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# Optoelectronic Oscillator Based on Fiber Ring Resonator: Overall System Optimization and Phase Noise Reduction

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**Abstract**— Theoretical and experimental optimization studies are presented in this paper, where the aim is to improve the phase noise of an optoelectronic oscillator based on a passive fiber ring resonator. Our experimental results demonstrate a significant reduction in the phase noise of the final optimized system, which is also compared to the best existing oscillator of the same type, an active cavity based coupled optoelectronic oscillator.

## I. INTRODUCTION

Optoelectronic oscillators (OEOs) are usually based on optical delay lines in order to generate high spectral purity microwave signals above 10 GHz. However, these systems are bulky (few-km-long optical fibres) [1], their thermal stabilization is difficult and they produce spurious modes which need bulky and complex systems to be reduced [2]. The design of compact and high performances oscillators is linked to the investigation of new resonators. In classical microwave resonators field, the quality factors ( $Q_{RF}$ ) decrease at high frequencies. This limits their efficiency to build high purity sources in the millimetre wave range. The best microwave resonators performance in terms of quality factor are today obtained using whispering gallery modes (WGM) sapphire crystal cylindrical resonators, with unloaded quality factors that can reach  $2 \times 10^5$  at 10 GHz frequency.

An alternative optical solution, other than delay lines, is the use of optical resonators, featuring ultra-high optical quality factors ( $Q_{Opt} > 10^9$ ) and relatively low dimensions. WGM optical resonances in disk or sphere resonators may lead to such Q factors [3]. However, the use of these tridimensional shape resonators in a system is delicate, because of the mechanical difficulty in setting up a reliable coupling with a light source. Another approach is to take benefit of low loss proprieties of optical fibers technology to realize high  $Q_{Opt}$  fiber ring resonators (FRRs). In the FRR case, the microwave signal is carried to the optical domain using a laser signal ( $\lambda_{laser} \sim 1.55\mu m$ ) via optical amplitude modulation, and the laser must be stabilized to an optical

resonance. These FRRs are compact (few meters long), easy to fabricate and to use.

In this paper, a 10 GHz OEO based on a passive FRR is theoretically and experimentally studied to reduce its phase noise. First we give a brief description on the FRR and the OEO based on. Optimization studies are then detailed in the other parts of the paper. Finally, noise results of an optimized 100m FRR based OEO are discussed and compared to the best existing and commercialized OEO of the same type: a 330m cavity based coupled optoelectronic oscillator (COEO) [4].

## II. OPTOELECTRONIC OSCILLATOR BASED ON A FIBER RING RESONATOR

### A. Fiber Ring Resonator

The optical FRR is depicted in Fig. 1. It is realized using two symmetrical and low loss directional couplers, linked with single-mode polarization-maintaining (PM) optical fibers. The total length of our first FRR realization was 10 meters.

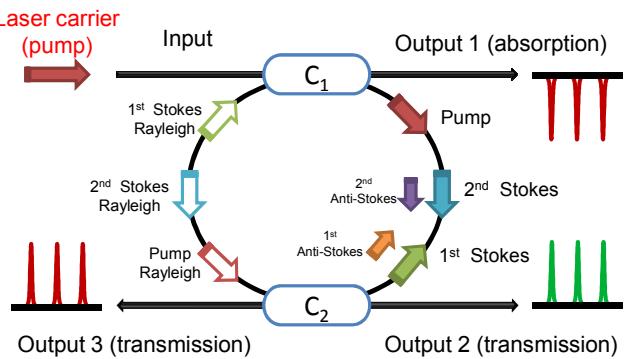


Figure 1. Double directional coupler fiber ring resonator, and the generation of nonlinear optical effects inside the 20m FRR.

Resonances occur in the resonator if the total integrated phase shift of the incident laser wave around the resonator ring is an integer multiple of  $2\pi$  radian. This resonator is thus characterized by a single transverse resonant frequency comb

with a free spectral range (FSR) related to the fiber length (L) and its refractive index (n) by:

$$FSR = \frac{c}{n \cdot L} \quad (1)$$

where c is the speed of light in free space.

The quality factor in this resonator depends on the couplers coupling factors and the overall losses in the resonator architecture (couplers excess loss, splices losses...). One of the advantages of this resonator is that its optical resonance 3dB bandwidth is maintained when used in the microwave domain. The equivalent  $Q_{RF}$  factor is linked to the  $Q_{Opt}$  factor and is directly proportional to the microwave application frequency  $f_{RF}$ . This relation is given below:

$$Q_{RF} = Q_{Opt} \cdot \frac{f_{RF}}{v_{Opt}} \quad (2)$$

where  $v_{Opt}$  is the laser optical frequency (193 THz).

From the relation above, it is clear that the resonator  $Q_{RF}$  increases with the RF application frequency for a fixed optical frequency. Thus, to reach quality factors higher than those obtained in microwave resonators,  $Q_{Opt}$  should be higher than  $10^9$  because of the frequency ratio between  $f_{RF}$  and  $v_{Opt}$ , which is about  $10^{-4}$  for a laser carrier at  $1.55 \mu\text{m}$  wavelength (around 193 THz) and a microwave signal around 20 GHz.

Also, the resonator  $Q_{Opt}$  factor is equivalent to a long optical delay line. This being said, the photons inside the resonator will encounter an optical delay ( $\tau$ ) as if they were travelling into a given equivalent optical fiber length in single-pass geometry. This equivalent length is given by:

$$L_{eq} = \frac{Q_{Opt} \cdot c}{n \cdot \pi \cdot f_{Opt}} \quad (3)$$

Thus, a resonator with a  $Q_{Opt}$  of  $3.5 \times 10^9$  (Q factor achieved with our second realization of a 20m FRR and accurately measured using the method described in [5]), is equivalent to a 1180 meter long optical delay line. This high  $Q_{Opt}$  leads to a significant circulating power inside the cavity [6], ( $P_{Cavity}/P_{Input} \sim 54$ ), which in turn reduces the thresholds of many nonlinear optical effects, as we will see later.

All these characteristics make the FRR interesting to be studied, especially when included in an OEO setup. We have thus theoretically and experimentally studied its behavior and then the OEO based on this FRR in order to get high performance, compact and low phase noise OEO.

### B. Optoelectronic Oscillator

Our 10 GHz OEO based on a FRR, is presented in Fig. 2. It includes a Koheras laser with a very narrow linewidth ( $\sim 1 \text{ kHz}$ ), a Mach-Zehnder modulator (MZM), a FRR, eventually an optical fiber EDFA amplifier and a fast photodiode (PD) - Discovery DCS30S. The laser frequency is then stabilized on one of the ring resonances using a low frequency Pound-Drever-Hall (PDH) feedback loop [7]. The microwave oscillation is then maintained by another high

frequency loop including two RF amplifiers, a phase shifter and a RF filter in order to get a single mode oscillation.

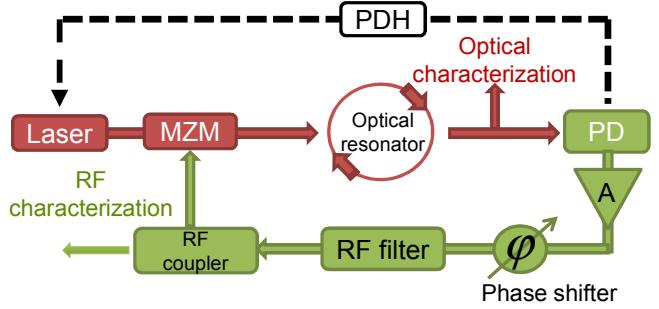


Figure 2. Optoelectronic oscillator based on a fiber ring resonator

### C. Laser Pound-Drever-Hall Stabilization Loop

The experimental setup for the PDH loop, used to stabilize the laser frequency to one of the resonator's resonances, is presented in Fig. 3.

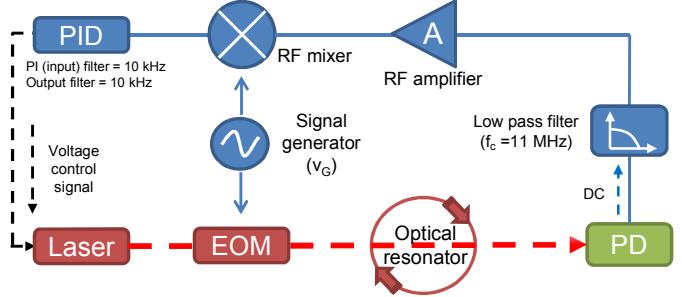


Figure 3. PDH laser stabilization loop. EOM: electro-optic modulator; PID: proportional-integral-derivative controller.

In this PDH scheme, the laser carrier is phase modulated with a large modulation index at an RF frequency ( $v_G$ , from a signal generator) by means of an electro-optic modulator (EOM). The beam passes through the resonator and the transmitted beam is sent to the same PD of the oscillation loop. The amplitude of the PD output voltage at  $v_G$  depends on the detuning between the laser frequency and the optical resonance. This voltage signal passes through a low-pass filter to reduce its noise and eliminate unwanted higher modulation harmonics. It is then amplified and sent to an electrical mixer to be mixed with a fraction of the RF signal ( $v_G$ ) used to drive the modulator. The mixer output represents an error signal proportional to the frequency detuning between the laser and the optical resonance. This error signal is then sent to a proportional-integral-derivative controller (PID) in order to drive the laser piezoelectric actuator (PZT) and adjust its wavelength. Through our experimental studies, we have found that it is very important to accurately adjust the PDH loop parameters, because the OEO phase noise can be severely affected, as we will see in section III-1-a. Also, the PDH loop bandwidth seems to be a very critical parameter, because if it is reduced (especially the PID input and output filters), it can considerably degrade the OEO phase noise, (see the green and orange curves in Fig.10).

### III. OEO OPTIMIZATION STUDIES

#### A. 10m FRR with PM Fibers

Our first OEO realization was based on a 10m FRR. We used optical PM fibers to maintain the polarization of the carrier inside the resonator and prevent the deformation of the optical resonance response in the RF domain. However, the coupling factor ( $\kappa$ ) in this 10m long FRR has not been optimized, (particularly the couplers excess loss was very high). The optical carrier to noise ratio at the resonator output was thus degraded. This directly affects the white frequency noise and the phase noise floor in the oscillator phase noise spectrum.

A  $Q_{\text{Opt}}$  of  $2 \times 10^8$  ( $Q_{\text{RF}}$  of  $1 \times 10^4$  at  $f_{\text{RF}} = 10$  GHz) has been obtained. This resulted in a high phase noise level for the OEO, (see the red curve in Fig. 9). To be able to get a better phase noise, the resonator  $Q_{\text{Opt}}$  must be increased. This cannot be done unless if the coupling factor is optimized and losses are reduced. Thus, a new optimized 20m long FRR has been designed.

#### B. 20m Long FRR with an Optimized Coupling

The OEO white frequency noise contribution is directly linked to the optical noise to carrier ratio (NCR) and inversely proportional to the resonator quality factor as shown in the relation below:

$$L(f_m) = 20 \cdot \log \frac{f_{\text{opt}}}{2\sqrt{2}Q_{\text{Opt}} \cdot f_m} + 10 \cdot \log(NCR) \quad (4)$$

where  $f_m$  is the noise modulation frequency (offset frequency).

From this relation, it is clear that to reduce this noise contribution part we have to increase the quality factor and reduce the NCR. However, these two parameters depend directly on the coupling factor, but change differently. A high  $Q_{\text{Opt}}$  needs a low  $\kappa$ , but the NCR needs a high  $\kappa$  to be reduced. Thus, the white frequency noise contribution has been evaluated versus  $\kappa$  and an optimized coupling factor of 1% has been finally found to design a new 20m long FRR. The detailed study can be found in [8].

Using this 20m FRR we have first measured a  $Q_{\text{Opt}}$  of  $5.1 \times 10^9$  ( $Q_{\text{RF}}$  of  $2.5 \times 10^5$  at  $f_{\text{RF}} = 10$  GHz); The  $Q_{\text{Opt}}$  has then degraded to  $3.5 \times 10^9$  due to the extremely high intra-cavity power inside the resonator (10 mW at the resonator input means approximately a 540 mW inside the resonator at the resonance, which is higher than the couplers power limit (around 300 mW)). However, despite this very high  $Q_{\text{Opt}}$  factor, the phase noise results obtained were far from theoretical expectations; (see the violet curve in Fig. 9). Consequently, different noise conversion processes have been suspected and studied. Also, nonlinear optical effects generation inside the resonator (because of its high  $Q_{\text{Opt}}$ ) have been the field of many studies.

##### 1) Laser Amplitude and Frequency Noise Conversions:

###### a) Laser Frequency Noise Conversion to RF Amplitude and Phase Noise:

The laser frequency (FM) noise effects on the RF phase (PM) noise of delay line based OEOs have been already

investigated in [9]. It has been found that this noise conversion process comes essentially from chromatic dispersion in the optical delay line. However, our FRR based OEO is a more complex system, and in order to evaluate the laser FM noise conversion trough the resonator, we had to use a dedicated simulation approach. To this purpose, we have developed a model of the resonator on a microwave simulation software, ADS (Agilent). This model has been experimentally validated and then implemented in a global OEO model using the same software. The global OEO model includes the laser, the MZM, the resonator, the PD, the RF filter and the RF phase shifter...The modeling of the resonator using ADS will be detailed in a future publication.

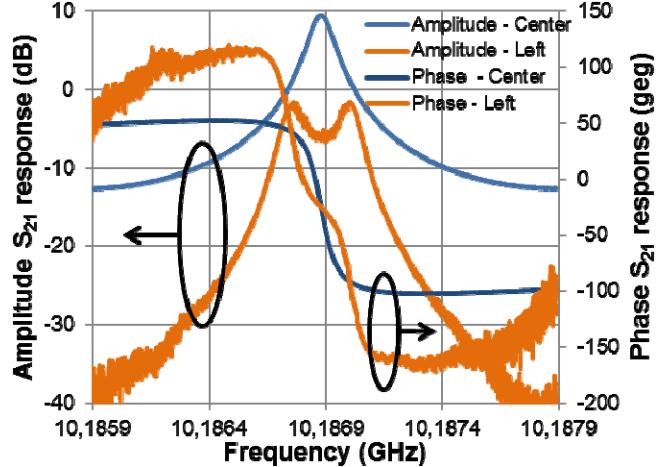


Figure 4. Experimental RF amplitude and phase responses of the resonance, deformed when the laser is stabilized at one of the resonance edges.

The OEO open loop response has been simulated by first stabilizing the laser carrier at the optical resonance center, and then by stabilizing the carrier to one of the resonance edges (right or left). The stabilization at the edges results in a deformation of the RF amplitude response (a splitted resonance) and a  $Q_{\text{RF}}$  factor degradation. Also the RF phase transition response at the resonance frequency becomes less sharp, with two phase transitions corresponding to the two splitted resonances. These results have been validated experimentally by changing the PDH loop stabilization set-point in order to stabilize the laser frequency on one of the resonance edges, (see Fig. 4).

These results confirm that the laser FM noise can be converted to RF AM and PM noise trough the FRR, especially if the resonator is not well stabilized to the resonance center. This means that the PDH loop is a critical parameter that must be carefully adjusted to prevent this kind of noise conversion in the OEO oscillation loop.

###### b) Laser AM Noise Conversion to RF AM and PM Noise:

It is well known that laser AM noise, called relative intensity noise (RIN), is one of the limiting factors of signals transmissions via optical links. This power fluctuation noise increases the link noise and degrades its NCR. Also, the baseband RIN can be up-converted to RF AM and PM noise via optical link nonlinearities, especially via the PD

nonlinearities as it has been reported in delay line OEOs in [10]. In our case, we have experimentally studied the PD nonlinear behavior versus the received optical power. The laser carrier was modulated at 10 GHz (the OEO frequency) via the MZM. The 10 GHz signal comes from a calibrated vector network analyzer (VNA) working in a CW mode. The amplitude and phase responses of the  $S_{21}$  parameter were accurately measured (average = 1000) while changing the received optical power by using an optical variable attenuator just before the PD (the MZM nonlinearities were thus discarded). The results are presented in Fig. 5.

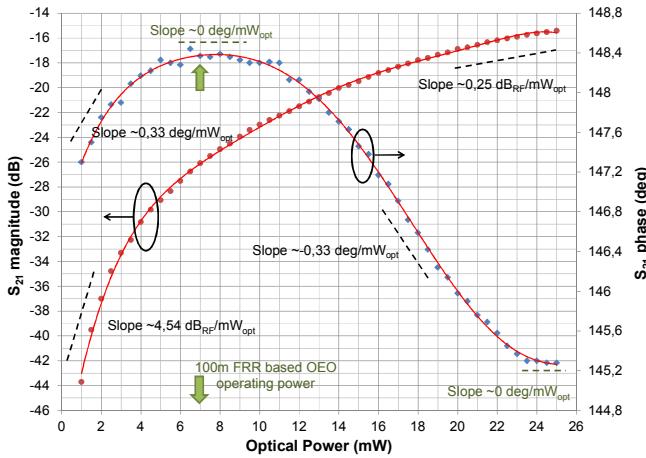


Figure 5. Discovery PD DCS30S  $S_{21}$  RF amplitude and phase responses versus received optical power.

The results of Fig. 5 reveal the presence of a reduced slope in the  $S_{21}$  amplitude response (near PD saturation) and interestingly, two zero slopes in the  $S_{21}$  phase response. Theoretically, one has to push the PD into saturation in order to reduce both RIN to AM and RIN to PM noise conversions. However, a 25 mW optical power is hard to get at the end of the OEO open loop optical link. Knowing that the RIN to PM noise conversion affects much more our OEO phase noise than the RIN to AM noise conversion, and that a 7 mW optical power at the optical link end is possible, we have chosen to work at this optical power in our new system based on a 100m FRR. In the 20m FRR based OEO, a 7 mW optical power was far from being achieved. In fact, the laser carrier saturates when passing through the FRR because of the generation of nonlinear optical effects inside the resonator, due to its very high  $Q_{\text{Opt}}$ . These nonlinear optical effects, essentially stimulated Rayleigh (STRS) and Brillouin scatterings (SBS), were mostly the cause of the phase noise degradation in the OEO based on the 20m FRR.

## 2) Nonlinear Optical Effects Generation in the 20m FRR and Degradation of the OEO Phase Noise:

Due to its very high  $Q_{\text{Opt}}$  ( $3.5 \times 10^9$ , after the  $Q_{\text{Opt}}$  degradation as mentioned before), the 20m FRR is equivalent to a 1180 m delay line. Thus, the thresholds of many nonlinear optical effects will be reduced in the 20m FRR and will be close to those of a 1180 m long optical fiber. Also, if we add the fact that at resonance, the circulating power inside the resonator is approximately 54 times higher than the input power, we can conclude that the threshold will be also divided

by 54. This has been experimentally observed by measuring the power of the different components in the optical spectrum at the second and third outputs of the resonator, versus the input optical power. We used an Agilent HP 86142A optical spectrum analyzer (OSA; with 0.06 nm resolution and  $\pm 1$  dB amplitude precision). These measurements have revealed the presence of other optical components than the laser carrier: the Rayleigh and the Brillouin scattering waves at the resonator's second output, as they are both essentially backscattered (see Fig. 1). Optical power measurement results for both 20m FRR and the new 100m FRR are depicted in Fig. 6.

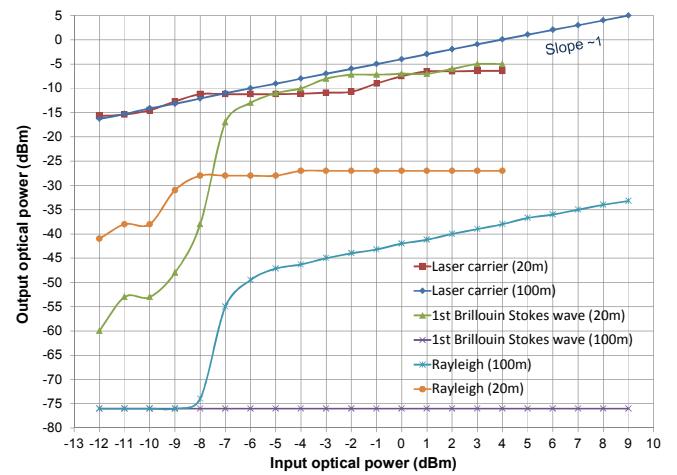


Figure 6. Power of the different optical components at the 20m and the 100m FRRs outputs versus the laser carrier optical power at the input. Rayleigh and Brillouin scatterings were measured at the FRRs second output.

In optical fibers, the Brillouin scattering is caused by the interaction between a light wave and an acoustic wave existing already at the optical medium thermal equilibrium. This interaction creates a scattered wave called Stokes wave; in this case we are in the spontaneous Brillouin scattering regime. In optical fibers, the backward scattered Stokes wave is privileged and is frequency downshifted from that of the incident pump light by an amount  $v_B$  set by the nonlinear medium characteristics ( $v_B \sim 11$  GHz in silica fibers, [11]). However, a very weak and also backscattered wave called anti-Stokes wave but up-shifted in frequency by  $v_B$ , can be also generated. At a critical incident light wave power, called stimulated Brillouin scattering threshold (SBST), the interference between the Stokes wave and the incident light wave amplifies the acoustic wave in a process called electrostriction. Thus, the scattered wave becomes more intense and reinforces the interference and so on; we are now in the stimulated regime. When the Stokes power exceeds the medium SBST, it creates a second order Stokes wave downshifted in frequency from the first Stokes wave by  $v_B$ , and thus by  $2v_B$  from the incident light wave.

The Rayleigh and Brillouin scattering and their effects and use have been intensively studied in literature [11- 13]. Their contribution to optical links noise degradation and also to phase noise degradation in delay line based OEOs have been well explained in [13]. From Fig. 6, we can see that for the 20m FRR, and at an input power level as low as -10 dBm, the first Brillouin Stokes wave appears and its power starts to

increase rapidly by converting the optical carrier power, making the carrier saturates. Also, the Rayleigh scattering power increases with the laser input power but remains constant after the Brillouin scattering process starts to be stimulated. Such a Rayleigh-Brillouin scattering behavior has been already thoroughly studied in single-pass geometry optical fibers [12, 13]. The saturation of the optical carrier prevents the PD from working at its optimal optical power and degrades the NCR of the optical link (see section III-B-1-b). Also, both Rayleigh and Brillouin scatterings introduce optical parasitic signals (higher order Brillouin Stokes and anti-Stokes waves, and their own Rayleigh waves) and noise which mixes with the OEO RF signal and degrades its phase noise.

We have experimentally studied the effect of these nonlinear optical phenomena on the OEO phase noise by reducing the input optical power, thus limiting the Brillouin scattering generation. The detailed study can be found in [14]. We have found that a better close to carrier OEO phase noise can be obtained when the optical power is decreased, and a relatively good phase noise result has been obtained at -10 dBm input optical power (below the first SBST), (see the blue curve in Fig. 9). However, the phase noise shape was unusual. Some of the possible causes of this phase noise shape are the Rayleigh scattering, the spontaneous Brillouin scattering and the PD noise conversions.

### C. 100m Long Immunized FRR

Knowing that a low optical power prevents optimal AM and PM responses of the PD and also degrades the OEO NCR, we have searched for a way to suppress the Brillouin scattering induced in the resonator and reduce the Rayleigh scattering, while maintaining a high optical quality factor.

The Brillouin scattering power depends essentially on the effective interaction length with the optical and acoustic waves in the optical fiber [11]. The fact that photons circulates many times inside the 20m long FRR, due to its high  $Q_{\text{Opt}}$  (high delay  $\tau$ ), as if it was a long delay line, increases the virtual interaction length ( $\sim 1180$ m) between the spontaneous Brillouin scattering and the optical and acoustic waves. Thus, the spontaneous Brillouin scattering will be intensified all along this virtual optical fiber and becomes stimulated. Then it also creates other higher order SBS waves with their own Rayleigh scattering waves. One of the severe consequences is the optical carrier depletion due to these phenomena.

Now, if a low loss isolator is inserted inside the resonator, it will completely prevent the SBS from building-up inside the resonator, due to the fact that virtually we will have a number ( $N$ ) of isolators, equals to the photons laps number inside the resonator. These virtual isolators will be spaced by the loop length  $L$ , thus, the SBST inside the resonator will be reduced to be the SBST of the real resonator length  $L$  and not the SBST of its equivalent length  $L_{\text{eq}}$ . Also the presence of the isolator will efficiently reduce the Rayleigh scattering.

Unfortunately, and despite the fact that the SBS will be suppressed and the STRS will be reduced, the isolator losses will be also multiplied by the number of turns  $N$ . So the  $Q_{\text{Opt}}$  will be reduced unless if we optimize the resonator on different parameters (length, coupling factor, architecture,

loss...) in order to compensate the isolator loss and get a satisfying quality factor and transmission loss, and finally a good phase noise result once the device is included in an OEO setup.

This optimization study has been performed using the FRR model over ADS, while always respecting the section III-B couplers optimization study. Using ADS, we have found that an optimized coupling factor of 8% in a 100m long FRR, while taking the resonator overall losses into account, must lead to a 92 kHz FWHM, thus a  $Q_{\text{Opt}}$  of  $2 \times 10^9$  ( $Q_{\text{RF}}$  of  $2.5 \times 10^5$  at  $f_{\text{RF}} = 10$  GHz), with a FSR of 2 MHz, a 4 dB optical transmission loss and a 22.5 dB rejection. Also, we have added an inline polarizer at the resonator input port in order to completely eliminate a possible two polarization states of the optical carrier at the input port, because PM fibers only maintain these states of polarization and do not ensure one state polarization behavior. The 100m immunized FRR (IFRR) architecture is depicted in Fig. 7.

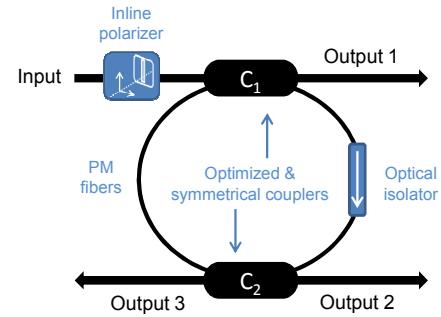


Figure 7. New 100m long immunized FRR.

Using equation (4), we can expect a phase noise level of -134 dBc/Hz at 10 kHz offset frequency, (see dashed curve in Fig. 10). But if we add the phase noise contribution of the optical amplifier and the RF amplifiers used in the OEO setup, we can expect a -128 dBc/Hz phase noise level at 10 kHz offset frequency, (see blue curve in Fig. 10).

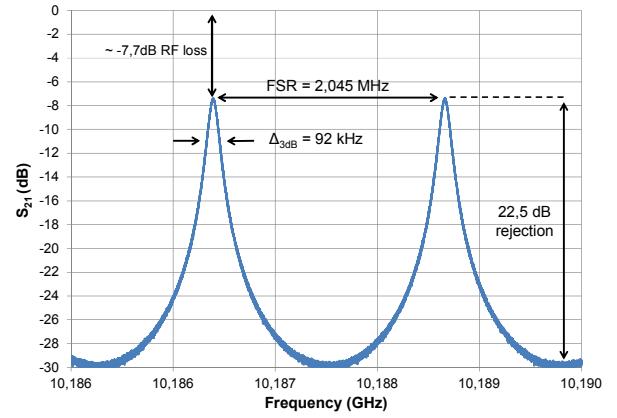


Figure 8. RF transmission characteristics of the 100m IFRR.

Once the resonator has been realized, almost all experimental results were at expectations ( $Q_{\text{Opt}}$ , rejection, FSR, transmission loss), (see Fig. 8). These characteristics were accurately measured using the VNA method described in

[5]. Also the SBS was completely suppressed, no carrier saturation has been observed (the carrier power at the resonator output increases linearly with a slope equal to 1) and the STRS was reduced (near 40 dB rejection), (see Fig. 6).

Finally, the 100m IFRR resonator has been included in the OEO experimental setup and a considerably reduced OEO phase noise has been measured, with a level of -128 dBc/Hz at 10 kHz offset frequency, and a -150 dBc/Hz noise floor, (see the green curve in Fig. 9).

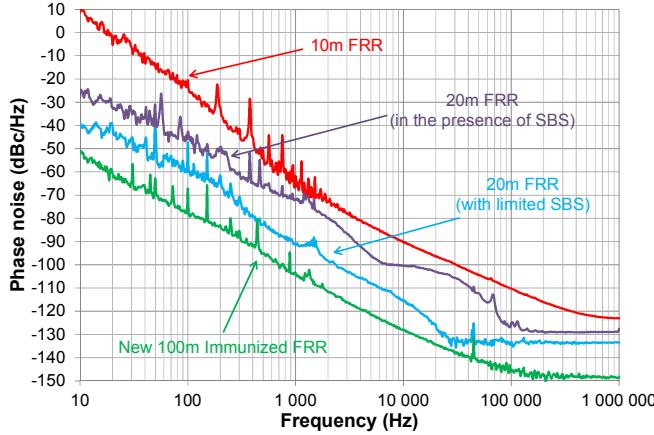


Figure 9. Different phase noise results obtained through the different noise studies made to improve the phase noise of a FRR based OEO. Measurements are performed with an Agilent E5052 B signal source analyzer.

#### IV. 100M IFRR PHASE NOISE RESULTS DISCUSSIONS AND COMPARAISION WITH THE COUPLED OEO RESULTS

The results obtained with the 100m IFRR are very interesting if compared with the 330m active-cavity based OEO, also known as coupled optoelectronic oscillator (COEO), currently commercialized by OEwaves [4]; see Fig. 10.

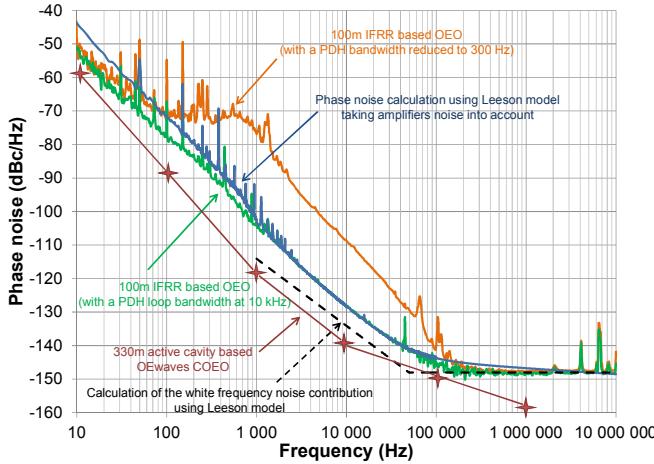


Figure 10. 100m passive IFRR based OEO phase noise calculation and comparison with OEwaves 330m active-cavity based COEO. The effect of the PDH bandwidth reduction on the OEO phase noise is also presented.

Also, we can expect to get an even better result than the one presented in Fig. 10, if RF amplifiers contribution to the

phase noise could be reduced, PDH loop is accurately adjusted and a low AM and FM noise laser is used.

#### CONCLUSION

We have presented theoretical and experimental studies performed in the aim to reduce the phase noise of a passive fiber ring resonator based optoelectronic oscillator (OEO). A phase noise level of -128 dBc/Hz at 10 kHz offset frequency has been measured in a 100m long passive-cavity based OEO. This result is close to the one obtained in a 330m active-cavity based coupled OEO. Improvement is still possible if the laser and RF amplifiers noise can be reduced.

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