Compact optoelectronic microwave oscillators using ultra-high Q whispering gallery mode disk-resonators and phase modulation

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Kirill Volyanskiy

Laurent Larger
Institut FEMTO-ST

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Kirill Volyanskiy,[1] **Patrice Salzenstein,**[2] **Hervé Tavernier,**[1]
Maxim Pogurmirskiy,[3] **Yanne K. Chembo,**[1,*] **and Laurent Larger**[1]

[1] *Optics Department, FEMTO-ST Institute (UMR CNRS 6174), 16 Route de Gray, 25030 Besançon cedex, France*
[2] *Time-frequency Department, FEMTO-ST Institute (UMR CNRS 6174), 26 chemin de l'Epitaphe, 25030 Besançon cedex, France*
[3] *National Research University of Information Technologies, Mechanics and Optics (ITMO), Saint-Petersburg, Russia*
**yanne.chembo@femto-st.fr*

Abstract: We demonstrate a compact optoelectronic oscillator based on phase modulation and ultra-high Q disk resonators. A 10.7 GHz microwave is generated, with a phase noise of -90 dBrad^2/Hz at 10 kHz from the carrier, and -110 dBrad^2/Hz at 100 kHz.

OCIS codes: (130.0250) Optoelectronics; (350.4010) Microwaves.

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1. Introduction

Optoelectronic oscillators (OEOs) are ultra-pure microwave generators based on optical energy storage instead of high finesse radio-frequency (RF) resonators [1]. These oscillators have many specific advantages, such has exceptionally low phase noise, and versatility of the output frequency (only limited by the RF bandwidth of the optoelectronic components). Such ultra-pure microwaves are indeed needed in a wide range of applications, including time-frequency metrology, frequency synthesis, and aerospace engineering.

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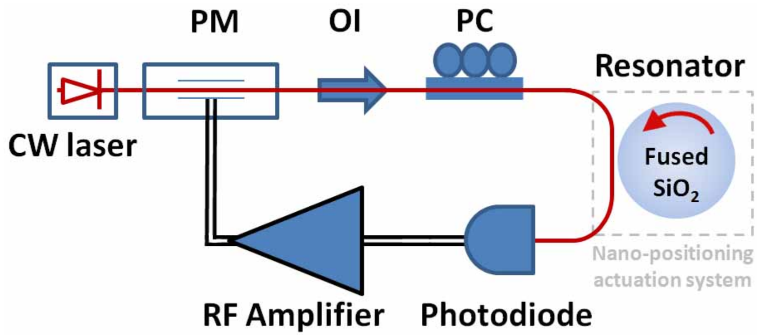

Fig. 1. Experimental setup of the compact OEO. CW: continuous-wave; OI: optical isolator; PC: polarization controller; PM: phase modulator; RF: radio-frequency; SiO_2: silica.

In the most usual versions of OEOs, the optical storage element is an optical fiber delay line, and the output microwave frequency of the system is defined by a narrow RF band-pass filter in the electronic segment of the feedback loop. This original configuration yields excellent phase noise performance, as low as -163 dBc/Hz at 10 kHz from a 10 GHz carrier [2]. However, it also has several drawbacks. The first one is that the optical delay line is bulky, so that the oscillators can not be considered as an optimal transportable microwave source. Along the same line, this bulky delay line element has to be temperature-stabilized, a feedback control process which is energy greedy. Finally, the fiber delay line generates spurious peaks very close to the carrier (few tens of kHz), which are highly detrimental in several applications.

An alternative to circumvent all these drawbacks is to replace the optical fiber delay line by an ultra-high Q whispering gallery-mode (WGM) optical resonator (see for example ref. [3]). In this case, the microwave oscillation frequency is defined by the free-spectral range (FSR) of the resonator, while energy storage is performed by trapping laser light into the ultra-low loss WGMs. This configuration provides an interesting solution to the problems raised above, as the same element (WGM resonator) at the same time defines the oscillating frequency and ensures the energy storage. In particular, these WGM optoeletronic oscillators are compact, they do not generate delay-induced spurious peaks in the RF spectrum, and they are compatible with compact temperature control system, since it is limited to a much smaller volume (that of the optical disk). This ultra-pure microwave source thereby becomes easily transportable. This is a highly desirable feature in many applications, such as in aerospace engineering for example.

The other advantage of this new configuration is the use of phase modulation instead of intensity modulation. Effectively, intensity modulators are environment sensitive devices, which is not desired when high device stability is required for pure tone generation. On the contrary, phase modulation involves a differential phase-to-intensity conversion, which is not sensitive to electro-optic drifts (slow charge re-distribution, which is varying the interference condition, and thus the operating point of the interferometric device). The fact that a resonator is an imbalanced interferometer is precisely the situation required for the differential phase-to-intensity conversion. This originates from standard differential optical phase modulation techniques, which are known in optical communications to offer superior performances as soon as the modulation speed is very high ($>$ 10 Gb/s).

In this letter, we report a new configuration where a microwave is generated using a single-loop OEO with ultra-high Q WGM disk resonator. In the next sections, we present in detail the experimental setup of this OEO, analyze theoretically its operating mode, and finally present the experimental results on phase noise measurement.

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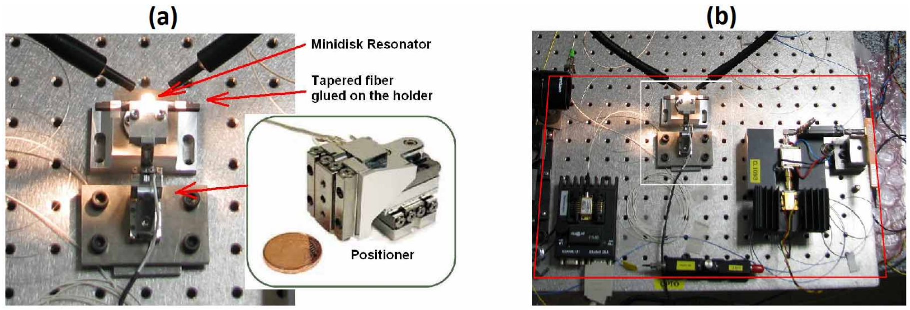

Fig. 2. (a) Picture of the coupled resonator, using a nano-positioning system. (b) Picture of the whole oscillator. The large (red) rectangle represents the A_3 format (297×420 mm^2), while the small (white) rectangle represents the coupled resonator as displayed in (a).

2. The experimental system

The OEO under study is presented in Fig. 1. This architecture is reminiscent of the original configurations of single-loop OEOs. Here, the main differences are that the fiber delay line has been replaced by a WGM resonator, while the Mach-Zehnder modulator has been replaced by a phase modulator. The fused silica optical resonator has a Q factor of 10^8, and diameter ~ 5 mm, yielding a FSR of 10.7 GHz. The phase modulator has a half-wave voltage $V_\pi = 2.8$ V, and it is driven by a 1550 nm semiconductor laser (RIO Orion laser module), internally stabilized with a precision of 2 pm. The phase-modulated laser beam is first polarization-controlled in order to select TE or TM modes, and then critically coupled into the resonator through a tapered fiber. In other words, the intrinsinc (Q_{int}) and extrinsic (Q_{ext}) quality factors are set to be equal. The difference of optical index between fused silica ($= 1.44$) and air $\simeq 1$ enables the internal reflection inside the resonator. Finally, the optical output signal of the tapered fiber is detected with a photodiode (DSC30S). A transduced microwave is obtained, and is used to close the feedback loop in the RF input of the phase modulator after amplification (AML 218L4401 driver with a 42 dB gain).

A major source of losses in the optical cavity is surface roughness and degradation through water vapor pollution. It is also known that fused silica is sensitive to hydroxyl groups [4]. In order to clean the impurities deposited on the surface and obtain a smoother surface, our resonator has been cleaned with a 90% diethyl ether $[(CH_3\text{-}CH_2)_2O_2]$ – 10% isopropyl alcohol $[(CH_3)_2CHOH]$ solution in an ultrasonic environment. This procedure enables to increase the value of the Q factor.

We have also significantly improved the coupling efficiency with the use of a 1 nm resolution nano-positioning system. Figure 2a represents this positioning system with tapered fiber and our disk-resonator. The tapered fiber is coupled to the fused silica disk-resonator. White light illumination is only for monitoring of the coupling zone via a video camera, which is helpful for the preliminary rough positioning of the taper close to the disk resonator. We can thereby monitor how close are the fiber and the resonator. The nano-positioning system provides enough space for movement in a 12×12 mm^2 surface.

A picture of the whole oscillator is represented in Fig. 2b. In our laboratory experimental setup, the WGM OEO is quite compact and easily fits into the A_3 format (297×420 mm^2). Optimized packaging could certainly reduce this size by a factor of ten, and even more if integrated photonics solutions are considered.

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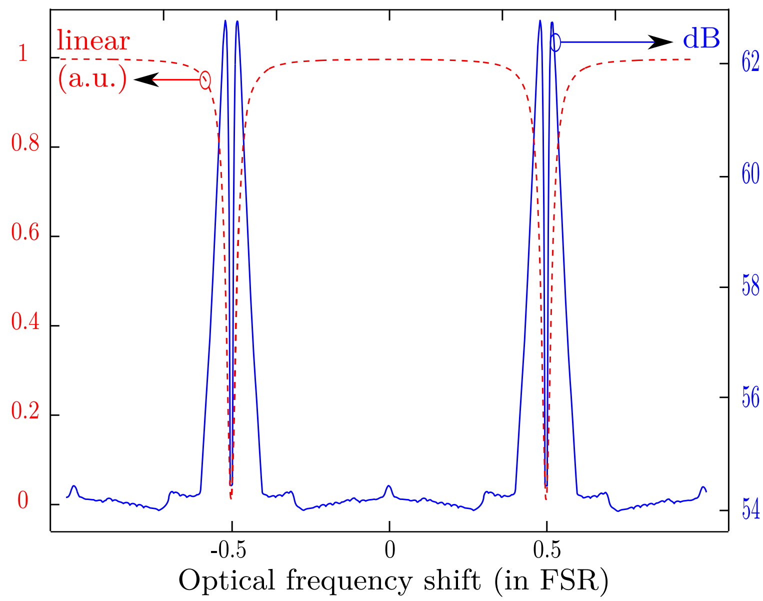

Fig. 3. Numerical simulation of the optical and RF responses of the disk-resonator, for $\kappa = 0.12$ and $\gamma = 0.9$. The red dotted curve is the standard static optical response in intensity of the disk, for a non-modulated laser beam of different central optical frequencies (horizontal axis) varied over more than an FSR [squared modulus of Eq. (2)]. The blue continuous line is obtained from a numerical simulation of Eq. (5), extracting the strongest Fourier peak detected in the RF fluctuations of the ring output intensity, when an optical phase modulation is applied at RF frequencies around the FSR. The right vertical scale indicates the maximum Fourier peak in dB, at a given optical central frequency, for RF modulation frequencies spanning 0.6 to 1.8 times the FSR; notice that the RF anti-resonance occurs at the doubled RF frequency, the second harmonic, whereas all the other points of this curve are maxima obtained at the usual fundamental of the RF modulation frequency.

3. Theoretical analysis

As mentioned earlier, the use of phase modulators in OEOs is unusual. The reason is that photo-detectors can only detect intensity modulations. Therefore, an imperative requirement to be met in the oscillation loop is the capability for the photodiode to detect the optical transduction of the microwave signal that is fed back in the optical segment *via* the phase modulator. This essential condition is generally fulfilled in optical fiber-based OEOs because the Mach-Zehnder modulator directly performs an intensity modulation of the laser light beam. Hence, it appears that for our system to oscillate, the WGM resonator should act as an optical phase-to intensity converter, which is expected to be highly selective with respect to optical side bands generated by the EO phase-modulation. Therefore, the efficiency of the oscillator will critically depend on the transmittance *in optical intensity* of the resonator.

In order to determine this transmittance, we consider a quadrupole approach [5] where E_1 and E_4 are respectively the input and output complex amplitudes fields of the tapered fiber (slowly varying envelopes) in the coupling zone, while E_2 and E_3 are respectively the input and output complex amplitude fields of the disk resonator in the same zone. These latter fields are

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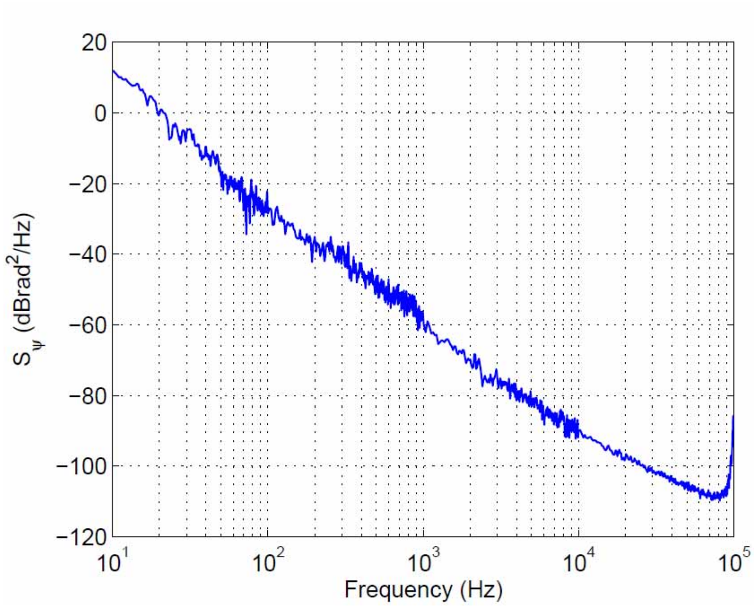

Fig. 4. A typical phase noise spectrum of the WGM OEO with phase modulation. The microwave has a frequency of 10.7 GHz and an output power of 1.6 dBm. The phase noise performance is −90 dBrad^2/Hz at 10 kHz from the carrier, and −110 dBrad^2/Hz at 100 kHz.

related as $E_2 = \sqrt{\gamma} e^{i\varphi} E_3$ after a round-trip in the disk. On the other hand, we also have

$$\begin{bmatrix} E_3 \\ E_4 \end{bmatrix} = \begin{bmatrix} i\sqrt{\kappa} & \sqrt{1-\kappa} \\ \sqrt{1-\kappa} & i\sqrt{\kappa} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \end{bmatrix}, \tag{1}$$

where κ stands for the energy coupling coefficient from the tapered fiber to the disk, and γ for the internal losses into the disk-resonator. On the other hand, $\varphi = 2\pi \nu n_0 L/c = 2\pi\nu/\Delta\nu_{\mathrm{FSR}}$ is the optical phase shift after one round trip inside the cavity, ν is the optical frequency, n_0 is the refraction index, L is the circumference of the disk and $\Delta\nu_{FSR}$ is the free spectral range of the resonator. The optical transmittance in amplitude can therefore be determined as

$$\mathscr{T}(\nu) = \frac{E_4}{E_1} = \frac{1}{\sqrt{1-\kappa}} \cdot \frac{1-\kappa-q(\nu)}{1-q(\nu)}, \text{ with } q(\nu) = \sqrt{\gamma(1-\kappa)} \exp\left(i2\pi \frac{\nu}{\Delta\nu_{\mathrm{FSR}}}\right). \tag{2}$$

In the steady state regime, the input electric field in the tapered fiber can be written

$$\mathscr{E}_{in}(t) = E_1(t)\, e^{i2\pi\nu_0 t} = \sqrt{P} \exp\left[i\pi \frac{V_0}{V_\pi} \cos\omega_{\mathrm{RF}} t\right] e^{i2\pi\nu_0 t}, \tag{3}$$

where P is the input laser power, ν_0 is the laser frequency, V_0 is the input microwave voltage amplitude at the phase modulator, and ω_{RF} is the microwave angular frequency (the phases for the laser light and the input microwave have been set to zero for the sake of simplification).

The Jacobi–Anger expansion

$$e^{ix\cos\theta} = \sum_{p=-\infty}^{+\infty} i^p \, \mathrm{J}_p(x)\, e^{ip\theta}, \tag{4}$$

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can be used to Fourier-expand the phase modulated terms in harmonics of $\omega_{\rm RF}$, with J_p being the p-th order Bessel function of the first kind. The output field of the tapered fiber becomes

$$\mathscr{E}_{out}(t) = E_4(t)\, e^{i2\pi\nu_0 t} = \sqrt{P} \sum_{p=-\infty}^{+\infty} i^p \, \mathrm{J}_p \left[\pi \frac{V_0}{V_\pi}\right] \mathscr{T}(\nu_p)\, e^{i2\pi\nu_p t}, , \qquad (5)$$

with $\nu_p = \nu_0 + p\,\omega_{\rm RF}/2\pi$. The output field is therefore a superposition of various spectral components and when phase-matching conditions are met, the output power $|\mathscr{E}_{out}|^2$ oscillates at the frequency of the generated microwave. The phase matching condition of interest for us is associated to the resonance condition $\omega_{\rm RF} = 2\pi\Delta\nu_{\rm FSR}$, ensuring that the microwave frequency will be equal to the free spectral range of the resonator. It should also be mentioned that higher orders of the FSR could also lead to resonance of the phase-to-intensity conversion. Figure 3 shows the numerical simulation of the optical and RF responses of the disk-resonator which have naturally the FSR period.

4. Experimental results

Figure 4 presents a typical phase noise spectrum measurement from our OEO. The phase noise was measured for a frequency offset ranging from 10 Hz to 100 kHz using a dedicated opto-electronic phase noise measurement bench, developed in our laboratory [6]. As theoretically predicted, the microwave has a frequency equal to the disk-resonator FSR (10.7 GHz), and an output power of 1.6 dBm. The phase noise performance is evaluated to -90 dBrad^2/Hz at 10 kHz from the carrier, and -110 dBrad^2/Hz at 100 kHz. This level of the phase noise can be significantly improved, for example through temperature stabilization, laser frequency-locking with respect to the absolute resonance frequency of the disk, or enhanced isolation from environmental vibrations. In fact, our OEO was built as a proof-of-concept oscillator and the topology has not been optimized. We expect that careful packaging and isolation from environmental vibrations would significantly increase the phase noise performance of this oscillator.

5. Conclusion

We have reported a new OEO architecture based on WGM resonators and phase modulation. This work contributes to show the high potentiality of optical millimeter-size resonator for high performance, compact and low consumption X-band microwave generators. We have chosen to work in the X-band but it could be interesting to synthesize higher frequencies. For example, frequencies above 20 GHz could potentially be generated with a 10^{-13} stability at 1 s. A particularly interesting feature is that this configuration is compatible with chip integration, and could therefore be a transportable source for ultra-pure microwave generation. From a purely scientific point of view, there are also several open issues we would like to address in future works. For example, this system would be interesting to analyze from a nonlinear dynamics perspective [7], while a stochastic analysis [8] would enable to investigate theoretically the phase noise performance of the oscillator. Finally, WGMs do strongly confine light in very small volumes, and this may trigger detrimental nonlinear effects such as Raman or Brillouin scattering. The influence of such parasitic phenomena is still to be investigated in detail.

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