Photonic Microwave Harmonic Generator driven by an Optoelectronic Ring Oscillator

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***Abstract* — We describe a new architecture to generate microwave signals by optical means. Our system combines the advantages of two techniques: frequency multipliers and loop oscillators. A frequency multiplier allows to obtain high frequencies using frequency harmonic generation, nevertheless, a very good quality reference signal is necessary to drive the system. In our setup, this reference signal is obtained using a loop oscillator. Optoelectronic loop oscillators generate signals with good performance in terms of phase noise and linewidth. We present the theory related to those techniques and the experimental data obtained.**

***Index Terms* — Faraday effect, harmonic generation, microwave generation, optical modulation, phase noise.**

I. INTRODUCTION

The generation of microwave or millimeter-wave signals by optical means has been broadly studied in the last decades since high-frequency signals, with very low phase noise, can be generated. Optoelectronic oscillators are fundamental pieces of modern communication systems; these are used to generate high quality reference signals for applications ranging from telecommunications to onboard systems.

Many different approaches have been proposed to design microwave sources, based on optoelectronic techniques. Among these, two are particularly attractive due to the good performances of the generated signals that can be achieved with these methods.

In the first group, Harmonic Frequency Generators (HFG) using optical phase modulators have been proposed [1], [2]. They offer the advantage of frequency doubling and quadrupling of the electrical drive signal; however, the scheme requires a stable external microwave source to drive the modulator, which is not convenient taking into account simplicity and cost. To improve these systems some authors have proposed some configurations of self-oscillation [3], [4], however, the frequency is limited to the bandwidth of the phase modulator.

In the second group, Optoelectronic Loop Oscillators have been extensively studied. They can be configured in a variety of architectures to meet a particular need [5]-[8]. To increase the frequency and obtain excellent phase-noise and linewidth, it is possible to include intensity modulators and two or more feedback loops. For high frequency generators the necessary components for the system become expensive, hence a multi-loop scheme can be used to facilitate the singlemode selection. Nevertheless, this scheme increases the complexity and size of the loop oscillator. To overcome this problem some authors have studied the use of microspherical resonators as the optical delay element in the optoelectronic feedback loop of the oscillator. These microresonators can lead to a significant reduction of the size by replacing the optical fiber storage element [7].

In this document a new setup is presented. The system is composed of a microwave harmonic generator driven by an optoelectronic ring oscillator. In our setup no electronic microwave synthesizer is needed, and harmonics of the oscillating microwave reference frequency are generated.

II. PRINCIPLE

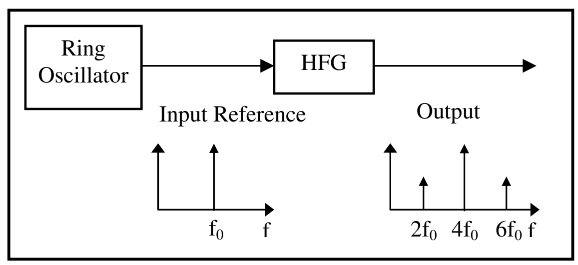

Fig. 1. System setup.

Our system is shown in Fig. 1. The Harmonic Frequency Generator (HFG) multiplyes the frequency of the reference signal by two, four or even six. An Optoelectronic Ring Oscillator provides the reference signal.

A. *Harmonic Frequency Generator (HFG)*

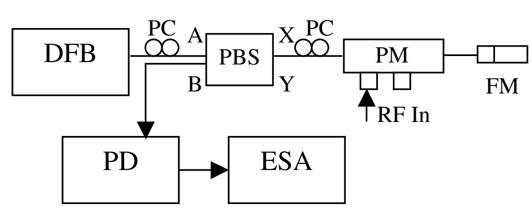

Fig. 2. HFG System.

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The experimental setup for the HFG is shown in Fig. 2. A Distributed Feedback (DFB) laser is used as a CW light source, the polarization of the optical signal is adjusted through a Polarization Controller (PC) for maximum transmission through a Polarization Beam Splitter (PBS), from port A to X. The signal at point X of the PBS is then injected into a $LiNbO_3$ phase modulator. At the output of the modulator, a Faraday Mirror (FM) is connected to create a reflective cavity, where the counter-propagating wave has an orthogonal polarization to the incident wave. Using a Faraday mirror the polarization orthogonality is preserved for counter-propagation waves in a linear media [1]. In this way the stability of the configuration is improved since the effect of perturbations on the fiber is cancelled. Then, the reflected optical signal passes by the Faraday mirror and the phase modulator in the opposite direction and enters in port X of the PBS through port A or B. The optical signal at port B will be modulated in amplitude, recovered with a photodetector and then, observed in an electrical spectrum analyzer (ESA).

The power at port B of the PBS is described by [1]:

$$P_{out}(t) = \frac{P_{in}}{2}\left(1+\cos\left\{\frac{\pi\left[V_{RF}(t)+\eta V_{RF}(t-t_d)\right]}{V_\pi}\right\}\right) \qquad (1)$$

where

$$V_{RF}(t) = A\cos(2\pi f_{RF} t) \qquad (2)$$

V_{RF} is the electrical signal applied to the electrodes of the modulator, V_π the voltage needed to shift the phase π radians, A is the amplitude of the sinusoidal signal and f_{RF} is the fundamental microwave frequency. P_{in} is the optical power emitted by the DFB laser, η and t_d are constants related to the phase modulator [1].

In (1) the cosine term can be expressed using Bessel series to obtain:

$$P_{out}(t) = \frac{P_{in}}{2}\begin{bmatrix}1+J_0(K)+2J_2(K)\cos(2\omega t)+ \\ 2J_4(K)\cos(4\omega t)+2J_6(K)\cos(6\omega t)+...\end{bmatrix} \qquad (3)$$

where:

$$K = \frac{A\pi(1+\eta)}{V_\pi} \qquad (4)$$

In (4) we observe that the relation between K and A is directly proportional, therefore, the K value can be controlled by increasing or decreasing A, the amplitude of the RF signal at the input of the phase modulator.

Fig. 3 illustrates the relation between K and $J_n(K)$ for n= 2, 4 and 6. Choosing a specific value of K we can find a point where J_2 is dominant over J_4 and J_6. We also can find a value of K for which J_4 has the highest value with respect to the other J_n. With a J_4 dominant value we verify from (3) that, at the output of the system, the 4th harmonic will be the dominant frequency. We placed our system at this operating state for the practical experiments. In practice the value of A to produce a 4th dominant harmonic is very high (28dBm in our case), therefore the phase modulator must be especially selected for this kind of application. This value is also the principal limitation for the generation of higher order harmonics. The phase modulator losses have to be taken into account also in the practical experiments to obtain the desired output power.

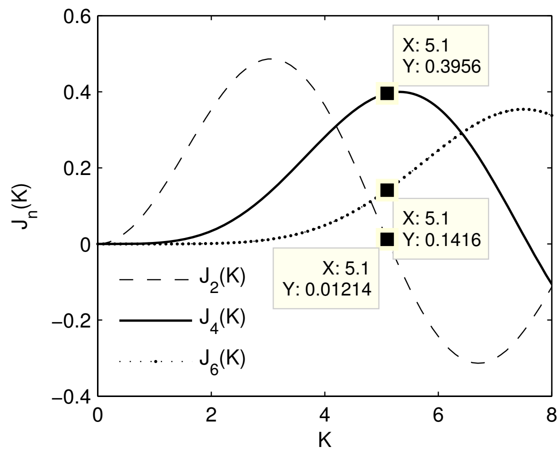

Fig. 3. Relation between $J_n(K)$ and K for n= 2, 4 and 6.

B. Ring Oscillator

In our system, the electrical signal used to drive the HFG is produced optically with an optoelectronic ring oscillator. The advantage of this proposal over others is the good quality of the signal in terms of phase noise and the cost and simplicity of the system. The importance of the reference is that the quality of the harmonic signal produced is limited by the reference signal phase noise with a degradation of 20log(h), where h is the number of the harmonic generated [1].

The optoelectronic loop oscillator can present slightly different architectures, but the principle is the same for all. The most simple configuration loop oscillator, (Fig. 4), uses a modulated laser diode together with a fiber-optic delay line to convert light energy into stable, spectrally pure microwave reference signals.

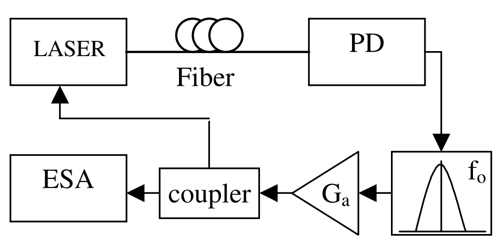

Fig. 4. Ring oscillator, simplest configuration.

In this configuration, oscillations start with noise that is filtered and amplified. Then, the modulated optical carrier is detected by a photodetector to provide a microwave signal, which is as well filtered, amplified and fed back to directly modulate the laser. This configuration supports self-oscillations, at a frequency determined by the fiber delay length and the bandpass characteristics of the filter.

The open loop transfer function of the loop oscillator can be written as [9]:

$$H_{OL} = H_{Laser} S P_o R_{ph} \alpha_E G_a \exp(j\omega\tau) \qquad (5)$$

where S is the photodetector responsivity, P_o is the optical power, R_{ph} is the load impedance of the photodetector, α_E is the electrical loss, G_a is the voltage gain of the RF amplifier and τ is the total group delay in the loop including phase shifts introduced by dispersive components. H_{Laser} is the transfer function of the laser. In the case of our experiments, we used a Vertical Cavity Surface Emitting Laser (VCSEL), due to some advantages of this one compared to an edge emitting laser diode, such as low power consumption. For a VCSEL the transfer function H_{Laser} can be written as [10]:

$$H_{Laser} = \frac{A_{vo}}{1 + j\omega\frac{2\xi}{\omega_n} - \frac{\omega^2}{\omega_n^2}} \qquad (6)$$

where A_{vo} is the voltage gain when the angular frequency ω=0, ω_n is the natural frequency of the system and ξ is the damping factor.

There are two conditions for self-sustained oscillations:

$$|H_{OL}| = 1 \qquad (7)$$

and

$$\omega\tau = 2\pi k, \quad k = 1,2,3,... \qquad (8)$$

Since the fiber is the principal source of delay of the oscillator, the free spectral range (FSR) of the oscillation modes is related with the fiber length according to [10]:

$$FSR = \frac{1}{\tau_C + \tau_D} = \frac{1}{\tau_C + \frac{Ln}{c}} \qquad (9)$$

where τ_D represents the delay in the fiber and τ_C represents the delay introduced by all other components, n is the refractive index of the fiber, c is the speed of light and L is the fiber length. According to (9) and the filter bandwidth, the fiber length has to be carefully selected. The length has to be small enough to permit one single oscillation mode into the system, and long enough to have an acceptable phase noise. It has been demonstrated [5], that phase noise is improved as the length of the fiber increases.

The simple configuration presented before has some limitations, with respect to the increment of frequency, since the modulation is realized directly in the laser diode. Some improvements can be achieved adding an external intensity modulator to the setup. In this way signals up to 75 GHz with a phase noise lower than –140 dBc/Hz at 10kHz could be generated [5]. In fact, the only limitation to achieve low phase noise at high frequencies is the availability of RF and optical components at these frequencies.

The mode selection and spurious level are determined by the quality of the RF filter. The closest mode to the peak frequency of the filter will oscillate. Spurious will show up at the frequencies of the natural modes. The spurious level will depend on the filter bandwidth. However, such filters are not always available at low cost and are harder to design at multi-GHz frequencies.

One method to improve these systems is obtained through an additional fiber loop or loops in parallel with the original fiber loop [11]. In these systems the modulated laser light in Fig. 4 is split into two optical fibers, a long fiber and a short one. Two photodetectors convert the light signals into separate microwave signals that are combined using a microwave power combiner. In one of the loops is inserted a RF phase shifter to tune one mode from the short loop close to a mode from the long loop within the filter band. This combined mode is enhanced in the oscillator forming a strong mode. All other mismatched modes are suppressed.

III. Experimental Results

In this section, we present some of the results obtained with our hybrid photonic microwave source, see Fig.1. First, we show the possible reference signals that can be obtained with different ring oscillators (Fig. 5 and Fig. 6); one of these reference signals is chosen to manage the HFG (Fig. 5-b). Then, we present the harmonics generated at the output of the HFG with the chosen reference (Fig. 7).

In Fig 5. we see three different spectra that have been generated with loop oscillators using different types of laser diodes. Fig. 5-a was obtained with a DFB laser, the DC current used to polarize the laser was 50mA, and the phase noise obtained was –108 dBc/Hz at 10kHz of the carrier. Fig 5-b was obtained with a multimode VCSEL, biased at 12.5mA and the phase noise obtained was –100 dBc/Hz. Fig. 5-c was generated with a monomode VCSEL with a DC current of 2.5mA but the power at the output was too low, therefore it was discarded as an option for a reference of the system. The linewidth of the signals was determined lower than 10Hz as the measure was limited by the resolution of the spectrum analyzer. In the experiments reported with the HFG, we chose the multimode VCSEL option due to the high power obtained at the output and the small biasing current employed.

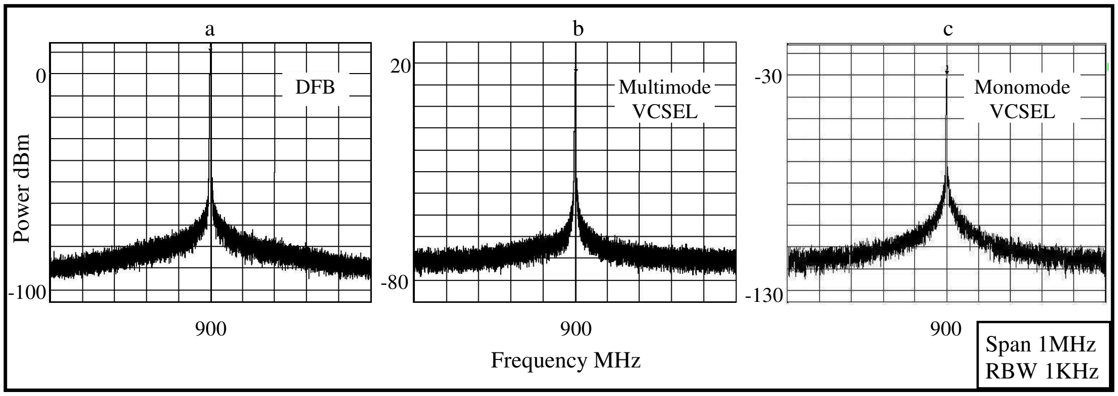

Fig. 5. Signals obtained with the simplest ring oscillator. Different kinds of laser diodes where used, a- DFB, b- Multimode VCSEL and c- Monomode VCSEL.

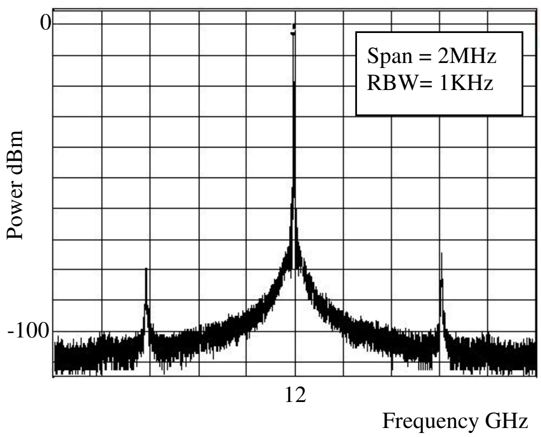

Fig. 6. Signal obtained with a dual loop oscillator. A DFB laser with an intensity modulator and double loop configuration where used.

In Fig. 6 we show the signal at the output of a double loop oscillator. For that case we used a DFB laser, an intensity modulator and a double loop configuration. This 12GHz signal has excellent characteristics of phase noise (-108 dBc/Hz at 10kHz of the carrier) and linewidth lower than 10Hz and can be used as a reference for the HFG. With this 12GHz reference signal we could obtain, at the output of the HFG, a signal at 48GHz or 72GHz. At the time of this publication we are limited by the bandwidth of the photodetector and the electric spectrum analyzer, hence, we cannot recover the output signal.

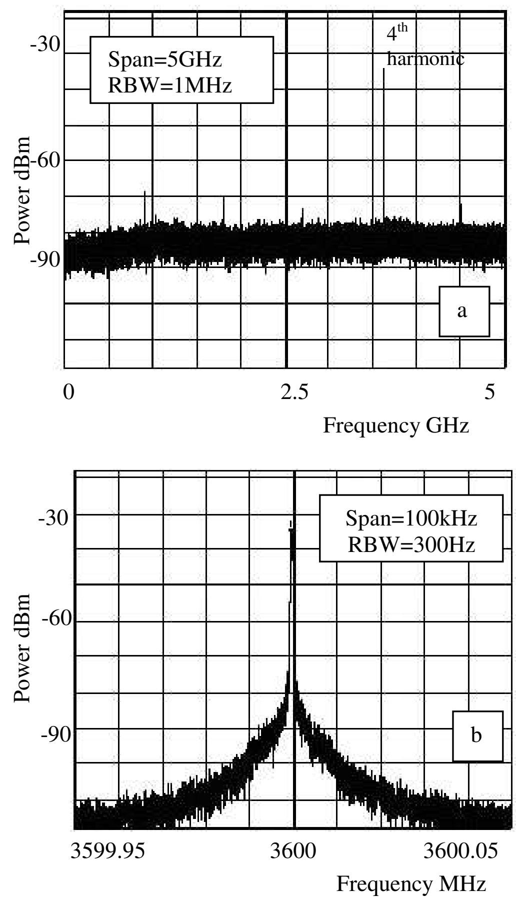

Fig. 7. Signal at the output of the HFG, obtained with a VCSEL- based oscillator. 7-a Harmonics at the output of the HFG, 7-b 4th dominant harmonic.

In Fig. 7 we show the output of the HFG observed in an ESA for an input signal of 0.9GHz produced with a VCSEL based oscillator. In this experiment, the output of the ring oscillator is taken from an electrical coupler (Fig. 4) and then is connected to the input of the HFG (RF In of the phase modulator in Fig. 2). In Fig. 7-a we observe the harmonics up to 4 and we confirm that 4^{th} harmonic is the predominant. In Fig. 7-b we see the 4^{th} harmonic in the ESA with a span of 100KHz. It is important to mention that the system has to use two lasers, one for the ring oscillator and another for the HFG.

IV. CONCLUSION

We have introduced a new architecture of hybrid opto-microwave oscillator with very good features in terms of stability, spectral-purity and possible rise in frequency. The system combines the advantages of the high frequencies that can be obtained with harmonic generators and the spectral purity of microwave optoelectronic oscillators. Some improvements can still be done, such as using an optical microresonator instead of the bulky optical fiber to reduce the oscillator size and weight, and VCSELs in the two architectures instead of DFB lasers to improve the integration and save power consumption.

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