SEARCH FOR HIGH FREQUENCY SIGNALS AT THE HANFORD 4K INTERFEROMETER

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It is well known that the sensitivity of the LIGO interferometers decreases at higher frequencies and indeed, for an "optimally" oriented g.w. (i.e. with the propagation vector normal to the plane of the arms) vanishes at the free spectral range (fsr) frequency $\nu = \nu_0 = c/2L$. However "optimal" orientation is a special case and when averaged over directions of incidence and polarization of the g.w. the interferometer response remains finite at $\nu = \nu_0$ [1]. Furthermore the response of the Fabry-Perot cavity at the fsr is greatly enhanced [1,2]. This can be understood as parametric conversion from the carrier frequency to the next longitudinal mode of the interferometer.

Such parametric conversion has been recently demonstrated at the Hanford 4K interferometer (IFO) for single arm operation as well as with the full IFO locked in power recycled mode [3]. The data were obtained by imposing a (longitudinal) sinusoidal drive on ITMX and sweeping the frequency around ν_0. Fig.1 shows the response of the AS_I signal for only the X-arm locked. The curve is the theoretical prediction using the mirror reflectivities and only the amplitude has been normalized for best fit.

The response with the full IFO is shown in Fig.2. We observe a broad enhancement at $\nu = \nu_0$ of the same width as found in Fig.1, (FWHM ~300 Hz) and superimposed on it a narrow peak with FWHM ~8 Hz. This latter peak reflects the, so called, "double cavity pole". Namely resonance in both the arm cavity and the power recycling cavity.

To express the signal quantitatively we use the following notation

E_2 carrier field incident on the beam splitter (BS).
E_S r.f. sideband field incident at the antisymmetric (AS) port .
E_A g.w. sideband field at AS.
V_A photodiode voltage at AS.
x_0 amplitude of ITMX motion.
Q quality factor of the arm, $Q = F(L/\lambda_c)$.
F finesse of the arm, $F \simeq \pi/(1 - r_1)$

The field at the AS port for $|E_A/E_2| \ll 1$, is [4]

$$\left|\frac{E_A}{E_2}\right| = 4\frac{x_0}{L}Q = 4\frac{x_0}{\lambda_c}F \tag{1}$$

and V_A can be expressed as

$$V_A = K\ |E_2|^2 \left|\frac{E_S}{E_2}\right| \left|\frac{E_A}{E_2}\right| \tag{2}$$

Here K is the conversion factor from the optical field (squared) to voltage. It is a product of the E/O shutter attenuation, of the diode conversion factor (0.54 A/W), and of the r.f. impedance (4K). Typical E/O shutter settings are 3% for single arm and "detect mode", and 7% for "common mode", operation. An additional attenuation factor of 4 is due to the splitting of the light from the AS port before it reaches the photodetector. We use $|E_S/E_2| \simeq 0.11$, and we take $|E_2|^2 = 20$ W, namely a recycling gain of 20 for a 1 W input. Furthermore $F_{\text{arm}} \simeq 220$ so that $Q = 8.4 \times 10^{11}$.

Data were obtained over a range of excitations x_0 and the results are shown in Fig.3 where the detected voltage V_A is plotted vs the equivalent strain $h = x_0/L$. To obtain x_0 in terms of the excitation applied to ITMX we excited the mass at 0.1 Hz and compared the result with the D.C. calibration. The value of x_0 at the fsr frequency $\nu_0 = 37.52$ kHz was obtained by decreasing its static value by the effect of a double pole at $\nu_P = 0.74$ Hz. Thus

$$x_0(\nu_0) = \frac{x_{DC}}{1 + (\nu_0/\nu_P)^2} = 8 \times 10^{-16}\ \text{m} \tag{3}$$

for 1 V excitation. Namely a strain $h = 2 \times 10^{-19}$ for 1 V excitation. Using this calibration for x_0, the observed signal is within a factor of 2 of the prediction of Eqs.(1,2) using for $K, |E_2|^2$ and $|E_S/E_2|$ the values discussed previously.

To give an indication of the noise floor we show in Fig.4 the spectrum of the response to excitation of ITMX at a fixed frequency $\nu = \nu_0$, and for 1 V excitation. Note the appearance of the roll and bounce mode natural frequencies as sidebands to the excitation. The signal to noise is ~ 150 with the noise level at $V_N = 0.2 \times 10^{-6}$ V for a bandwidth BW = 0.125 Hz and 11 averages. Thus for a 24 hour period one can expect a noise level $V_N \simeq 6 \times 10^{-9}$ V, and therefore

$$\frac{x_0}{L} \simeq 4 \times 10^{-23} \tag{4}$$

should be observable with S/N = 1. This sensitivity is applicable for a 300 Hz (FWHM) frequency band around $\nu_0 = 37,520$ Hz.

Such high frequency is outside the band of conventional gravitational signals. However it is possible that the stochastic background spectrum extends to and beyond ν_0. Of course the higher the frequency the lower the wave amplitude $h(t)$. The commonly accepted spectrum for the stochastic background has a $1/\nu$ dependence, and we write

$$\Omega_G = \frac{1}{\rho_c}\frac{d\rho_G}{d\log\nu} = \frac{1}{\rho_c}\nu\frac{d\rho_G}{d\nu} \tag{5}$$

Here Ω_G is a constant, ρ_c the closure density and ρ_G the density in gravitational waves. The wave amplitude is then given by

$$h(t)_{\nu,\Delta\nu} = \frac{H_0}{\pi}\,\frac{1}{\nu}\,\sqrt{\frac{3}{4}\Omega_G\frac{\Delta\nu}{\nu}} \tag{6}$$

where H_0 is the Hubble constant, which we take as $H_0/\pi \simeq 0.7 \times 10^{-18}$ s^{-1} and $\Delta\nu$ the measurement bandwidth.

Numerically, for $\nu = 37.5$ kHz, $\Delta\nu = 300$ Hz

$$h(t) \simeq 3 \times 10^{-24}\sqrt{\Omega_G} \tag{7}$$

The limits on Ω_G are at $\Omega_G < 10^{-6}$ so that the expected value is well below the sensitivity given by Eq.(4). The arguments for pursuing the measurement are two-fold. While the limits on Ω_G are for the entire universe it is possible to have a local enhancement of Ω_G within the galaxy. Furthermore if the spectrum differs from that of Eq.(5) and is peaked around ν_0, then $h(t) = 3.5 \times 10^{-23}\sqrt{\Omega_G}$. To account for the random orientation and polarization of the stochastic background the limiting sensitivity given by Eq.(4) must be further increased (derated) by a factor of $\sqrt{5}$ [1,5].

The measurements at $\nu = \nu_0$ can be carried out parasitically to the normal operation of the IFO by using the AS_I monitor output directly into the SRS-785 spectrum analyzer. After averaging for periods of 1 hour the data would be transferred to a PC and written on disk for further off line analysis. Alternately the AS_I output would be mixed down to an audio frequency and the signal recorded in the DAQ stream.

References

1. See for instance R. Schilling, Class, Quant. Grav. 14, 1513 (1987).

2. Frequency response of the LIGO interferometer LIGO-T970084-00-D, D. Sigg ed; M. Rakhmanov et al. Phys. Letters A 305, 239 (2002); W.E. Butler, A.C. Melissinos and F.J. Raab, "Experimental Determination of the Mode Spectrum of the Locked Arms of the H4K Interferometer". Internal note June 2002.

3. W. Butler and A.C. Melissinos "Parametric Conversion in the H4K Interferometer" 12/2002. See also www.ligo-wa.caltech.edu/~wbutler

4. See for instance T.T. Lyons "An Optically Recombinded Laser Interferometer for Gravitational Wave Detection", California Institute of Technology Ph.D. Thesis, 1997; or ref. [2] above.

5. P.R. Saulson, "Fundamentals of Interferometric Gravitational Wave Detectors", World Scientific 1994.

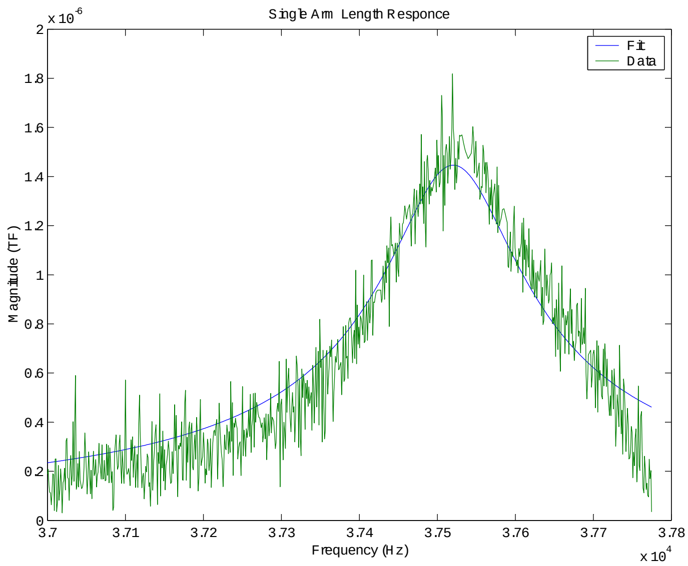

Figure 1: Parametric conversion response to swept sine excitation around $\nu = \nu_0$ (shaking ITMX). The normalized theoretical prediction is shown by the solid curve. Single arm.

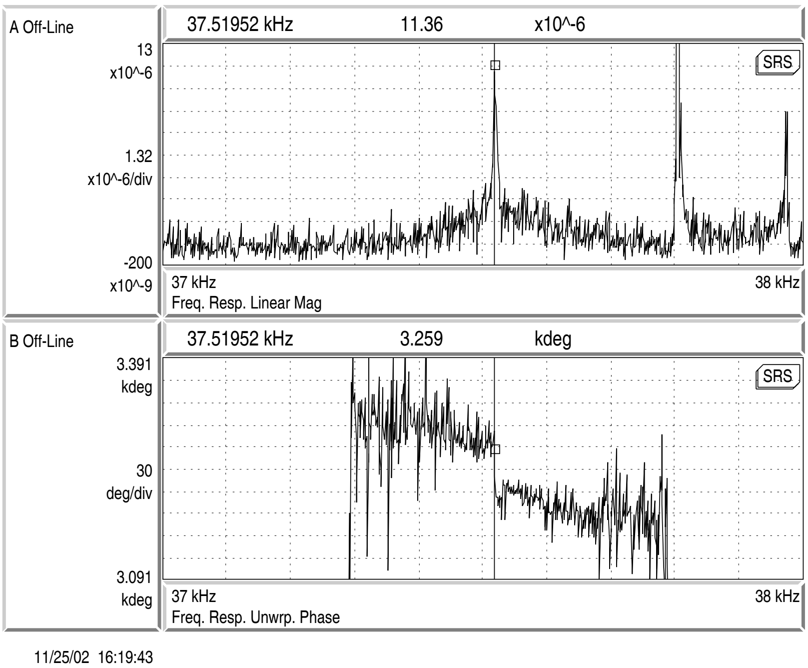

Figure 2: Parametric conversion response to swept sine at AS_I, around $\nu = \nu_0$. Fully locked interferometer.

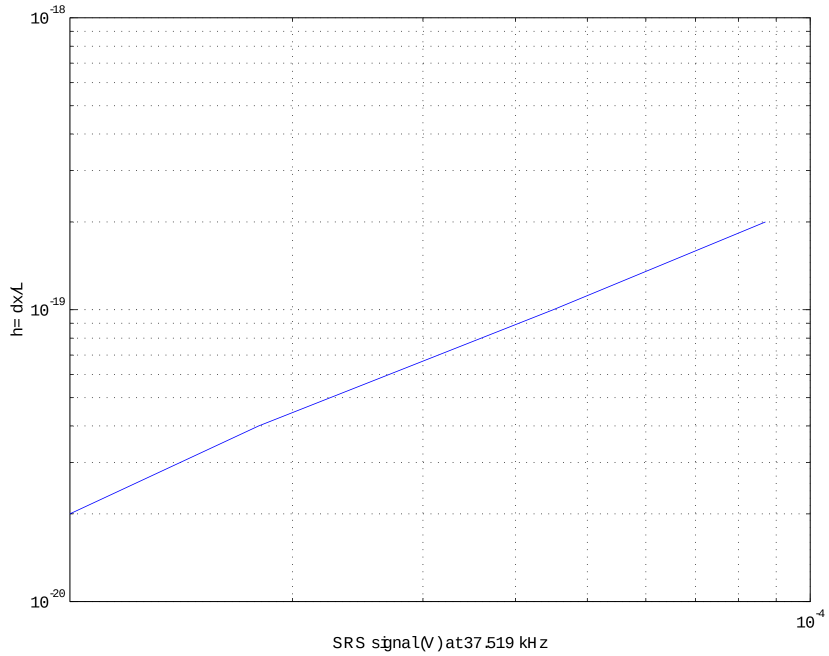

Figure 3: Plot of the equivalent strain h as a function of the observed AS_I signal at frequency $\nu_0 = 32.519$ kHz

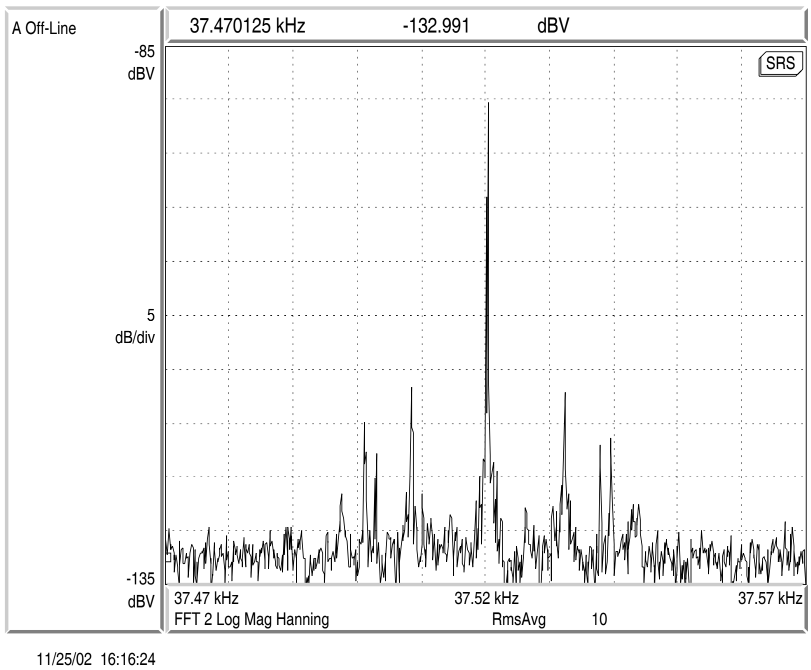

Figure 4: Parametric conversion signal at AS_I for fixed $\nu = \nu_0$. Fully locked interferometer in common mode.