity:

$$o(t) = \sum_{q=-N}^{N} e^{i[(\omega_0+q\Delta\omega)t+\phi_q]}. \quad (1)$$

According to the mode locked condition, each mode is locked with each other because they have the same phase relation. Therefore equation (1) can be rewritten changing the term ϕ_q in ϕ:

$$o(t) = \sum_{q=-N}^{N} e^{i[(\omega_0+q\Delta\omega)t+\phi]}. \quad (2)$$

The two selected adjacent laser modes with a detuning equally to the laser repetition rates $\Delta\omega$ are:

$$o_1(t) = o(t) \otimes h_{OF1}(t) = Ae^{i[\omega_0 t+\phi]}, \quad (3)$$

$$o_2(t) = o(t) \otimes h_{OF2}(t) = Ae^{i[(\omega_0+\Delta\omega)t+\phi]}. \quad (4)$$

The EOM output signal $y(t)$ represents the modulated radar signal obtained through the electro-optical modulator and can be written as

$$\begin{aligned} y(t) &= T_{EOM}[x(t), o_1(t)] \\ &= A\left\{\frac{1}{2} + \frac{1}{2}\cos\left[\frac{\pi(x(t) + V_{bias})}{V_\pi}\right]\right\}e^{i[\omega_o t+\phi]}. \end{aligned} \quad (5)$$

The modulator transfer function is defined with the term T_{EOM}, $x(t)$ is the baseband radar signal, V_π is a characteristic parameter of the Mach Zehnder modulator, and V_{bias} is the selected voltage useful to drive the modulator in a quadrature point.

The signal $v(t)$, before the photodetection process, can be written as

$$\begin{aligned} v(t) &= y(t) + o_2(t) \\ &= A\left\{\frac{1}{2} + \frac{1}{2}\cos\left[\frac{\pi(x(t) + V_{bias})}{V_\pi}\right]\right\}e^{i[\omega_o t+\phi]} \\ &+ Ae^{i[(\omega_o+\Delta\omega)t+\phi]}. \end{aligned} \quad (6)$$

The photodiode realizes the beating between the modulated and the unmodulated signal and the output is given by

$$r(t) = (v(t))^2 = (y(t) + o_2(t))^2. \quad (7)$$

Some higher frequency terms, on the order of hundreds of THz, such as the ones at $2\omega_o$ and $2\omega_o$+$2\omega_o$+$2\Delta\omega$ have been filtered out by the photodetector with an analog bandwidth of the order of GHz. Therefore, the photodetector output signal can be written as

$$r(t) = A^2\left\{\frac{1}{2} + \frac{1}{2}\cos\left[\frac{\pi(x(t) + V_{bias})}{V_\pi}\right]\right\}e^{i[\Delta\omega t+\phi]}. \quad (8)$$

The signal $r(t)$ is then amplified by the HPA and the transmitted signal is given by

$$z(t) = r(t) \otimes h_{HPA}(t), \quad (9)$$

where $h_{HPA}(t)$ represent the HPA transfer function.

As previously stated, the proposed scheme offers the capability of reconfigurable transmission. As a matter of fact, by tuning the filters, it is possible to select laser modes at different detuning frequencies at any multiple of the laser repetition rate (i.e. the mode at frequency $2\pi\omega_o$ and the mode at frequency $2\pi\omega_o$+$2\pi N\Delta\omega$, where N represents the mode spacing). Moreover, the use of a digital baseband signal generator allows to match the RF signal modulation to the target and the environment.

III. X BAND SIGNAL GENERATION EXPERIMENT

A) Single carrier experiment

The architecture set up of the single-carrier experiment (Fig. 2) consists of a FMLL provided by PhoTrix operating at 10 GHz and able to emit 4 ps very stable pulses centered at 1550 nm. An erbium-doped fiber amplifier is used before the filtering process to guarantee sufficient optical power at the photodiode and a band pass filter with a 3 dB bandwidth of 0.15 nm and steep edges has been used to select two adjacent laser lines.

Figure 3 shows the filtered optical spectrum taken by an optical spectrum analyzer with a resolution bandwidth of 0.01 nm (corresponding to 1.25 GHz), compared with the original spectrum of the FMLL. The undesired modes are

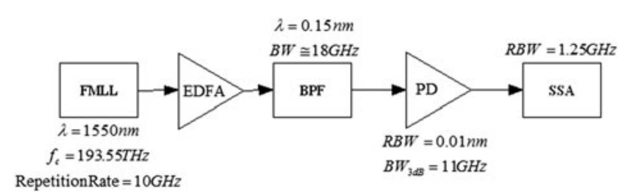

Fig. 2. Single-carrier experiment setup.

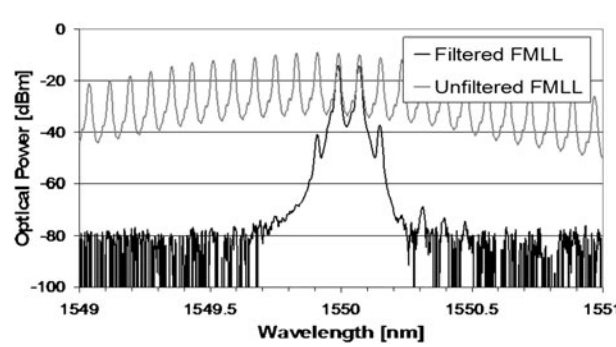

Fig. 3. Optical spectrum of the FMLL and the two selected adjacent modes.

suppressed more than 20 dB. The two selected modes are then injected in an amplified photo-detector with a 3 dB bandwidth of 11 GHz. Since the photodiode realizes a quadratic function of its optical input, the two inserted laser modes beat together generating a RF signal at a frequency that is equal to their detuning frequency (i.e. 10 GHz).

The microwave signal thus generated is analyzed by means of a signal source analyzer (Agilent E5052A). The obtained results are shown in Fig. 4, where the phase noise of the beating signal is compared with other RF sources, namely a VCO at 10 GHz (Narda FFCM), a state of the art synthesizer (Agilent E8257D), and the Anritsu RF generator. The performances of the heterodyning of two distributed-feedback (DFB) lasers with a detuning frequency of 10 GHz (EXFO IQS-2400 modules) have been presented in [7].

The comparison represented in Fig. 4 is realized for a frequency offset in the range 100–40 MHz. These range limits are due, respectively, to the usual time duration of the radar measurements (generally longer than 1 ms), and to the intrinsic limitation of the measurement instruments.

It should be noted from Fig. 4 that the proposed architecture (black line) and the state of the art RF synthesizer provided by Agilent (light gray line), show comparable behaviors, whereas the other RF generation methods present the worst performance, with phase noise levels tens of dB higher along most of the analyzed frequency range.

The proposed RF generation technique works better than the synthesizer in a wide range of frequency, from about 5 kHz up to 1 MHz. For offset frequencies above 1 MHz, even though the synthesizer shows less phase noise, both the RF sources perform well. On the other hand, for offset frequencies lower than 5 kHz, the state-of-the-art synthesizer shows extremely low phase noise, whereas our proposed photonic RF generation becomes more instable, although its behavior is still better than other RF sources.

Integrating the phase noise curve reported in Fig. 4 it is possible to calculate the timing jitter of the RF signal. The numerical equation used to calculate the signal time jitter is shown below [11]:

$$JITTER_{RMS} = \frac{1}{2\pi f_0} \times \sqrt{2\sum_{k=1}^{K-1} 10^{\nu_k/10} f_k^{-s_k/10}\left(\frac{s_k}{10}+1\right)^{-1}\left[f_{k+1}^{(s_k/10)-1} - f_k^{(s_k/10)-1}\right]}. \quad (10)$$

The terms f_o and f_k in equation (10) represent, respectively, the carrier frequency (equal to 10 GHz) and the frequency interval between two adjacent values of frequency offset (where the frequency offset axis has been divided into $K-1$ values used for the numerical integration).

Instead the terms ν_k and s_k represent, respectively, the phase noise value at a frequency offset f_k and the relative slope in the same point (the term Φ represent the phase noise level expressed in dBc/Hz) [12]:

$$\nu_k = \Phi(f_k), \quad (11)$$

$$s_k = \frac{\Phi(f_{k+1}) - \Phi(f_k)}{\log(\Phi(f_{k+1})) - \log(\Phi(f_k))}. \quad (12)$$

The integration interval should be chosen accordingly with the observation time related to the radar application (i.e. the phase coherence must be maintained for the whole observation time necessary to obtain a coherent detection of the target) and due to the limits of the measurement device.

We performed the calculation for different frequency intervals starting for example from 100 Hz up to 40 MHz, from 1 kHz up to 40 MHz and so on. The results comparing the proposed RF generation method and the Agilent synthesizer are reported in Fig. 5.

When the phase noise is integrated starting from 1 kHz up to 40 MHz, the obtained jitter for the filtered MLL decreases with respect to the time jitter of the Agilent RF synthesizer (i.e. between 1 kHz and 40 MHz, the obtained jitter is 12.1 fs for the filtered MLL and 15 fs for the Agilent synthesizer).

On the other hand, when the integration time starts from 500 Hz the timing jitter from the photonic architecture is larger than the microwave state of the art source (27.3 fs for the filtered MLL and 15.1 fs for the Agilent synthesizer).

The electrical spectra have been calculated, with a resolution bandwidth of 100 Hz, for the proposed technique and the RF Agilent synthesizer. The results have been presented in a previous work showing the same value of signal to noise floor ratio (above 80 dB) for both the signals and presenting very narrow line widths [13].

B) Multicarrier generation experiment

For the multicarrier RF generation experiment, we exploit integrated optics technology and specially designed dual-

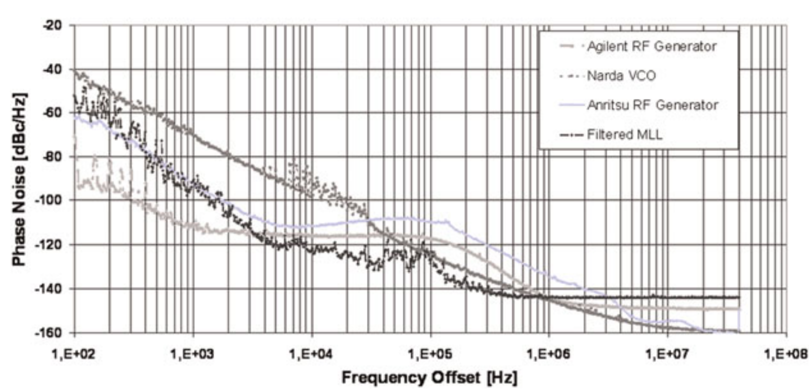

Fig. 4. Comparison of phase noise levels for different RF sources at 10 GHz.

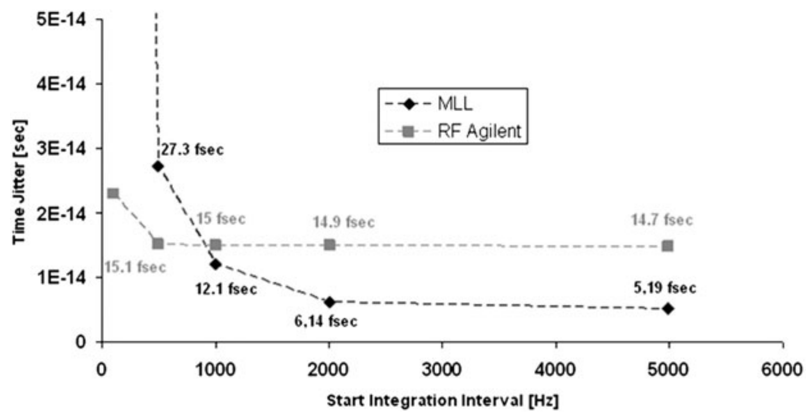

Fig. 5. Time jitter values for filtered MLL and Agilent E8257D synthesizer at 10 GHz.

wavelength fiber Bragg gratings (DFBG) which allow to select two different laser modes from a FMLL.

Under this assumption we do not separate the physical paths of the two modes avoiding any additional reciprocal phase fluctuations due to mechanical vibrations of the structure. The DFBGs are designed in order to reflect two narrow bands with a detuning frequency, respectively, of 20 and 30 GHz and so on, up to 100 GHz [14].

Therefore, the two selected modes are then injected into an amplified photo-detector with a given 3 dB bandwidth. Figure 6 shows the before mentioned optical spectrum measured by an optical spectrum analyzer with a resolution bandwidth of 0.01 nm (corresponding to 1.25 GHz),

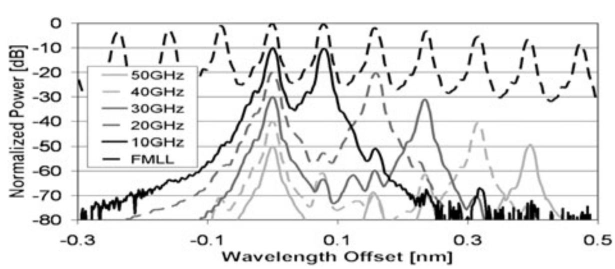

Fig. 6. Optical spectrum of the FMLL and the selected modes at multiple frequencies.

compared with the original spectrum of the FMLL. The undesired modes are suppressed more than 20 dB.

The relative phase noise measurements are shown in Fig. 7, where the phase noise values are compared between the 10 and 40 GHz RF generation for both optical and electrical carrier. The 40 GHz phase noise level increases for lower frequencies and, as expected it is slightly higher for higher carrier frequencies and shifted up of few dBs. In this case the frequency interval starts from 1 kHz in order to better distinguish each line. Each curve decreases rapidly with the offset frequency, reaching very low levels from around 5 kHz.

In this experiment the two carriers are simultaneously generated. Accordingly, this set-up shows a non-perfect equalization of the selected modes and the loss of responsivity of the photodiode. As a consequence, a phase noise degradation at higher frequencies has been experimented. As shown in Fig. 7 the optical microwave generation performs better than the classical electrical generation in particular starting from 5 kHz.

The time jitter analysis has been carried out separately for each RF generated carrier when the others have been switched off. Under this assumption, the evaluated time jitter (see equation (10)) appears to be constant for the multicarrier generation, with frequency integration upper limit fixed to 40 MHz, where the thermal noise is dominant (Fig. 8). It should be noted that considering an integration interval

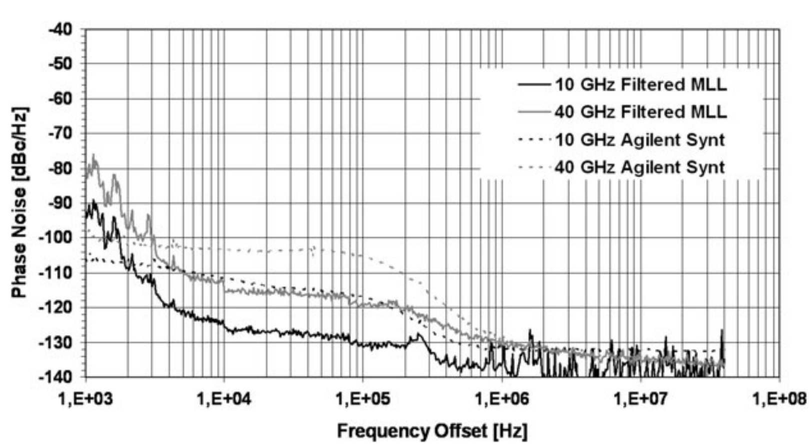

Fig. 7. Phase noise levels at different carrier frequencies (10 and 40 GHz) for the FMLL and for Agilent synthesizer.

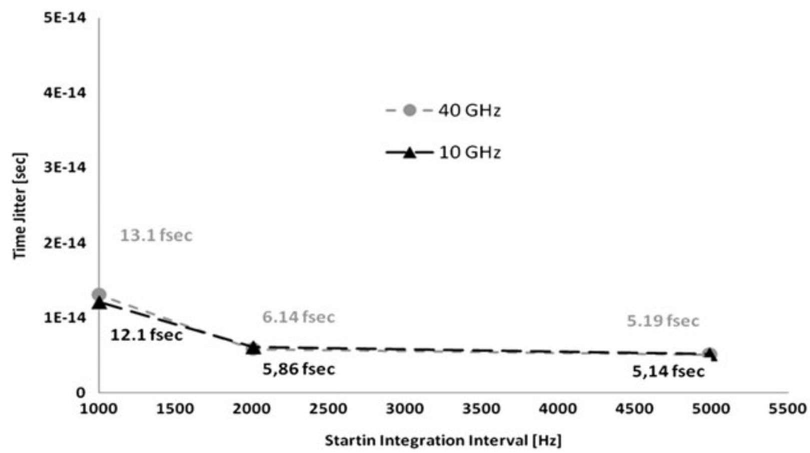

Fig. 8. Time jitter evaluation for a filtered MLL at 10 and 40 GHz.

starting from 100 Hz up to 1 MHz (where the thermal noise is not dominant), the time jitter values for 10 and 40 GHz generated carrier are still comparable [7]. Therefore, the proposed RF generation based on photonic techniques allows to generate high stable signals up to the W band suitable for the new generation of radar applications.

IV. CONCLUSION

The architecture of a photonic microwave radar transmitter based on the beating in a photodiode of two laser modes coming from a FMLL has been presented in this paper. The stability performance in terms of time jitter of the RF source have been evaluated at 10 and 40 GHz. The results, at 10 GHz, show excellent spectral purity above 5 kHz for the proposed technique compared to a state of the art Agilent synthesizer even though the time jitter increases for integration time greater than 10 ms. This architecture offers the capability for reconfigurable transmission, as a matter of fact by tuning the filters it is possible to select laser modes at different detuning frequencies, thus generating into the photodiode an RF carrier at any multiple frequency of the laser repetition rate. Moreover, the evaluated performances are guaranteed up to ultra-high frequencies (an example at 40 GHz have been presented) differently from conventional microwave sources whose performance strongly deteriorates with increasing frequencies. The proposed technique represents a cost-effective solution for microwave signal generation and has also been proposed for digitizing the received signal via an electro-optical sampling.

ACKNOWLEDGEMENT

This work is partially supported by the 7th FWP EU project PHODIR.

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