

A low phase noise oscillator prototype at 10GHz using Sapphire Cavity for the Brazilian gravitational wave detector Mario Schenberg.

Mosso.M.M¹; Magri.V.P.R²; Barucke.C.L¹;
Souza.J.A.M¹

1. CETUC, (Centro de Estudos em Telecomunicações)
PUC-Rio Rio de Janeiro , Brazil, marbey@cetuc.puc-rio.br
2. UFF (Universidade Federal Fluminense) Niterói, RJ,
Brasil

O.D. Aguiar, S. R. Furtado (In Memoriam)
INPE – Instituto Nacional de Pesquisas Espaciais
São José do Campos, São Paulo, Brasil

Abstract—This work describes the development of an oscillator prototype at 10GHz that consists of a feedback loop amplifier using a Sapphire loaded cavity and a tunable cylindrical cavity filter. Measurement procedures involving a phase detector circuit technique are described. The phase noise performance obtained at room temperature is -127,32 dBc/Hz at 3KHz and the electrical quality factor (Q) is around 10⁵.

Keywords—Sapphire Cavity, ultra low phase noise microwave oscillator, feed back loop amplifier.

I. INTRODUCTION

The performance, in terms of phase noise, of the feedback oscillators of Fig. 1 is given by $\mathcal{L}(f_m)$ according to (1):

$$\mathcal{L}(f_m) = \frac{S}{2} = \frac{1}{2} \left[b f_m^{-1} + \frac{F k_b T}{P_s} \right] \left[1 + \left(\frac{f_0}{2Q f_m} \right)^2 \right] \quad (1)$$

Where b is associated with flicker noise, f_0 is the oscillation frequency, f_m is the offset frequency, Q_L is the loaded quality factor of the resonant circuit, F is the noise factor of the amplifier, k_b is Boltzmann's constant, T is temperature, and P_s is the carrier oscillating power.

As showing in Fig. 1, the output power (P) of the feedback oscillator consists only of noise power amplified by the positive feedback and then “filtered” by a high Q cavity. The feedback Q^i given by (2), indicates that the loaded quality factor Q_L of the resonant circuit plays a important hole in the noise filtering.

$$Q^i = Q_L \frac{2}{\pi} \frac{P}{F k_b T} \quad (2)$$

Aiming to obtain a maximum value of Q, an electromagnetic cylindrical mode near $f = 9.6$ GHz was selected.

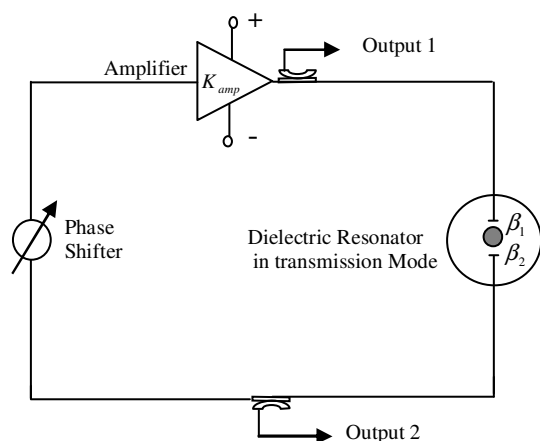


Fig. 1- Schematic diagram of a Feedback oscillator.

Electrical resonators composed by cylindrical cavities loaded with high dielectric constant and low loss materials are employed as high “Q” cavities in microwave oscillators. Devices using barium titanate with $\epsilon_r \ll 50$ has been reported in microwave and telecommunications circuits since early 80s [2],[3]. As the unloaded “Q” of these devices can reach 10³ values, their performance as noise filters in oscillator loops provide low phase noise performance. However, applications of those resonators in experimental physics, aerospace and relativity theory tests require an unloaded “Q” over 10⁷. Metallic cylindrical cavities loaded with a Sapphire crystal resonator has been studied and presents unloaded “Q” in this range. [1],[5]

In this paper, the development and measurement of a microwave oscillator operating with a Sapphire crystal loaded cavity is presented. A phase noise performance of -127 dBc in an offset frequency at 3.2 KHz from carrier is obtained.

This paper is organized as follows: Besides this introduction, in Section II a cylindrical cavity loaded with a Sapphire crystal resonator is simulated through the 3D electromagnetic computational tool Ansoft HFSS. Using the simulation results, a cavity prototype is realized and resonant mode's insertion losses and quality factors are measured.

Section III, describes the Sapphire crystal loaded cavity inserted in a feedback loop with cables, isolators, tunable cylindrical cavity filter and a power amplifier to produce oscillations using a selected mode. The oscillator is then simulated and measured. Section IV describes the phase noise measurement results using a microwave phase detector. In section V it is presented final comments, conclusions and it is indicated future works.

II.SIMULATION AND MEASUREMENT OF A CILINDRICAL CAVITY LOADED WITH SAPPHIRE.

The 3D electromagnetic Sapphire cavity model is presented in Fig. 2 and analyzed using S parameters simulations through 3D full wave electromagnetic field simulation – Ansoft HFSS. The electrical and magnetic coupling probes are characterized experimentally and their dimensions are obtained for achieve an adequate electromagnetic coupling with a loaded quality factor $Q = 10^5$ at 300K. The Fig. 3 presents the simulation results for insertion loss $S_{21}(\text{dB})$ from 9 GHz to 11 GHz band indicating some resonant modes.

The Sapphire crystal used in the low phase microwave oscillator was expected to oscillate based on the chosen resonance frequency of the high order mode for Whispering gallery mode, electric and Magnetic, WGH or WGE. [1],[6] Fig. 4 shows the Mode Chart of Resonant Modes simulated in 3D electromagnetic tools that have High Q above 10^6 at temperature of 300K.

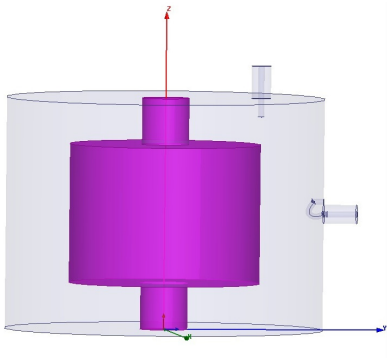


Fig. 2 – Cylindrical Cavity 3D EM Model with a Sapphire Cristal loaded.

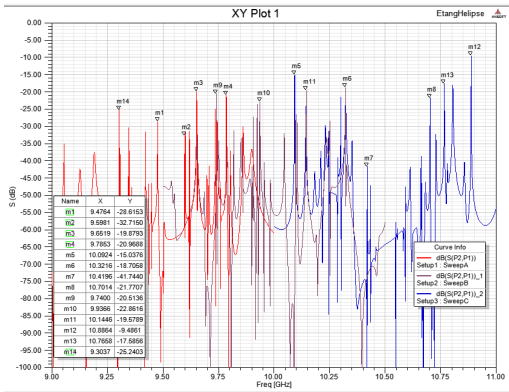


Fig. 3 – Simulation Results for insertion loss in 3D EM Model from 9GHz to 11 GHz band.

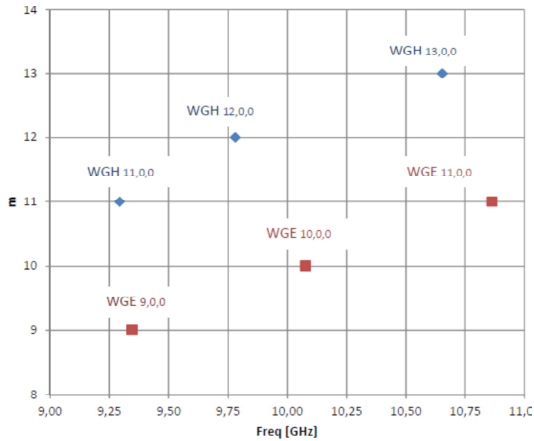


Fig. 4 – Mode Chart of Resonant Modes from cavity loaded with a Sapphire Resonator.

The prototype cavity (Fig. 5), which is a fundamental part of the oscillating circuit, is loaded with a Sapphire crystal with simulated dimensions for resonating at specific frequencies [1]. In Fig. 6 it is shown the cavity's inside, highlighting the Sapphire crystal and the connectors using electrically and magnetically coupling.

The cavity characterization at room temperature is made using a Vector Network Analyzer HP8757A. For the insertion loss S_{21} (dB) and return loss $S_{11}(\text{dB})$ measurements, a magnetically coupled connector was used and for the $S_{22}(\text{dB})$ measurement a electrically coupled connector was used.

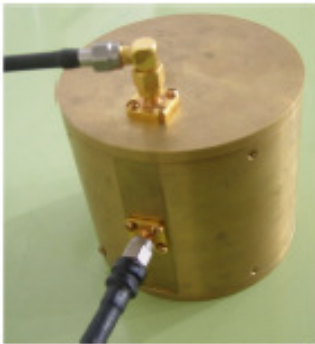


Fig. 5 – Picture of a cylindrical cavity, which is loaded with a Sapphire resonator.

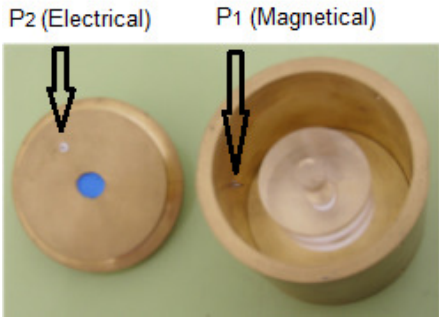


Fig. 6 – The cavity inside with a Sapphire crystal and the electrical and magnetic connectors.

The resonant mode at $f = 9.5668$ GHz was selected due the project specifications. Fig. 7 shows the experimental results obtained for insertion losses from 9 GHz to 11 GHz. Fig. 8 shows the quality factor $Q = 0.36495 \cdot 10^5$ measured for the selected mode (at frequency of 9.5668 GHz) with $\Delta f = 262.14$ kHz.

III.OSCILLATOR PROTOTYPE

The oscillator configuration is simulated in ADS software platform according the circuit shown in Fig. 9 for Loop Gain ≥ 1 and Loop Phase= $2n \pi$, according Berklauer method. [4] The simulated center frequency response results are presented in Fig. 10. When the feed backed signal reaches the cavity, the first electric probe excites the resonant modes of the Sapphire resonator.

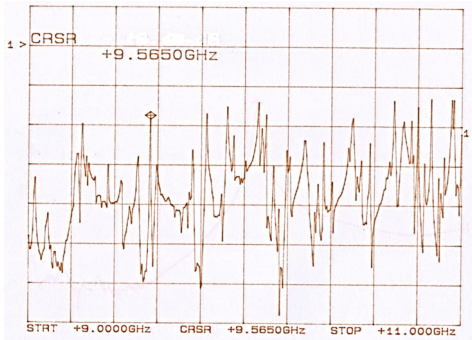


Fig. 7 – Experimental Results obtained from 9 GHz to 11 GHz band.

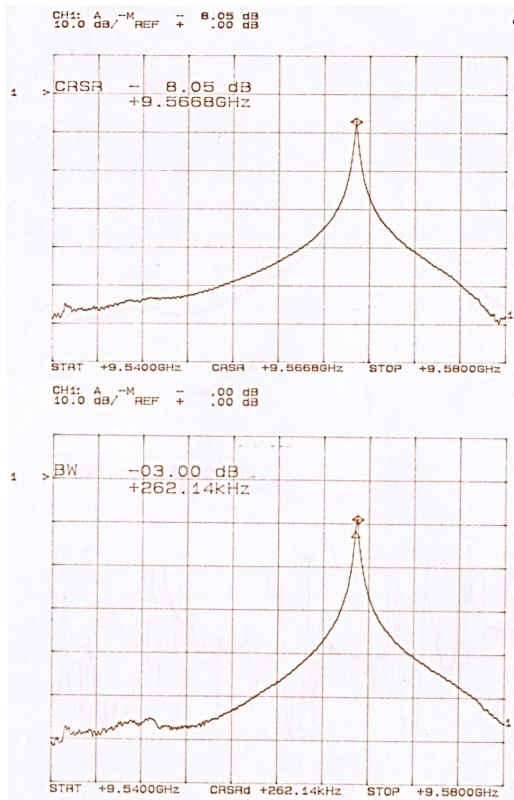


Fig. 8 – Quality Factor of $Q = 0.36495 \cdot 10^5$ Measured at 9.5668 GHz

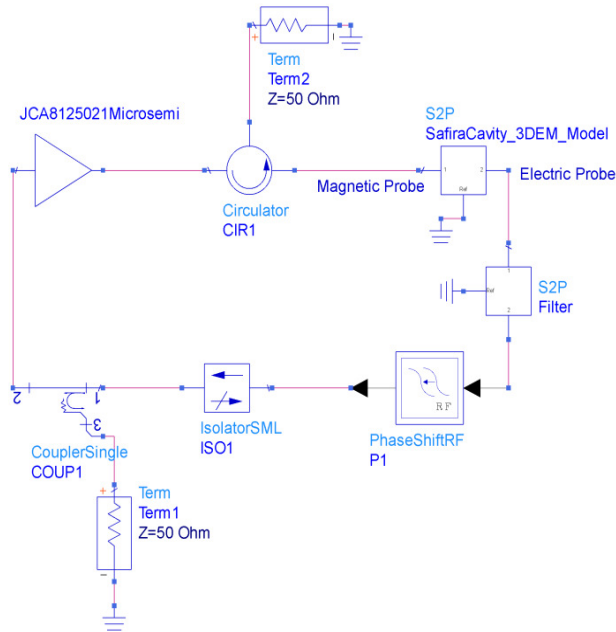


Fig. 9 - Simulated Oscillator feedback loop configuration

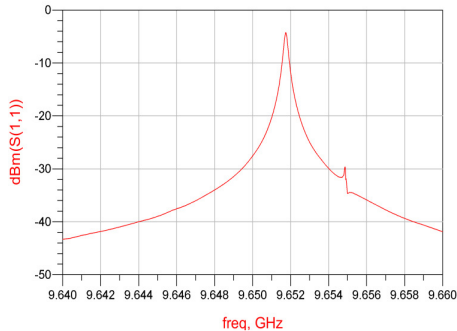


Fig. 10 – Simulated Circuit result for the Sapphire Cavity Oscillator: Frequency response in the coupled output port (Term 1) as Fig. 8 is presented.

The energy is transferred to all frequencies of the resonant modes. Each resonant mode acts as a high-quality factor LC filter. As the present project is focused in $f = 9.5668$ GHz frequency, a band pass filter must be placed in order to truncate all others resonant modes. Then, a tunable cavity filter with bandwidth of 4.75 MHz is added in the loop to suppress other modes than the selected one. The Sapphire cavity and the tunable filter are modeled in the 3D simulator and the results for insertion loss and return loss are used in the oscillator circuit simulation.

Fig. 11 shows the oscillator realized at microwave lab bench in CETUC. A Peltier refrigerator is used to maintain the cavity temperature at $T = 300$ K.



Fig. 11 – Cavity Oscillator Circuit mounted at Microwave Lab at CETUC

To measure the oscillator's resonant frequency a Spectrum Analyzer model MS2668C is employed. The oscillator signal is extracted from the loop through a directional coupler placed after the electrical probe and it has a 0 dBm power level. In Fig. 12 it is showed the results in a Spectrum Analyzer with 50 kHz of resolution, centered at 9.5664 GHz.

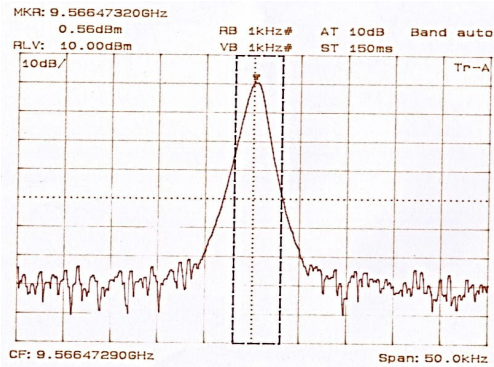


Fig. 12 – Spectrum Analyze with 50 kHz of resolution at 9.56 GHz in the coupled output port

IV. PHASE DETECTOR: OSCILLATOR PHASE NOISE EXPERIMENTAL CHARACTERIZATION.

The most precise way to measure the phase noise of an oscillator is by the phase-detector method using two identical oscillating uncorrelated signals. The measurement is done with the two oscillators synchronized by injection locking. [2],[3] However, this procedure was not possible, because the oscillators did not oscillate at sufficient close frequencies for locking. Therefore, a different procedure was adopted.

The two signals that drive the phase detector are extracted from the same oscillator loop, one before and the other after the high "Q" Sapphire cavity. The signals are uncorrelated due the long delay introduced by the energy stored during a long time because of the very high "Q". [7][8] As the two signals driving the mixer are at the same frequency, the spectrum obtained at mixer output is converted to the frequency zero. The Phase detector circuit is extremely sensible and is presented in Fig. 13. This scheme is similar to an experimental setup presented in Fig. 14.

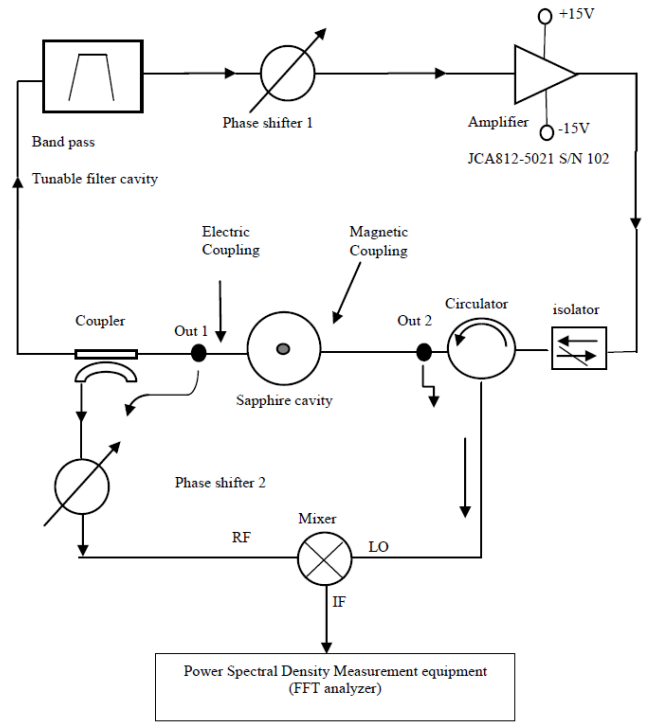


Fig. 13 – Phase detector set-up to measure phase noise of the oscillator extracting two uncorrelated signals from the same loop..



Fig. 14 – Experimental Setup to measure phase noise from an oscillator loaded with a Sapphire crystal mounted at CETUC.

The phase noise measurements are made using a FFT analyzer SR70 in two steps: the first step measures the PSD (Power Spectral Density) in dBVrms/√Hz at 3 kHz from the carrier (presented in Fig. 15 a). The second step measures the Vrmspeak, which is the carrier signal level at 0 Hz. In Fig. 15 b it is illustrated the second step of the phase noise measurement. The phase noise L(f) measured result is defined by (3).

$$L(f) = \frac{(V_{rms}/\sqrt{Hz})^2}{4(V_{rmspeak})^2} \quad (3)$$

The oscillator contains a cylindrical cavity loaded with a Sapphire crystal (mounted at Microwave Labs at CETUC), which has presented a phase noise equal to -127,32 dBc/Hz at 3 kHz from carrier at room temperature of 300K. Another oscillator with the same type of crystal but at temperature of 77K, has presented a value of -135,2 dBc/Hz at 3,2 kHz from the carrier.[1]

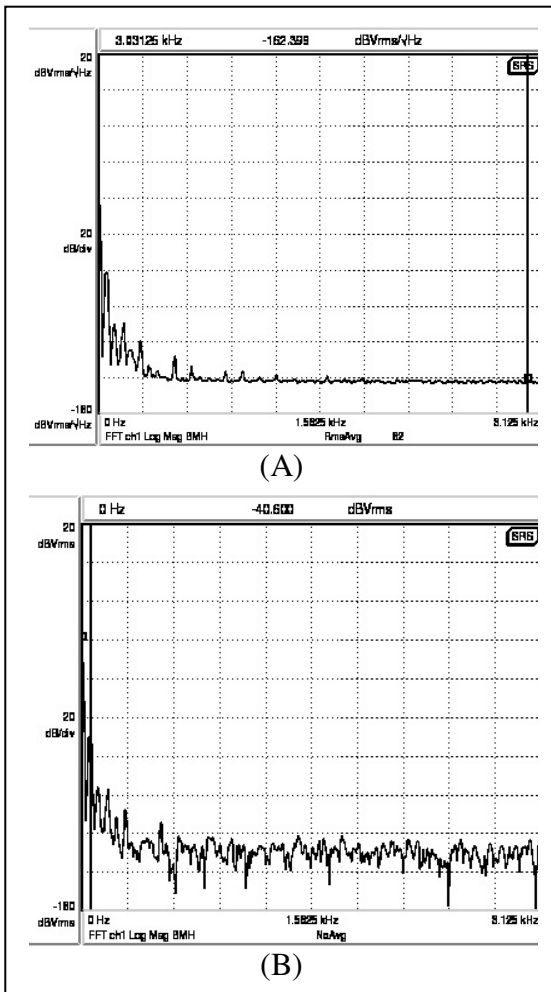


Fig. 15 – Oscillator noise level PSD in band-base at carrier 3 kHz which is equal to -162 dBVrms/√Hz (A) and noise level at 0 Hz which is equal to -40 dBVrms.

V.CONCLUSIONS AND PRINCIPAL LANDMARKS

This work show the development of a microwave oscillator that provide a ultra low phase noise near 10GHz, which can be used in the Brazilian gravitational wave detector Mario Schenberg. Many simulation procedures and experimental setups are realized.

A 3D electromagnetic model was simulated to characterize the Sapphire loaded cavity prototype, connected with electric and magnetic probes. The quality factor Q at room temperature for different resonance modes of the Sapphire cavity was analyzed and the resonant mode at 9.56 GHz was selected. It presented a $Q = 0.36495 \cdot 10^5$ measured for the selected mode with $\Delta f = 262.14$ kHz. Therefore, sapphire crystal resonators can present much higher loaded quality factors ($Q = 10^5$) then Barium Titanate dielectric resonant cavities ($Q \approx 10^3$).

The phase noise results measured is -127.32 dBc/Hz at 3.2 kHz from the carrier at room temperature of 300K, which presents values similar to one obtaining using two different oscillators.

A new electromagnetic coupling mechanism and others resonant modes are being studied to design new oscillator with

high Q feedback loop. Special attentions are being dedicated to degenerated modes.

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