Merging of Optoelectronic Techniques for Microwave Signal Generation

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***Abstract*—This paper describes some recent evolutions about optical generation of microwave signals. Among these, multi-loop ring oscillator and harmonic generation allow both rise in frequency and wide tunability. Besides, using microresonators and optical sources like VCSEL (Vertical Cavity Surface Emitting Laser) induces better integration and lower power consumption. Taking advantage of these attractive features, a new architecture of photonic microwave source is proposed.**

I. INTRODUCTION

Since many years, the need of high frequency microwave signals for telecommunication and datacom systems is growing. Many methods to generate them have been explored using, either totally electronic based architectures, or hybrid architectures, combining photonic and RF components. These last structures concentrate features inherent to photonic technology: possibility to generate very high frequency signals and the transportation of the signal to a remote location, taking advantage of the low losses of optical fibers.

Several architectures have been proposed to optically generate microwave signals. The first one is the optical hererodyning using two frequency-offset lasers [1]-[2]. This is one of the most interesting techniques because of the high achievable frequencies and the wide tunability. Nevertheless, even if spectral purity and phase noise can be improved by using an optical phase-locked loop or an optical injection locking, the use of two lasers and the complexity of the feedback loop make this system power consuming and noisy. In the same way, a second technique is based on the beat-signal obtained from a bimode laser [3], whose interest is to correlate the frequency drifts of the two laser modes, but whose drawback is a weak accordability. The well-known optoelectronic oscillator using a long, fibered feedback loop provides a microwave signal presenting a very high spectral purity [4]. New configurations have appeared to rise in frequency. We review in this paper the dual-loop optoelectronic microwave oscillator and present a new technique of harmonic generation taking advantage of the good features of the ring oscillator. We present also two ways leading to a low-cost high integration of such systems, using a Vertical Cavity Surface Emitting Laser (VCSEL) and a microresonator.

II. OPTICAL FIBER BASED MICROWAVE OSCILATOR

A. *Single loop microwave oscillator*

The optoelectronic microwave oscillator is composed of a loop containing a laser diode, a Mach Zehnder electrooptic modulator (MZM), an optical fiber, a photodetector, a microwave filter, and a microwave amplifier [4]. This is the architecture presented in Fig. 2 without taking into account the loop 2. The intensity modulated laser beam is injected into an optical fiber whose output is connected to a photodetector which generates the microwave signal. This signal is then filtered and amplified before being fed back to the RF modulation port of the MZM. Oscillations start thanks to noise sources described below. Only frequency components satisfying the phase and gain conditions are amplified in the loop and emerge from the noise floor. These modes appear at regularly spaced frequencies. The frequency space between two successive modes is the free spectral range (FSR), closely dependent of the length of the loop, equal to $1/[\tau_e+(n_{of}.L/c)]$, where τ_e is the delay due to electrical components, n_{of} is the optical fiber index, L, its physical length and c is the speed of light in vacuum. The RF bandpass filter selects only one among these multiple oscillation modes.

Using the Leeson's model [5], the phase-noise spectral density can be theoretically evaluated, taking into account the following noise sources contributing to the total intensity noise at the photodetector:

- Relative Intensity Noise (RIN_{LAS}) of the laser source due to spontaneous emission.
- Double Rayleigh scattering, modelized by a relative intensity noise RIN_{DRS} and consisting in scattering twice of a fraction of the optical power by inhomogeneities in the optical fiber resulting in a weak delayed replica copropagating with the original optical wave.

- Reflected Rayleigh scattering, modelized by a relative intensity noise RIN_{RRS} and consisting in scattering once by inhomogeneities in the optical fiber and reflection at the fiber's input of a fraction of the optical power.

Besides these sources of intensity noise, we must take into account the two noise sources:

- Shot noise due to the statistical nature of the generation of photoelectrons and modelized by the mean square value of noise current in a bandwidth Δf, $<i_{sh}^2>$.
- Thermal noise, generated by two components: the photodetector through its load impedance Z_{ph} and the amplifier through its input impedance Z_e. This noise is modelized by the mean square value of noise current in a bandwidth Δf, $<i_{th}^2>$.

Finally, the total noise current in a bandwidth Δf is given by :

$$<i_N^2>=<i_{th}^2>+<i_{sh}^2>+I_{ph}^2\,(RIN_{Las}+RIN_{DRS}+RIN_{RRS})\,\Delta f \qquad (1)$$

where I_{ph} is the mean photocurrent.
Then, the noise power at the input of the amplifier is :

$$P_N=<i_N^2>.Z_e.[Z_{ph}/(Z_{ph}+Z_e)]^2=S_N.\Delta f \qquad (2)$$

Where S_N is the noise spectral density at the input of the amplifier. Then, the Leeson's model gives the phase noise spectral density $S_\phi(f)$ at the output of the oscillator as:

$$S_\phi(f)=\left(1+\frac{1}{f^2}\left(\frac{f_{osc}}{2.Q_c}\right)^2\right)\frac{S_N(f).G_A^2}{P_{osc}}\left(1+\frac{f_c}{f}\right) \qquad (3)$$

Q_c is the quality factor of the resonator equivalent to the feedback loop, G_A is the microwave amplifier voltage gain and f_c is its Flicker frequency (to take into account the amplifier Flicker noise) , P_{osc} is the microwave oscillation power, f is the offset frequency from the carrier. The quantity $S_N(f).G_A^2/P_{osc}$ is the noise to signal ratio (NSR), whose noise contributions appear in Fig.1. This figure shows that the noisiest element in the oscillator is the optical fiber. Otherwise, thermal fluctuations affect the long-term frequency stability, particularly through the fiber sensitivity, that forces us to place it in a bulky thermally controlled box. Consequently, the use of an optical microresonator instead of the bulky optical fiber is a good way to reduce box, and so, oscillator dimensions.

B. Dual loop optoelectronic oscillator

In the previous architecture, the single frequency working mode is obtained by introducing an RF filter in the loop. As the phase noise decreases when the loop delay increases, an easy way to improve noise features of the oscillator is to use a longer fiber. However, because the FSR decreases dramatically when fiber's length increases, and because of the difficulty to find filters narrow enough, particularly at high frequencies, to select only one mode, this architecture is no longer relevant to generate single mode signals at frequencies beyond a few gigahertz. Using a dual (one short and one long) loop architecture is a good way to overcome this matter [6-7]

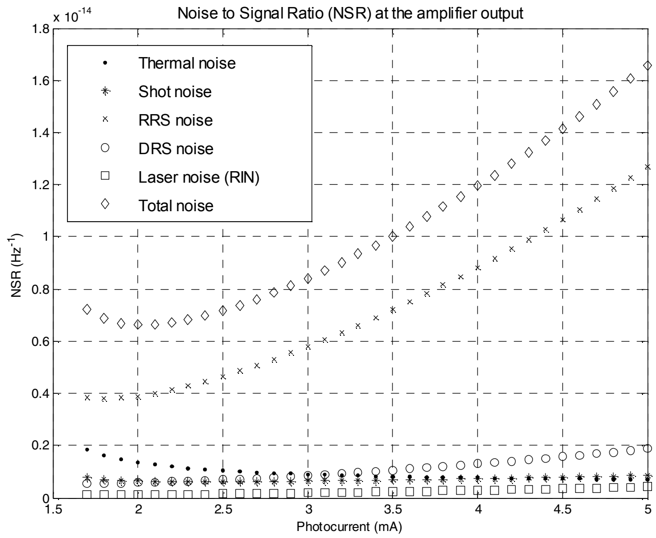

Figure 1. Simulated noise to signal ratio relating to different noise sources and total NSR at the amplifier output for a 1 km fiber length.

(Fig. 2). The transfer function of this dual loop oscillator is given by:

$$P(f)=[G_A^2V_N^2/2R_{ch}]/[1+G_{bo}^2(A_1^2+A_2^2)+2G_{bo}^2A_1A_2\cos(\omega(\tau_1-\tau_2)) -2G_{bo}(A_1\cos(\omega\tau_1+\varphi_e)+A_2\cos(\omega\tau_1+\varphi_e))] \qquad (4)$$

where V_N is the noise voltage, R_{ch} the load impedance of the amplifier, G_{bo}, the open loop gain of the electric part of the loop, A_1, A_2, τ_1, τ_2 are respectively the amplitudes and time delays associated to transfer functions of the two optical fibers, ω is the frequency of the generated microwave signal and φ_e is the phase associated with the microwave components. In this case, we ensure a loop gain slightly below unity in each loop, so as modes satisfying phase condition do not emerge from the noise. However, by adjusting the phase in one of the loops, the phase condition can be satisfied in each loop for the same frequency, which induces a global gain higher than unity, initiating oscillations (Fig. 3). A dual loop oscillator has been designed using two fibers of 300 and 1000 meters length. The oscillation frequency is 12 GHz, the phase noise of the realized oscillator is below –108dBc/Hz at 10 kHz from the carrier for a linewidth below 10 Hz (phase noise and linewidth measurements are limited by the noise and resolution features of the spectrum analyzer).

C. VCSEL based optoelectronic oscillator

The aim of such an oscillator is to take advantage of the low cost of VCSEL to realize cheaper systems. On the basis of the single loop optoelectronic oscillator, we have realized an architecture replacing the DFB (Distributed Feedback) laser emitting at 1550 nm, the MZM and the monomode optical fiber by a directly modulated multimode VCSEL laser emitting at 850 nm and a multimode fiber [8]. Fig. 4 shows the spectrum of this new oscillator. The oscillation frequency is 900 MHz, the linewidth is narrower than 10 Hz and the phase noise is –100dBc/Hz at 10 kHz from the carrier.

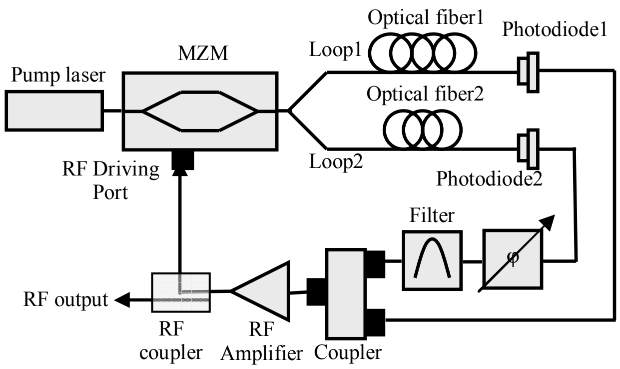

Figure 2. Block diagram of the dual loop oscillator.

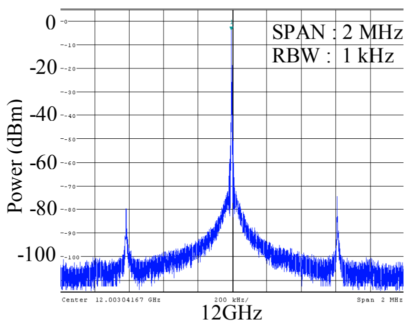

Figure 3. Dual loop oscillator spectrum.

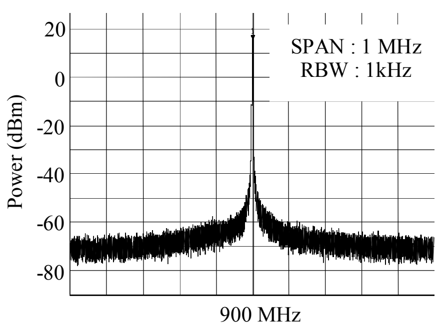

Figure 4. Spectrum of the VCSEL based optoelectronic oscillator.

III. OPTOELECTRONIC MICROWAVE RING OSCILLATOR USING AN OPTICAL MICRORESONATOR

The emergence of optical microresonators with very high quality factors (about 10^9–10^{10}) [9] as photonic components several years ago, offers new perspectives in the field of microwave photonics. For microwave signals generation, they can be used as filter component. Among them, dielectric spheres made of silica are particularly interesting since they are easy to make.

Modes in a dielectric sphere of radius R_{sph} are described by their TE or TM polarization and three integers defining the spatial distribution of the field: l, the polar mode number, m, the azimuthal mode number and n, the radial mode number. In the case of Whispering Gallery Modes (WGMs), the value of n is near unity and $m \approx l$. Under these conditions, the field propagates near the surface, close to the equatorial plane of the sphere and, assuming a time harmonic dependent field, it is described by the following equations (Fig. 5.a. and Fig. 6):

$$\vec{E}^{TE} \approx E_\theta.\vec{e}_\theta = \frac{-jm}{\sin\theta} z_l(kr) P_l^m(\cos\theta) e^{-jm\varphi}.\vec{e}_\theta \qquad (5)$$

$$\vec{H}^{TE} = \frac{j}{\omega\mu_0}\left[j\frac{m}{r.\sin\theta} E_\theta.\vec{e}_r + \frac{1}{r}\frac{d(rE_\theta)}{dr}\vec{e}_\varphi \right] \qquad (6)$$

$$\vec{H}^{TM} \approx H_\theta.\vec{e}_\theta = \frac{-jm}{\sin\theta} z_l(kr) P_l^m(\cos\theta) e^{-jm\varphi}.\vec{e}_\theta \qquad (7)$$

$$\vec{E}^{TM} = \frac{-j}{\omega\varepsilon_r\varepsilon_0}\left[j\frac{m}{r.\sin\theta} H_\theta.\vec{e}_r + \frac{1}{r}\frac{d(rH_\theta)}{dr}\vec{e}_\varphi \right] \qquad (8)$$

with $z_l(kr) = j_l(n_{sph}k_0 r)$ for $r \le R_{sph}$ and $z_l(kr) = h_l^{(2)}(k_0 r)$ for $r > R_{sph}$, where n_{sph} is the sphere index, j_l and $h_l^{(2)}$ are the bessel and hankel functions, respectively, k_0 is the wave number in vacuum, r, θ, φ are spherical coordinates defined in Fig. 5.

Resonance wavelengths in the microsphere are determined by solving the characteristic equation, obtained by matching tangential fields at $r=R_{sph}$. Coupling can be realized through an evanescent wave coupling technique such as total reflection on the face of a prism or using tapered fibers. On the basis of the single loop oscillator architecture, we realized an optoelectronic oscillator using a microresonator instead of the optical fiber and two high index prisms (Fig. 5.b and Fig. 7). The first prism is used to couple optical power in the sphere, the second prism, to extract it. The distance between the sphere and each prism is a few hundreds of nanometers. That's why prisms are moved around the fixed sphere by piezoelectric drives. For the moment, we couple an optical power of a few microwatts. Further experiments are being realized to improve this coupling.

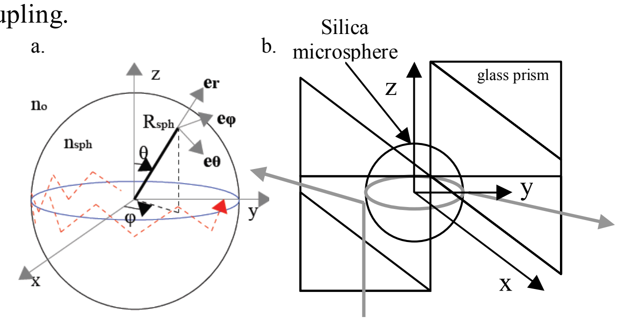

Figure 5. a. Coordinate system used. b. principle of the prism coupling.

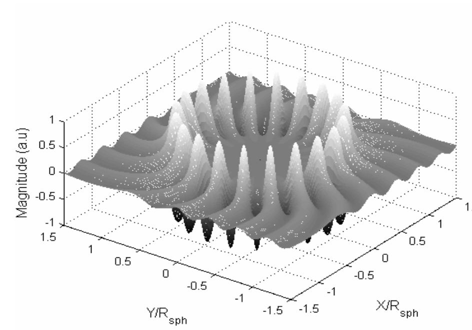

Figure 6. Normalized calculated magnitude of the electric field for the mode TE (l,m,n)=(20,20,1).

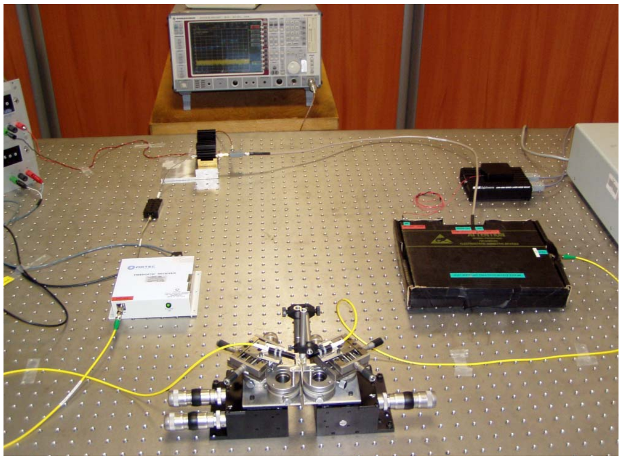

Figure 7. Photography of the optoelectronic microwave oscillator using a microresonator.

IV. Application to the Harmonic Generation of Microwave Signals

The good spectral features of the ring oscillator can be used to produce a signal at a higher frequency by the harmonic generation depicted in [10,11] and in Fig. 8. Based on the previously described VCSEL based oscillator at 900 MHz, this architecture generates harmonic frequency signals using the polarization dependent characteristics of a phase modulator. It converts phase variation into intensity variation with a very stable configuration in which, the effects of the perturbations in the fiber are cancelled. Fig. 9 shows the fourth harmonic generated at 3.6 GHz.

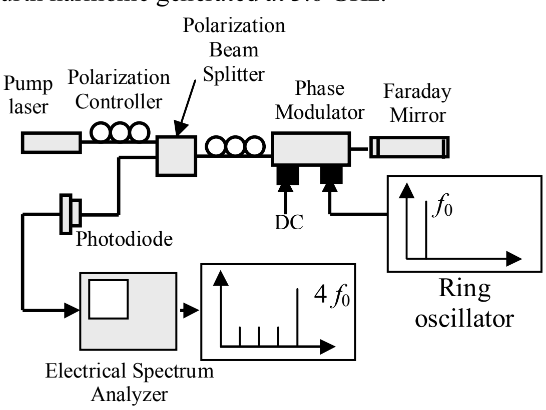

Figure 8. Block diagram of the harmonic frequency generator.

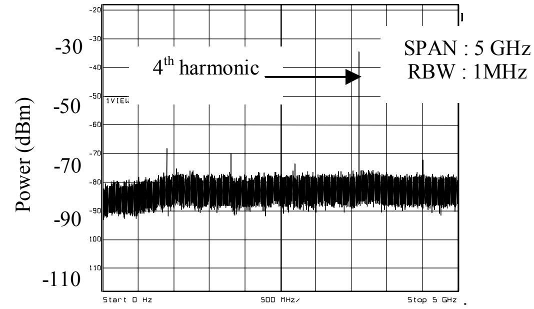

Figure 9. Spectrum of the output of the harmonic frequency generator.

V. Conclusion

We have presented several studies relating to the optoelectronic ring oscillator: multi-loop configuration, microresonator in place of fiber delay line, VCSEL as optical source. Then, taking advantage of the potentialities of each component, we have proposed a new architecture of photonic microwave source which could generate microwave signals with good spectral purity, wide frequency tunability and could be packaged in a small volume.

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