Investigation in compact optoelectronic oscillator with mini-disk resonator

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ABSTRACT

This study deals with a design, fabrication and characterization of compact optoelectronic oscillators (OEO). The resonator - a disk measuring a few millimeters in diameter with rounded edges - behaves as a sphere because the energy is trapped in whispering-gallery modes in the equatorial region. For this purpose, Fused silica and MgF_2 are suitable, due to their mechanical characteristics and their low attenuation at 1.55 µm wavelength. In fact, the hardness of 6-7 degrees Mohs of these materials allows us to obtain a quite easy precision processing and surface polishing. Our prototype owns a quality factor of approximately 3×10^8, which is certainly limited by the available technology. The resonator is coupled to an tapered optical fiber with a few nm position resolution system. The microwave carrier is generated by locking the optical phase modulation to a free spectral range resonator, which occurs in the 10 GHz region. Moreover, this carrier is detected by a standard low-noise InGaAs p-i-n telecom photodiode. The oscillator prototype is assembled on a 0.12 m^2 optical breadboard. In principle, this surface can be reduced to those of the oscillator main parts (resonator, laser, photodiode, amplifier and optical modulator). The oscillator phase noise measured by a dual-delay-line instrument, which has been developed in Besancon, corresponds to –90 $dBrad^2/Hz$ at 10 kHz off carrier. According to this result, the oscillator suffers from severe noise limitations due to several reasons: the thermal coefficient of the resonator, the low power that the resonator can accept, and the small volume of the energy-confinement region in the resonator ($\approx 2\times10^{14}$ m^3). But our oscillator could be packaged in a small volume, contrarily to a classic OEO based on an optical fiber of a few km.

Keywords: fused silica, MgF_2, Optoelectronic oscillator, phase noise, X-band, mini-disk, whispering-gallery resonator

INTRODUCTION

Early works have been focused on the OEO including fiber loop [1,2] and offering compatibility with telecommunication systems, where the oscillation frequency is selected according to the band filter value. However, on the one hand, optical fibers are still bulky with typically several km and most of all, they are unadapted to an efficient temperature control. On the other hand, the use of optical fibers offers an ability to achieve low noise performances. Using a 4 km optical delay line, we have measured respectively – 63 $dB.rad^2/Hz$ at 10 Hz, and a noise floor of – 153 $dB.rad^2/Hz$ at 10 kHz for a 10 GHz carrier [3]. The integration of a mini-resonator is helpful in order to solve the problems related to the temperature control and to work in a small volume: this allows us to perform transportable applications. Thus, the optical fiber previously used in OEO is replaced by a whispering gallery mode (WGM) optical mini-resonator. Then an optical signal can be propagated by a total internal reflection inside the crystal resonator by WGM. One can achieve a long equivalent delay line into a mini-disk of a few millimeters in diameter. As I. S. Grudinin *et al.* [4] have been proved, we should expect a high quality factor up to 6.10^{10}. In this work we investigate the ability to build a compact oscillator by the use of a mini-disk resonator without any optimized topology of the OEO. The aim of our study deals with the first oscillating prototype in a limited volume. Despite the technical problems of coupling optical fiber to the resonator, it is interesting to achieve a first OEO and perform first measurements related to its signal. First, we have focused on the resonator fabrication and characterization. Then we describe the choice of the technology for coupling the fiber to the resonator and the resonance measurements. Finally, we present the implementation in OEO and perform experiments in order to process the power spectrum and the spectral density of the phase noise related to the signal delivered by the OEO, which is based on an optical resonator element.

1. FABRICATION OF THE OPTICAL RESONATORS

According to its tetragonal crystal shape and its efficient behavior in presence of polluted water, CaF_2 seems to be a potential candidate. However, in order to perform our first experimental study, we have avoided due to its bad reaction to mechanical shocks. We have opted for a resonator with MgF_2 or fused silica, which own good properties [5]. Actually, their hardness is in the range of 6 Mohs and they both respond efficiently to precision machining and polishing. This aspect helps us to produce mini-disks containing these materials. They belong to different crystal class, the MgF_2 crystal being tetragonal and the fused silica being non crystalline. Moreover, while MgF_2 is not water sensitive, it is necessary to perform specific treatments in order to diminish the H_2O inclusion inside the fused silica. Both of these materials are relatively easy to manipulate without damaging the surface. A specific tool has been developed in order to manufacture the MgF_2 resonator. A dedicated polishing machine affords a 200 nm small eccentricity and a precision adapter. System is held on the air bearing support in order to mechanically prevent influence of vibration on the external tore surface of the mini-disk resonator. Our process starts from an initial MgF_2 high quality material, which corresponds to a diameter of about 6 mm, and a thickness of 500 µm. A hole must be performed in the center in order to allow us an easy position during process: this has to be process in order to avoid problems of the eccentricity during polishing. The coupling zone must be reduced to less than 50 µm, that is why two 20 degree angles bevels are performed on the disk to form a sharp edge. At this step, it is necessary to proceed carefully using an appropriate grindstone and disk speed, in order to avoid any splinter that can enlarge dramatically the edge and forbid future coupling. The figure 1, shows a profile of a MgF_2 mono-crystal resonator pre-shaping. Manual polishing is then carefully realized with a low speed. We need a high optical quality including a tiny and regular roughness, all around the torical surface of the disk periphery. Powders with decreasing grain size are used (for example silica colloidal), cerium oxide, alumina oxide. Moreover, their dilution and acidity have to be checked.

Figure 1. Resonator pre-shaping.

We work simultaneously with our own MgF_2 optical resonators manufactured in the laboratory and also our fused silica optical resonators manufactured in Russia. It is well known, that fused silica leads to troubles in presence of Hydroxyl groups [6]. Actually, they exist as an isolated group and exercise an influence on the crystal sensitivity to water. That is why a thermal annealing is necessary on fused silica crystal. Surface is then cleaned with a 90% diethyl ether (CH3-CH2)2O – 10% isopropyl alcohol (CH3)2CHOH solution in a ultrasonic environment. It helps the impurities deposited at the surface to move in order to smooth the surface enough to insure a good signal propagation.

2. TAPER COUPLING AND RESONANCE MEASUREMENTS

The best way to couple the fiber to an optical resonator certainly consists in using a prism with a signal provided by a cut optical fiber. However, an appropriate reproducible way in a lab consists of using a tapered fiber. Figure 2 presents the tapered fiber glued on the holder.

Figure 2. Taper glued on the holder.

Holder alloy and geometry match the thermal expansion of the glass. The waist is less than 3 µm. For coupling we first used a nano-positioning system manufactured by the French firm *Laseo* [7], with its 3-axis nano-positioning and a resolution of 20 nm. We have improved the nano-positioning system by the use of a 1 nm theoretical resolution *SmarAct* German system [8] as shown in figure 3.

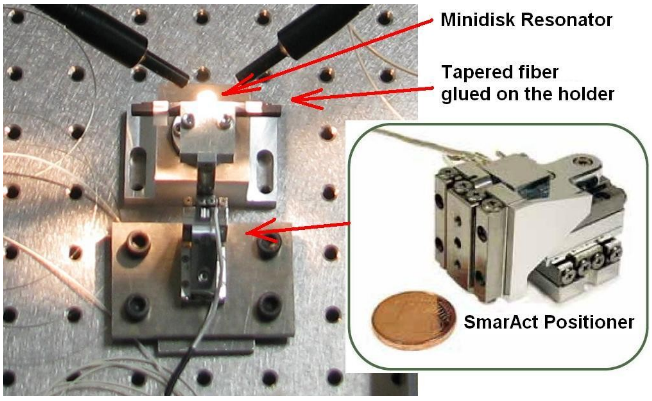

Figure 3. SmarAct nano-positioning system.

In order to measure the resonance, a signal from a 1550 nm tunable laser diode 3 mW output power has been used [9]. The 50 pm wavelength weep corresponds to a 6 GHz frequency in the spectrum. Fast digital real time 8600A-type *Lecroy* oscilloscope provides an analysis of the very sharp phenomena at the peak of resonance. It is necessary to employ a high speed resolution oscilloscope, in order to analyze very short phenomenas. An oscilloscope is inserted after a photodiode that detects an optical signal, which is coming from the mini-disk resonator coupled to the fiber glued on the holder. The resonance peak detection corresponds to a single mode excitation. A small taper size is helpful to select a thin excitation area.

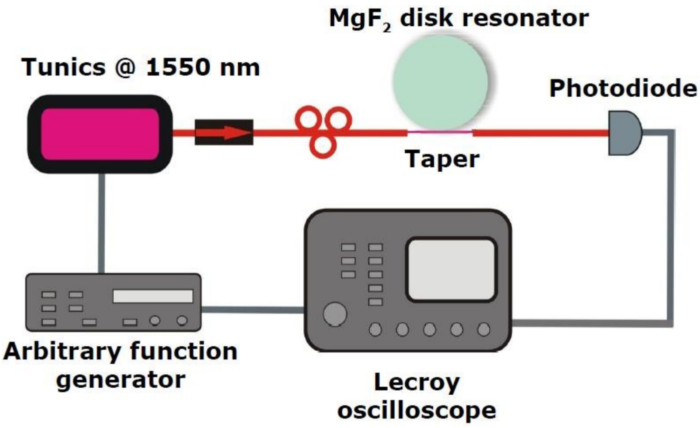

Figure 4. Resonance measurement set-up.

Figure 4 shows the resonance measurement set-up in open loop. Although the wavelength span is too small in order to scan a full free spectral range (FSR) and scan rate is 50 Hz, it let be possible Q factor measure with the self homodyne methodology [10]. Notice we also need polarization controller. Oscillation damping then provides $Q = 3.4\text{x}10^8$ for MgF_2 optical resonator and in the range of 10^8 for fused silica resonator. The quality factor is extracted from the time delay of interference path between two beams. A first beam comes from the laser and a second one comes from the cavity. The laser light and the other one delayed by the cavity own different wavelengths. Some damped oscillations are observed during the cavity unloading. The Q factor can be deduced by $Q = \omega T/2$. It strongly depends on coupling conditions and deduced value is different according to the way the resonator is coupled to the optical fiber. It can indeed be decomposed in two terms: Q_0 represents an intrinsic quality factor and the other term Q_e corresponds to the coupling Q-factor. They are linked by the relation: $Q^{-1} = Q_0^{-1} + Q_e^{-1}$. In order to perform a high efficient measurement of the quality factor, the variable Q must be close enough to the intrinsic Q_0 which depends on the properties of the resonator. This aspect explains why the taper has to be well coupled. It is not that easy to achieve concretely because the tapered fiber tends to touch the resonator surface, leading to a too strong over-coupling.

3. OEO IMPLEMENTATION

We assembled a OEO prototype making use of MgF_2 or fused silica resonators of 5mm to 5.5 mm diameter. Block diagram and actual implementation are shown in Fig. 5 and 6, respectively. This oscillator provides microwave oscillations stabilized to the resonator free spectral range, in the 10–11 GHz region.

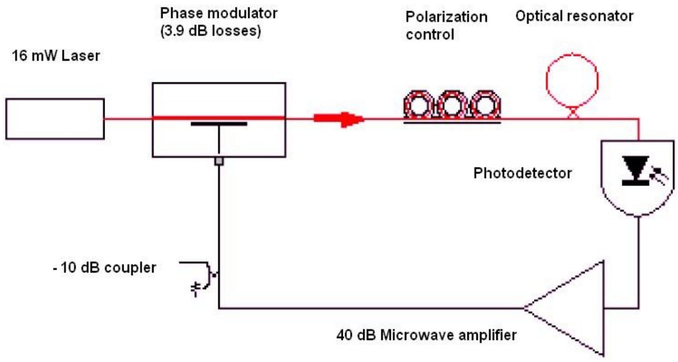

Figure 5. Optical resonator inserted in OEO.

Inside the resonator, the light propagates according to Whispering Gallery Modes (WGM) and the differences related to the optical indexes between the optical cavity and the air provides a quasi total reflexion of the signal inside the resonator, even if it depends on the roughness of the surface that also causes losses. The phase modulator is optically driven by the laser. The resonator is coupled to the optical fiber at the output of the phase modulator. The microwave signal is converted into microwave by the photodiode, and amplified. The microwave signal is made available through a 10 dB directional coupler. For demonstration purposes, we show that the oscillator fits in an A3-size breadboard. Of course this is *not* a miniaturized version. This compact topology was realized for first MgF_2 resonator based OEO [5] and then reduced lately for fused silica resonator based OEO.

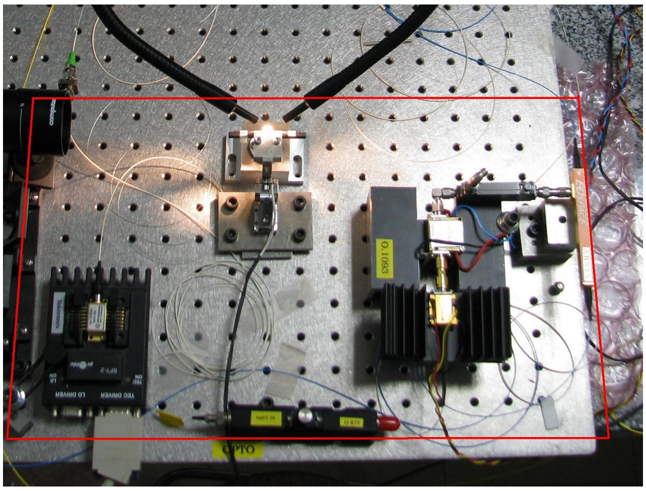

Figure 6. Fused silica resonator based OEO realized in the beginning of 2010 at the laboratory. The red line shows the size A3 requirements for compact prototype to be developed at this step of the work.

The figure 6 shows how this new system improves the gain of the compact oscillator. We clearly see the positioning system which combines the tapered fiber and the mini-resonator. The red line represents the limit of a A3 size compact oscillator which is certainly much in the range of a A4 size now. Note that specification for building a compact OEO is necessary for potential applications of such an oscillator. It is under light in order to focus the camera (left top edge of the picture) on the coupling zone to watch on the screen of a camera-connected computer how closed is the fiber from the resonator. The nano-positioning system provides enough space for the moves in a 12x12x12 mm^3 volume and is controlled by a joystick including three different speeds to approach the resonator and the selected tapered fiber.

4. PHASE NOISE OF THE OEO PROTOTYPE

At the time of writing the laser temperature control is still not fully operational, hence the optical frequency drifts away from the resonance after a few minutes, and the microwave oscillation stops. After that, some manual adjustment is necessary. Since we are interested in the demonstration of short-term phase noise, this technical detail is not relevant.

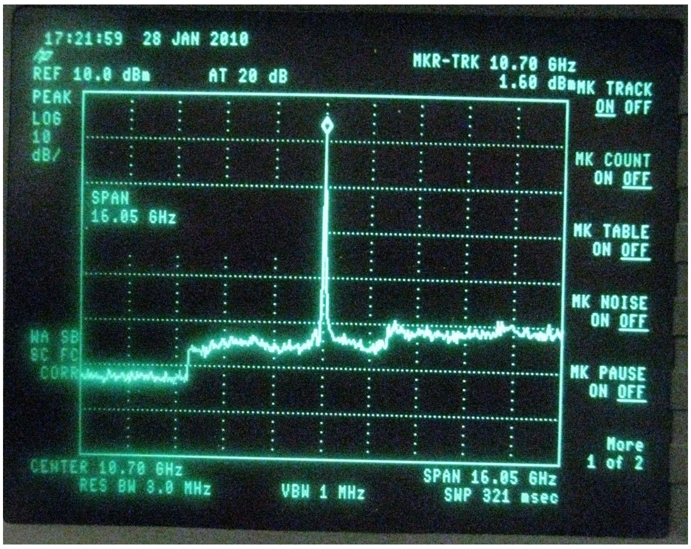

Figure 7. 10.7 GHz fused silica resonator based OEO signal measured in January 2010 with a spectrum analyzer. Power is given in dBm versus frequencies in GHz.

Figure 7 shows a typical spectrum of the OEO prototype. This OEO has not the spurs modes often found in fiber-based OEOs. The carrier oscillation frequency indicates 10.7 GHz and the delivered power is located in the range of 1.6 dBm. The 16 GHz span explains why the noise floor is due to the analyzer and not to the OEO. Despite the signal does not remain enough stable, it is possible to measure the phase noise of the OEO at the Fourier frequencies between 10 Hz and 100 kHz from the carrier using dedicated optoelectronic phase noise measurement bench developed at the laboratory [3,11]. Although our OEO does not behave as efficiently as other related published results have exposed [12] – related to a mini-disk used as a selective filter - it is possible to present a first phase noise spectrum.

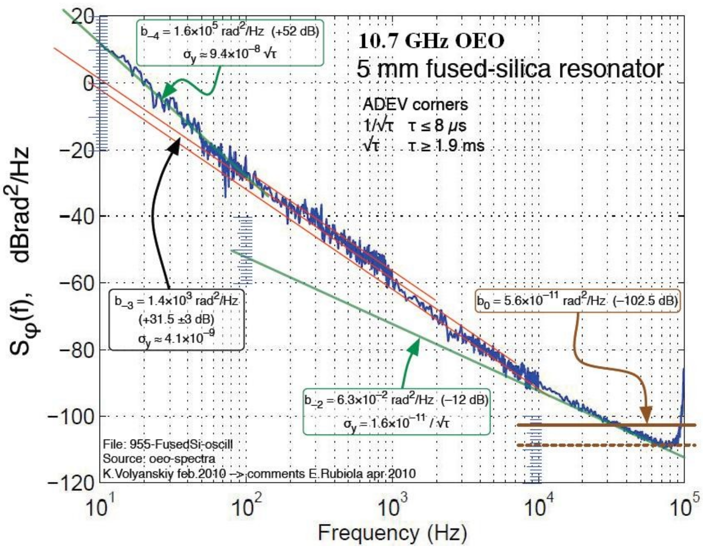

Figure 8. First phase noise spectrum obtained on fused silica resonator based 10.7 GHz OEO.

The phase noise spectrum is $S\varphi(f) = 5.8\times10^{-11} + 6.3\times10^{-2}/f^2 + 1.4\times10^{3}/f^3 + 1.6\times10^{5}/f^4$ rad²/Hz, as shown in Figure 8. The spectrum is measured with the delay-line instrument extensively discussed in [3]. Notice that the oscillator white noise is 6 dB higher than the dip just below 100 kHz. This 6 dB difference is a property of the delay-line instrument, and has nothing to do with the specific oscillator. Reading the plot, the frequency flicker has an uncertainty of 3 dB due to the difficulty of fitting the experimental curve to the expected behavior. We still not know whether this irregular shape is the signature of a physical phenomenon or it is the effect of averaging several spectra in the presence of laser drift. Phase flicker is hidden below the other phenomena, and not visible in the spectrum. Frequency flicker and random walk, converted into Allan deviation, yield $\sigma_y(\tau) = 4.1\times10^{-9} \sqrt{\tau} + 1.6\times10^{-11}$. The white phase noise is omitted because it would be visible at short integration time, where the Allan deviation is not a suitable tool.

Let us point out the following facts: a) the topology has not been optimized at all, b) the mini-disk is only used as a resonator. We consider this work as a first exploratory one, dealing with such a new structure. The fused Silica micro-sphere resonators have been previously produced [13] and integrated into the OEO. However, they have not been yet adapted to a mini-disk containing our material. Moreover, the signal was not that stable enough during the process and has probably caused a significant drift, that has changed a bit the frequency. By the way, one can point out, that the light is confined in a very small volume at the periphery of the disk and such a concentration possibly leads to a non linear effect on this type of structure.

CONCLUSION AND DISCUSSION

This work contributes to show the potentialities of an optical mini-disk resonator in order to increase the reduction of the OEO dimension. Let us mention, that our work has not been concerned yet by an optimization of the phase noise of such a basic structure (i.e, FSR OEO), but has mainly focused on the investigation of a relatively compact OEO, based on an optical resonator.

This experience shows that a number of improvements can help in getting more stable or more spectrally-pure oscillators. Yet, three major problems have to be tackled before getting a true benefit from these improvements. The first problem is that the quality factor Q that goes in the Leeson effect is approximately the optical quality factor Q_{opt} multiplied by the factor ν_{microw}/ν_{opt}. With 1.55 µm optical wavelength and 10.8 GHz microwave frequency, we get $\nu_{microw}/\nu_{opt} = 5.6\times10^{-5}$. To be more precise, the actual Q is lower because the microwave signal is generated using two (contiguous) lines of the resonator response, and because the optical intensity is detected instead of the electric field. So, the equivalent microwave Q of our resonator is of about 5000. Though it possible to increase Q by increasing the microwave frequency, the actual improvement is no more than a factor of 5, limited by the photodetector technology. The second problem is the small optical power that a WG can handle, before Raman oscillation or other nonlinear phenomena that spoil the oscillator operation. Experience indicates that with $Q_{opt} = 6\times10^{-10}$ the maximum safe power is of the order of 10 µW. In this case, shot and thermal noise limit the white noise to some –100 dBrad^2/Hz. The maximun power scales with Q^2_{opt}. This explains the lower white noise of our prototype, and also indicates that high stability and low white noise are incompatible. The third problem is that flicker is approximately proportional to the inverse of the volume. Presently, this statement is only supported by heuristic reasoning and experience, without a quantitative theory. Since in the case of the disk resonator the optical energy is confined in an really tiny volume, of the order of 10^{-14} m^3, we need to know more about the volume law before extrapolating spectral purity and frequency stability from technical improvements.

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