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Ultra-low phase noise 10 GHz oscillator to pump the parametric transducers of the Mario Schenberg gravitational wave detector

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Abstract
We developed a 10 GHz feedback oscillator with ultra-low phase noise. The oscillator was constructed to operate as the pump for the parametric transducers of the Mario Schenberg gravitational wave detector. We calculated the performance of the detector with this pump oscillator and determined how much improvement in phase noise would be necessary in order to reach the standard quantum limit in sensitivity.

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1. Introduction

The Mario Schenberg gravitational wave detector [1] consists of a spherical resonant 1150 kg mass coupled to six electromechanical transducers [2]. It was designed to operate in a bandwidth of 200 Hz with a central frequency of 3.2 kHz and to be able to observe events such as instabilities in neutron stars with high angular momentum within our galaxy limits. In order to have reasonable possibilities of event detection, it is necessary to construct state-of-the-art electromechanical transducers. Schenberg will use microwave parametric electromechanical

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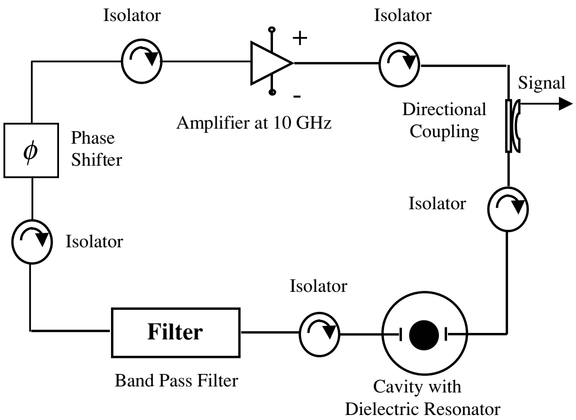

Figure 1. Schematic diagram of an ultra-low phase noise 10 GHz oscillator.

transducers with re-entrant cavities [3, 4]. For the detector to reach high sensitivity it is necessary to develop an ultra-low phase noise 10 GHz oscillator to pump the parametric transducers.

2. The 10 GHz oscillator

An amplifier feedback from a resonant circuit works like an oscillator. The necessary conditions for the circuit to oscillate are that the effective gain in the loop must be equal to or greater than 1 and the loop length must be equal to an integer number of wavelengths, i.e. the total phase must be 2π. Figure 1 shows a schematic diagram of an ultra-low phase noise 10 GHz oscillator.

The oscillator performance can be analysed theoretically from the physical parameters [5] presented in the equation

$$\frac{N_O}{P} = \frac{1}{2}\frac{FKT}{P_{\text{inc}}}\frac{1}{4Q_L^2}\left(\frac{f_0}{f_m}\right)^2 \tag{1}$$

where N_O is the noise density, P is the total power generated by the oscillator, f_0 is the oscillation frequency, f_m is the offset frequency, Q_L is the quality factor of the resonant circuit, F is the noise figure of the amplifier operating in the linear region, K is the Boltzmann constant, T is the thermodynamic temperature and P_{inc} is the output power of the oscillator. For practical reasons equation (1) can be rewritten as

$$\begin{aligned}\pounds\left(\frac{\text{dBc}}{J}\right) &= F(\text{dB}) + 20\log\left(\frac{f_0}{J}\right) - P_{\text{inc}}(\text{dBm}) - 20\log\left(\frac{f_m}{J}\right)\\ &\quad - 20\log(2Q_L) - 174\,\text{dBm} + 10\log(J)\end{aligned} \tag{2}$$

where J is the observation window given in Hz. The input parameters for the oscillator are $f_0 = 10.21$ GHz, $f_m = 3.2$ kHz, $Q_L = 3200$, $F = 2$, $T = 293$ K and $P_{\text{inc}} = 13$ dBm. The phase noise obtained for the oscillator with these parameters is £ = −133 dBc at 3.2 kHz.

3. Simulation of the spherical antenna

Figure 2 shows a schematic diagram of Schenberg detector coupled to a parametric transducer.

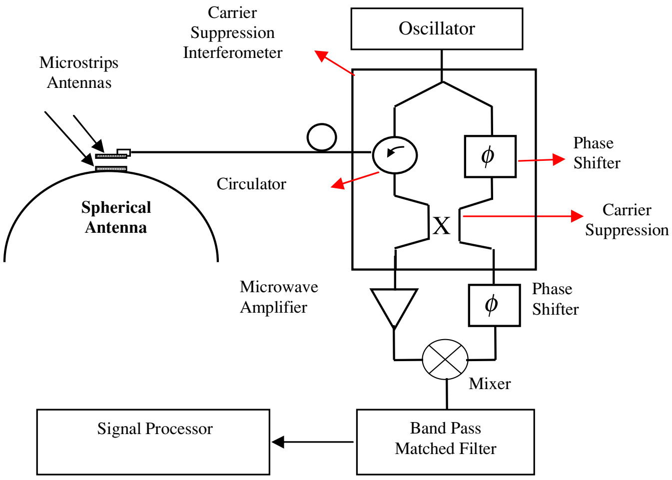

Figure 2. Schematic diagram of the Schenberg detector coupled to a parametric transducer.

The equations of motion for the antenna [6] coupled to six two-mode parametric transducers with all Gaussian noise sources included are given by

$$\begin{pmatrix} M_s\mathbf{I} & \mathbf{0} & \mathbf{0} \\ M_{r1}\alpha\mathbf{B}^T & M_{r1}\mathbf{I} & \mathbf{0} \\ M_{r2}\alpha\mathbf{B}^T & M_{r2}\mathbf{I} & M_{r2}\mathbf{I} \end{pmatrix} \begin{pmatrix} \ddot{\mathbf{a}} \\ \ddot{\mathbf{q}}_1 \\ \ddot{\mathbf{q}}_2 \end{pmatrix} + \begin{pmatrix} k_s\mathbf{I} & -k_{r1}\alpha\mathbf{B} & \mathbf{0} \\ \mathbf{0} & k_{r1}\mathbf{I} & -k_{r2}\mathbf{I} \\ \mathbf{0} & \mathbf{0} & k_{r2}\mathbf{I} \end{pmatrix} \begin{pmatrix} \mathbf{a} \\ \mathbf{q}_1 \\ \mathbf{q}_2 \end{pmatrix}$$
$$= \begin{pmatrix} \mathbf{I} & -\alpha\mathbf{B} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} & -\mathbf{I} \\ \mathbf{0} & \mathbf{0} & \mathbf{I} \end{pmatrix} \begin{pmatrix} \mathbf{F}^{GW} + \mathbf{F}_s^N \\ \mathbf{F}_1^N \\ \mathbf{F}_2^N \end{pmatrix}$$

where the first matrix has the mass terms, the second matrix has the amplitudes of acceleration of the sphere quadruple modes and of the transducer modes, the third matrix has the effective spring constants for the model, the fourth matrix has the amplitudes of motion for all modes and the last two have the force terms.

Using this model two calculations for the sensitivity of the detector were made, the first one using as detector parameters the following values: thermodynamical temperature $T = 50$ mK, mechanical quality factors of the sphere and the transducer resonators ($Q_{\text{sphere}} = Q_{\text{res1}} = Q_{\text{res2}}$) 10^7, effective mass of the transducer resonators (M_{res1}) 53 g and (M_{res2}) 10^{-2} g, microwave cavity electrical quality factor (Q_{elec}) 2×10^7, microwave pump frequency 10.21 GHz, frequency tuning coefficient ($\mathrm{d}f/\mathrm{d}x$) 6×10^{14} Hz m^{-1}, phase noise (£) -133 dBc Hz^{-1} at 3.2 kHz, amplifier noise temperature (T_{amp}) 8 K and incident power (P_{inc}) 10^{-10} W. For the second simulation the following parameters were changed: $T = 15$ mK, £ $= -145$ dBc Hz^{-1} at 3.2 kHz, $T_{\text{amp}} = 0.4$ K, $Q_{\text{elec}} = 2 \times 10^7$ and $P_{\text{inc}} = 10^{-8}$ W. Figure 3 shows the results of the calculations. Similar work can be found in [7] and [8].

4. Conclusions and future work

The phase noise calculated from measured parameters of the oscillator was -133 dBc Hz^{-1} at 3.2 kHz. With this value and the parameters mentioned above we found a noise temperature of 2.03×10^{-6} K, and a strain sensitivity density (noise power spectral density) of 5.9×10^{-23} Hz $^{-1/2}$. The noise temperature necessary for the detector to reach the quantum limit in

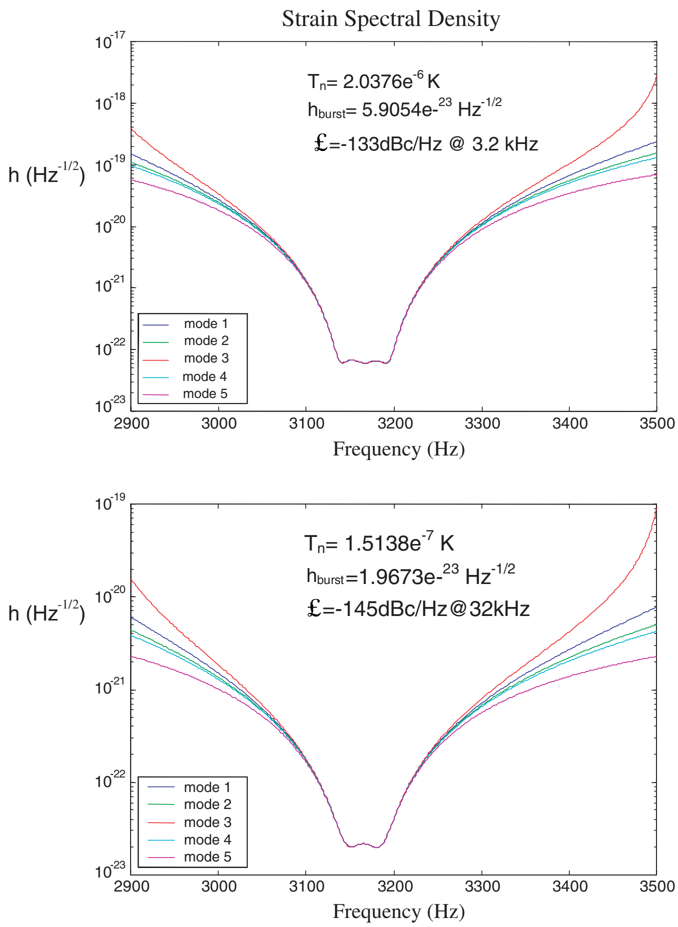

Figure 3. Strain spectral density in the two cases studied.
(This figure is in colour only in the electronic version)

sensitivity is ~0.15 μK. The simulations showed that the value for the phase noise necessary to make the detector to reach the quantum limit is -145 dBc Hz^{-1} at 3.2 kHz. This value was found by optimizing the parameters with following values: $P_{\mathrm{inc}} = 10^{-8}$ W, $T_{\mathrm{amp}} = 0.4$ K (quantum amplifier), $T = 37$ μK (thermodynamic temperature). The strain sensitivity density found was 1.9673×10^{-23} Hz $^{-1/2}$ and the noise temperature, 1.51×10^{-7} K. These results are better than the ones presented in [7] and [8] for two reasons: first, the parameters chosen for the detector are expected to make it reach the quantum limit; second, we are using transducers with very low masses in these calculations.

The next step is to measure directly the phase noise of the 10 GHz oscillator.

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