Very high Q frequency-locked Fabry-Perot Cavity

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(Submitted to Review of Scientific Instruments)

DFPD 95/EP/60

UNIVERSITÀ DEGLI STUDI DI PADOVA
DIPARTIMENTO DI FISICA
"GALILEO GALILEI"

ISTITUTO NAZIONALE DI FISICA NUCLEARE
SEZIONE DI PADOVA

Via Marzolo, 8 - 35131 PADOVA (ITALIA)

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We report measurements on a 1.75 m long Fabry-Perot cavity locked to a Nd:YAG tunable laser using the Pound-Drever technique. The cavity decay time was measured to be about 291 μs corresponding to a quality factor Q of about 5×10^{11}, the highest value ever reported for an optical resonant cavity.

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I. INTRODUCTION

Fabry-Perot cavities have found applications in several advanced fields, for instance QED tests[1], gravitational wave detection with interferometers[2], optical sensors for gravitational wave bar antennas[3]. High finesse Fabry-Perot cavities are also commonly used as a frequency reference to which a tunable laser is locked[4].

In this Letter we report measurements on a very high quality factor Fabry-Perot cavity locked to a Nd:YAG nonplanar ring oscillator (NPRO) laser by means of the Pound-Drever technique[5]. The beam phase modulation was obtained using the technique recently published in ref. 6, i.e. using the laser itself as the optical phase modulator.

The cavity length d was 1.75 m; the cavity decay time τ was measured to be 291 μs corresponding to a finesse F of 157000 and a linewidth $\Delta\nu_c$ of about 550 Hz. The corresponding quality factor $Q \cong 5 \times 10^{11}$ is, to our present knowledge, the highest ever published for an optical resonant cavity.

II. APPARATUS

The scheme of our apparatus is shown in Fig. 1. The light source is a tunable NPRO laser[7] (Lightwave Electronics, Model 124) emitting 10 mW of power at a wavelength λ_l=1064 nm (ν_l=2.82 10^{14} Hz). Tunability is achieved by changing the geometry of the NPRO crystal: either by means of a piezoelectric transducer (bandwidth $\approx$ 100 kHz, dynamic range = 200 MHz) or by varying the temperature of the crystal (bandwidth $\approx$ 1 Hz, dynamic range = 30 GHz).

Laser light, after crossing a two stage optical isolator OI (Gsänger, Model FR1060/5TS), enters the polarising cube beam splitter P which is set for maximum transmission. The Faraday cell FC (Gsänger, Model FR1060/5) then rotates the polarisation by a 45 degree angle. A lens L is used to match the laser beam to the cavity FP. Mirrors M1 and M2 are used to steer the light into the cavity. These two mirrors are mounted on tilting stages to allow the alignment of the direction of the beam with the optical axis of the cavity. When the cavity and the beam are properly aligned, light coming back from the cavity follows the same optical path as the incoming light. After crossing the Faraday cell FC the polarisation angle of the reflected light is rotated by another 45 degree so that the reflected light can be extracted from the main path as the ordinary ray of the polariser prism P. Finally the photodiode PD_r collects the reflected light giving the main signal for the Pound-Drever locking scheme. The photodiode PD_t on the other hand collects the light transmitted by the cavity. The lens C focuses the transmitted light onto this photodiode.

Fig. 2 shows a drawing of the mechanical set-up of the cavity. The Fabry-Perot cavity is based on two very high reflectivity curved mirrors supplied by Research ElectroOptics (Boulder, Colorado USA) (Reflectivity $R>0.999994$, radius of curvature $R_c = 5$ m, BK7 substrate). The two Fabry-Perot mirrors, CM_1 and CM_2, were mounted on two tilting stages MM_1 and MM_2 (Oriel. Model 14351 Precision Mirror Mounts) fixed to the two ends of an aluminium tube IT. The set-up was kept in a steel tube ET designed to be vacuum pumped. Two windows W_1 and W_2 allowed the light to enter and exit the ET tube. At each end of the IT tube we also had 3 screws that were used to centre the IT tube with respect to the ET vessel.

III. THE LOCKING SCHEME

The locking scheme used to lock the laser to the Fabry-Perot cavity can be seen in Fig. 1 along with the optics set-up. A main oscillator MO at a frequency Ω_0 was used both to modulate the laser beam phase, as required by the Pound-Drever locking technique[5,8], and as a reference signal for the mixer MX (Mini-Circuits, Model MCLZP-10514). The signal V_r coming from the photodiode PD_r, after being filtered by a passive highpass filter HF, was the second input for the mixer MX. Following ref. 6, we used the laser itself as a phase modulator. The phase $\varphi(t)$ can be written as[6]

$$\varphi(t) = \int_0^t \left(2\pi\nu_l + A\cos(\Omega_0 t + \varphi_0)\right) dt = 2\pi\nu_l t + \beta\sin(\Omega_0 t + \varphi_0) + \varphi(0) \quad (1)$$

where A and φ_0 are the amplitude and the phase of the frequency modulation given to the laser and $\beta = A/\Omega_0$ is the index of modulation. The output of the mixer MX is the error signal V_e

$$V_e = \chi V_r(t) \cos(\Omega_0 t + \varphi_{ref}) \quad (2)$$

where χ is the efficiency of the mixer MX and φ_{ref} is the phase of the reference signal. In principle, when there is no phase difference between the reference signal and the modulation signal, the DC value of the error signal is maximum. When the resonance frequency ν_c of the Fabry-Perot cavity and the frequency of the laser ν_l differ by less than half the cavity linewidth $\Delta\nu_c$, the error signal V_e shows a linear dependence on $\Delta\nu_l = \nu_l - \nu_c$. If the cavity mirrors are equal and their reflectivity $R \approx 1$, the maximum value of the slope of the signal around $\Delta\nu_l = 0$, can be written as[8]

$$D_0 = \left.\frac{\partial V_e}{\partial \Delta\nu_l}\right|_{\Delta\nu_l = 0} = -16\,\chi\, V_0\, \frac{TF^2 d}{\pi c}\, J_0(\beta) J_1(\beta) \qquad (3)$$

where V_0 is the value of V_r out of resonance ($\nu_l \neq \nu_c$) at the frequency Ω_0, T is the mirror transmittivity, c is the velocity of the light in vacuum; $J_0(\beta)$ and $J_1(\beta)$ are the Bessel function of order 0 and 1 respectively. The product $J_0(\beta)J_1(\beta)$ has its maximum value of 0.34 at $\beta \approx 1.1$.

The error signal V_e was given as input to the servo system we have developed[6].

The electrical circuit of our servo system is shown in Fig. 3. It consisted of an amplification stage and a four stage integrator. It provided a fast correction signal (bandwidth ≈ 50 kHz) used to drive the piezoelectric transducer and a slow correction signal (bandwidth ≈ 0.16 Hz) used to change the temperature of the crystal. After the amplification stage of gain g, the error signal V_e could be monitored by looking at its amplified value $V_m = g\, V_e$. The first integration stages and the slow correction signal could be switched off the feedback loop by appropriately designed switches. A final stage, Σ, summed the fast correction signal to the signal V_{MOD} coming from the main oscillator MO. We could also, at this stage, sum to the modulation signal a triangular wave signal V_{RAMP} disconnecting the integration stages using the switch S. This feature was used during fine alignment of the cavity to sweep the laser frequency and consequently to continuously monitor the resonance lines of the cavity. Finally, during locking operation, one could sum to the fast correction signal a calibration signal V_{CAL} to study the closed loop features of the servo system.

IV. METHOD

To obtain a good resonance condition the cavity has to be properly aligned. We used mirrors M_1 and M_2 to obtain a preliminary alignment between the laser beam and the geometrical axis of the mechanical support of the cavity. The cavity mirror nearer to the photodiode PD_t was then cleaned with pure ethanol and put in its tilting stage MM1. The stage MM1 was then used to send the beam reflected back by the mirror itself exactly on the same path as the incoming beam. The same procedure was followed for the second mirror.

The frequency of the laser was then driven by the triangular wave signal V_{RAMP}. Fine tuning of the cavity to maximise the light transmission of the cavity at resonance could then be effected by slightly adjusting stages MM1, MM2, M1, M2. Finally the ET vessel could be closed and pumped by a diaphragm pump. During data taking the pressure inside the vessel was of few mbars.

To operate the servo system we have chosen a frequency of 650 kHz for the main oscillator MO. The amplitude of the modulation given to the laser piezoelectric transducer ranged between 30 ÷ 50 mV. At the selected frequency we checked that 50 mV corresponded to $\beta \approx 1$ with a Residual Amplitude Modulation RAM $< 10^{-4}$. Since the frequency shift ν_{offset} is given by $\nu_{offset} \approx \text{RAM}\, \Delta\nu_c / \pi$, in our case this was less than 2×10^{-2} Hz.

The typical amplitude of the reference voltage given to the mixer MX was 0.6 V and the efficiency χ was measured to be about 0.5.

The error signal V_e was optimised by varying the phase φ_0 and looking at the error signal in correspondence of a resonance peak while the laser was driven by the triangular wave signal V_{RAMP}.

Finally, to lock the laser to the cavity the servo system was switched in the standard configuration with the fast correction signal connected and the triangular wave signal off. Using the manual thermal control of the laser frequency one could slowly bring the laser frequency ν_l to the resonance value. The control of the laser frequency was then taken by the servo system itself realising the locking. In general the laser was initially locked to the cavity with only the last integration stage on. Afterwards the other three integration stages could be switched on together with the slow correction signal. With the laser locked to the cavity, the photodiode PD_t showed a constant signal V_t and the fast and slow correction signal went promptly to an average 0 Volt level.

The locking was very stable and when no unusual environmental noises were present, it could last for more than half an hour.

To measure the cavity decay time τ we observed the exponential decay of the light coming onto photodiode PD_t following the interruption of the beam entering the cavity. The decay time τ is related to the cavity parameters by[9]

$$\tau = \frac{F\,d}{\pi c} = \frac{1}{2\pi \Delta\nu_c} = \frac{Q}{2\pi \nu_l} \qquad (4)$$

To interrupt the laser beam we simply switched the laser to the standby mode, the exponential decay was registered by properly triggering a digital oscilloscope. With the cavity removed, the switching lifetime was measured to be about 30 µs.

To study and optimise the locking scheme we monitored on a spectrum analyser the frequency spectrum of the amplified error signal V_m and of the signal from photodiode PD_t. The possibility to sum a calibration signal V_{CAL} to the fast correction signal allowed us to study the behaviour of our servo system. Giving as calibration signal a sine wave of constant amplitude at the frequency ν_{CAL}, where the transfer function at open loop of the servo system $G(\nu)$ is greater than 1, the corresponding amplitude in the frequency spectrum of the amplified error signal $V_m(\nu_{CAL})$ can be written as[8]

$$V_m(\nu_{CAL}) = g\frac{V_{CAL}(\nu_{CAL})}{G(\nu_{CAL})}. \qquad (5)$$

In this way we measured $G(\nu)$ and compared it with the theoretical values.

V. RESULTS

In Fig. 4 we show the voltage signal from the photodiode PD_t obtained when studying the decay of the light within the Fabry-Perot cavity. The continuous curve in the figure refers to the case when the cavity is traversed by the light. The dashed curve, on the other hand, which exhibits a much shorter decay time, represents the switching lifetime of the laser. In the first case, the decay time is determined by the cavity parameters, while in the latter case the shorter decay time is dominated by the laser characteristics.

Fig. 5 shows the cavity decay curve together with a best fit to an exponential function. We obtained a decay time τ equal to 291 μs which corresponds to a linewidth $\Delta\nu_c$ of 547 Hz and a quality factor Q of 5.14×10^{11}. The value of the finesse F derived from τ is 157000. This is slightly less than the value calculated on the basis of the reflectivity given by the mirror manufacturers. This is probably due to the mirror cleaning. The fact that in some tests with different cleaning procedures we obtained decay times different from the above result confirms this hypothesis. The fraction of the transmitted light η_{FP} was measured to be 0.09 and the mirror transmittivity T about 6×10^{-6} for both mirrors. With these experimental parameters the maximum value of the light power density on the reflective surface of the mirrors is about 3×10^4 W/cm^2.

The calculated transfer function G of the servo system is shown in Fig. 6. We also show the experimental data taken with the method described in the previous paragraph based on the calibration signal. The agreement between the two is good. At a frequency lower than 3 kHz the G function decreases like $1/\nu^4$, at 1 Hz the gain being about 10^{14}. The bandwidth of the servo resulted to be 50 kHz.

Fig. 7 shows the noise spectrum of the V_m signal. The peaks are due to electrical (50 Hz and harmonics due to the mains) and mechanical environmental noise. The region of minimum locking noise is between 100 and 1000 Hz corresponding to about $V_{noise} = 1.5\times10^{-7}\ V_{rms}/\sqrt{Hz}$. To obtain the noise in the difference between the cavity resonant frequency and laser frequency ($\Delta\nu_{noise}$) for frequencies lower than $\Delta\nu_c/2$, one can scale V_{noise} for the gain g of the amplification stage and divide by D_0. Since we had $g = 7$, $\chi = 0.5$, $V_0 = 1.4$ V, $T = 6\times10^{-6}$, $F = 1.57\times10^5$, $d = 1.75$ m and $J_0(\beta)J_1(\beta) = 0.1$ we can calculate $D_0 = 3.1\times10^{-4}$ V/Hz and $\Delta\nu_{noise} = 0.7\ mHz/\sqrt{Hz}$.

Fig. 8 shows the relative intensity noise spectrum of the signal collected on the photodiode PD_t. The continuous curve was measured when the laser was locked to the Fabry-Perot cavity while the dashed curve corresponds to the noise of the laser with the cavity removed.

Acknowledgements

This work has been done in the framework of the PVLAS collaboration whose aim is to measure the vacuum magnetic birefringence predicted by quantum electrodynamics[1]. Measurements have been conducted at the Legnaro Laboratory of Istituto Nazionale di Fisica Nucleare (INFN). We wish to thank all our colleagues, in particular D. Bakalov, M. Del Colletto, E. Di Capua, P. Favaron, U. Gastaldi, M. Moretti, R. Pengo, G. Petrucci.

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FIGURE CAPTIONS

FIG. 1. Schematic drawing of the apparatus.

FIG. 2. Exploded view of the mechanical set-up of the Fabry-Perot cavity.

FIG. 3. Electrical circuit of the servo system.

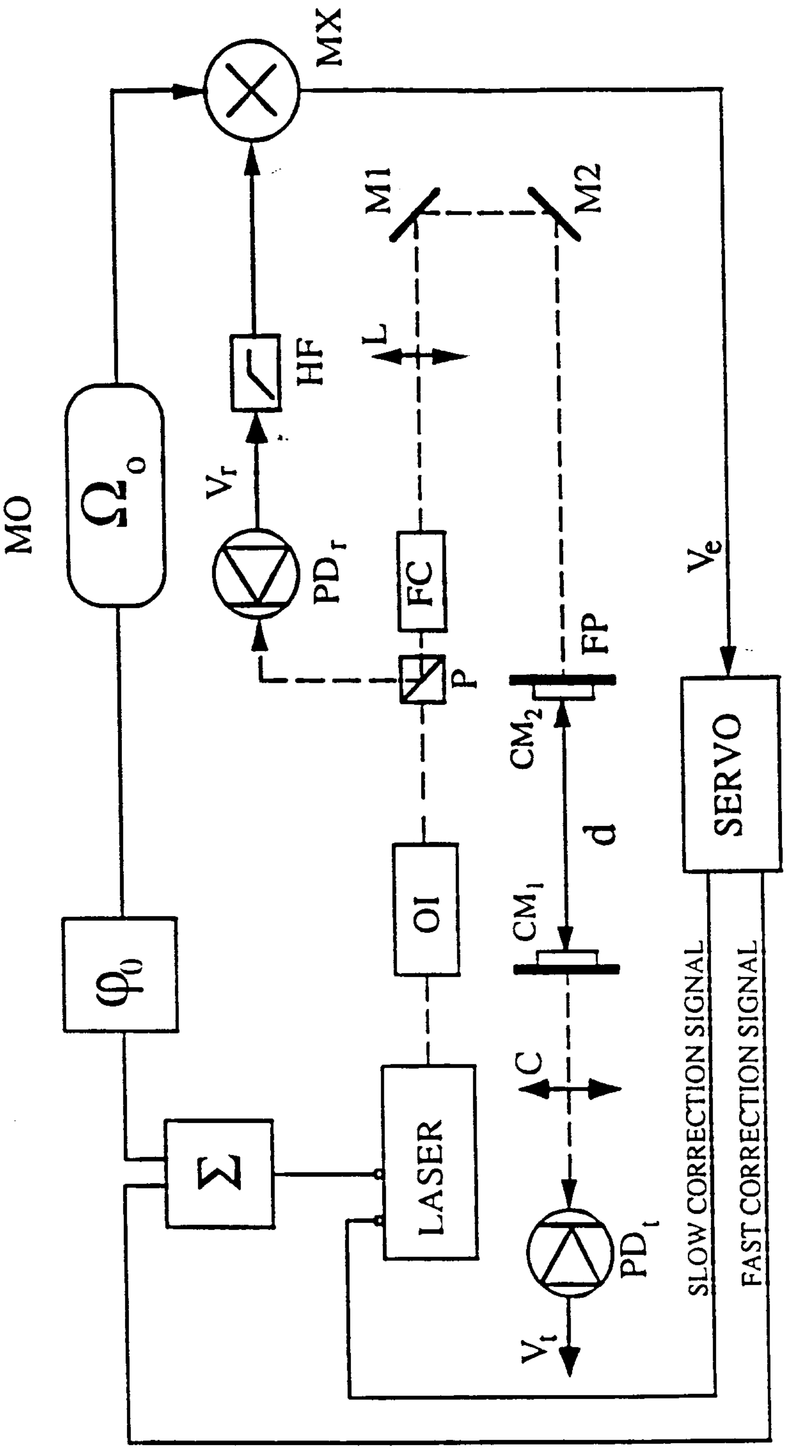
FIG. 4. Decay of the signal collected on the photodiode PD_t with the laser locked to the cavity (solid line) and with the cavity removed (dashed line).

FIG. 5. Cavity decay curve together with the best fit to an exponential function.

FIG. 6. Theoretical transfer function $G(\nu)$ of the Servo system (solid line) and experimental data (points).

FIG. 7. Spectral density of the V_m signal versus frequency.

FIG. 8. The relative intensity noise spectrum of the signal collected on the photodiode PD_t with the laser locked to the cavity (solid line) and with the cavity removed (dashed line).


MO
Ω_o
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Σ
LASER
OI
P
FC
PD_r
V_r
HF
L
M1
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MX
FP
CM_2
d
CM_1
C
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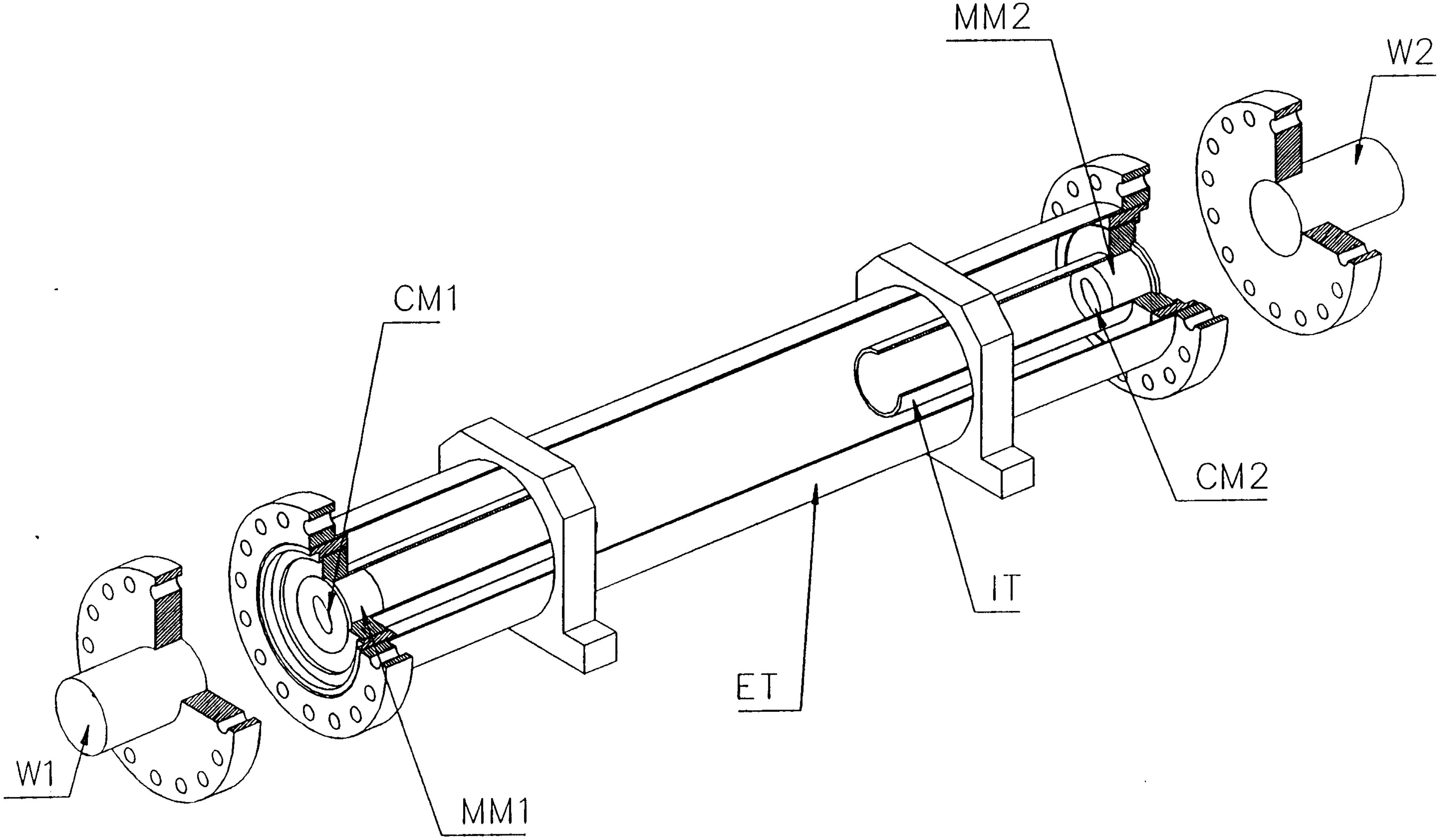
V_t
V_e
SERVO
SLOW CORRECTION SIGNAL
FAST CORRECTION SIGNAL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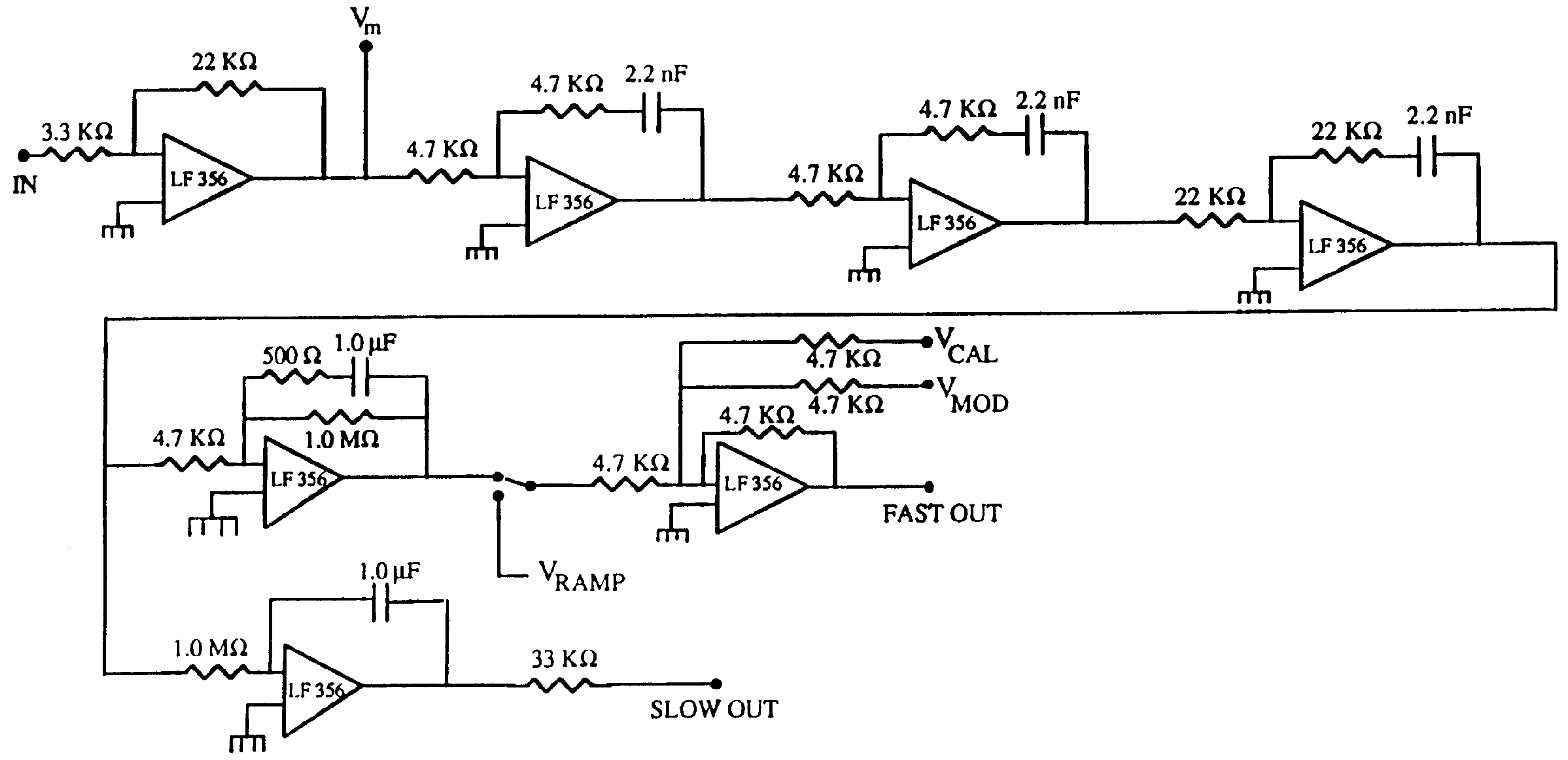
ET
W1
MM1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Vm
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2.2 nF
LF 356
22 KΩ
22 KΩ
2.2 nF
LF 356
500 Ω
1.0 µF
4.7 KΩ
1.0 MΩ
LF 356
VRAMP
4.7 KΩ
4.7 KΩ
VCAL
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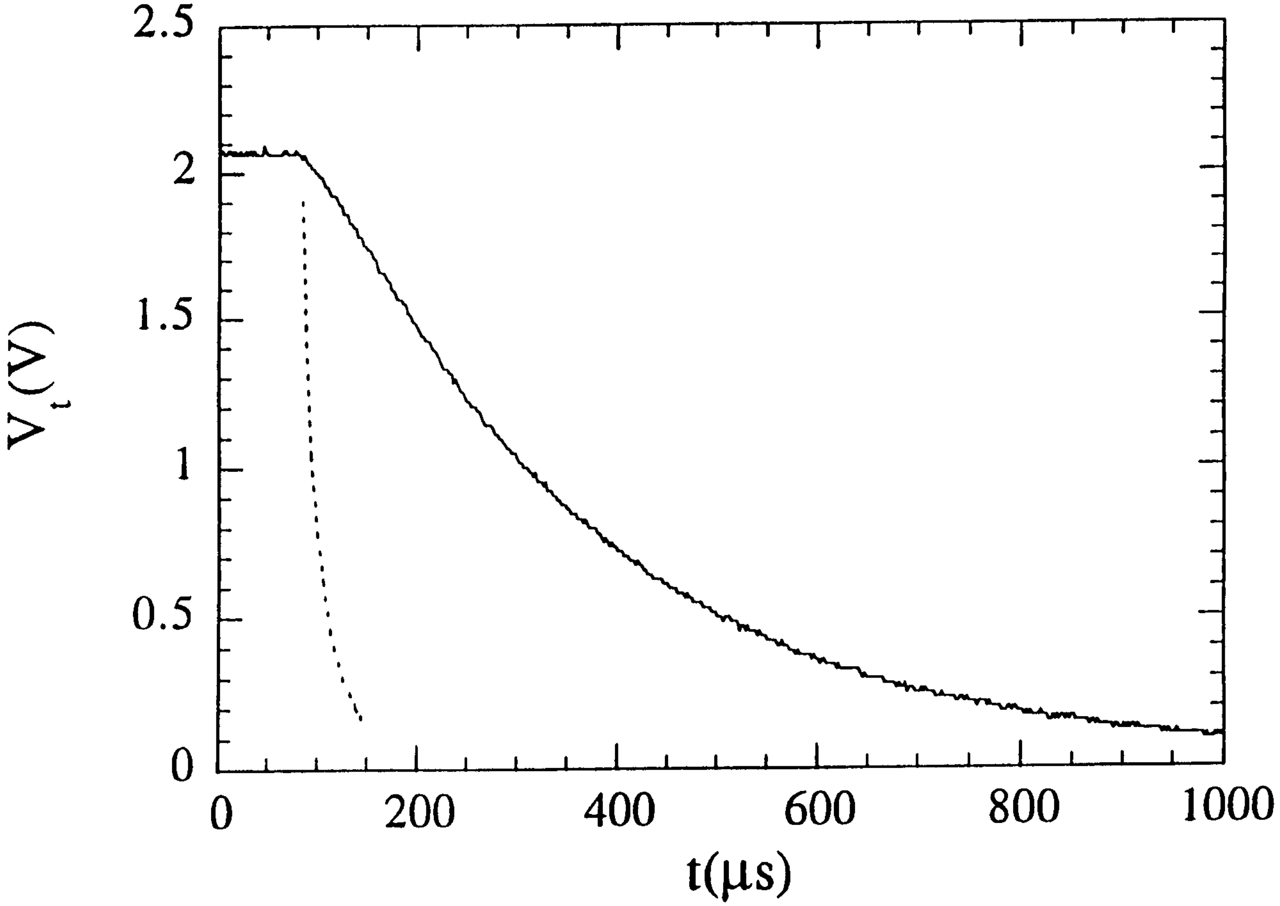
LF 356
33 KΩ
SLOW OUT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1.5
1
0.5
0
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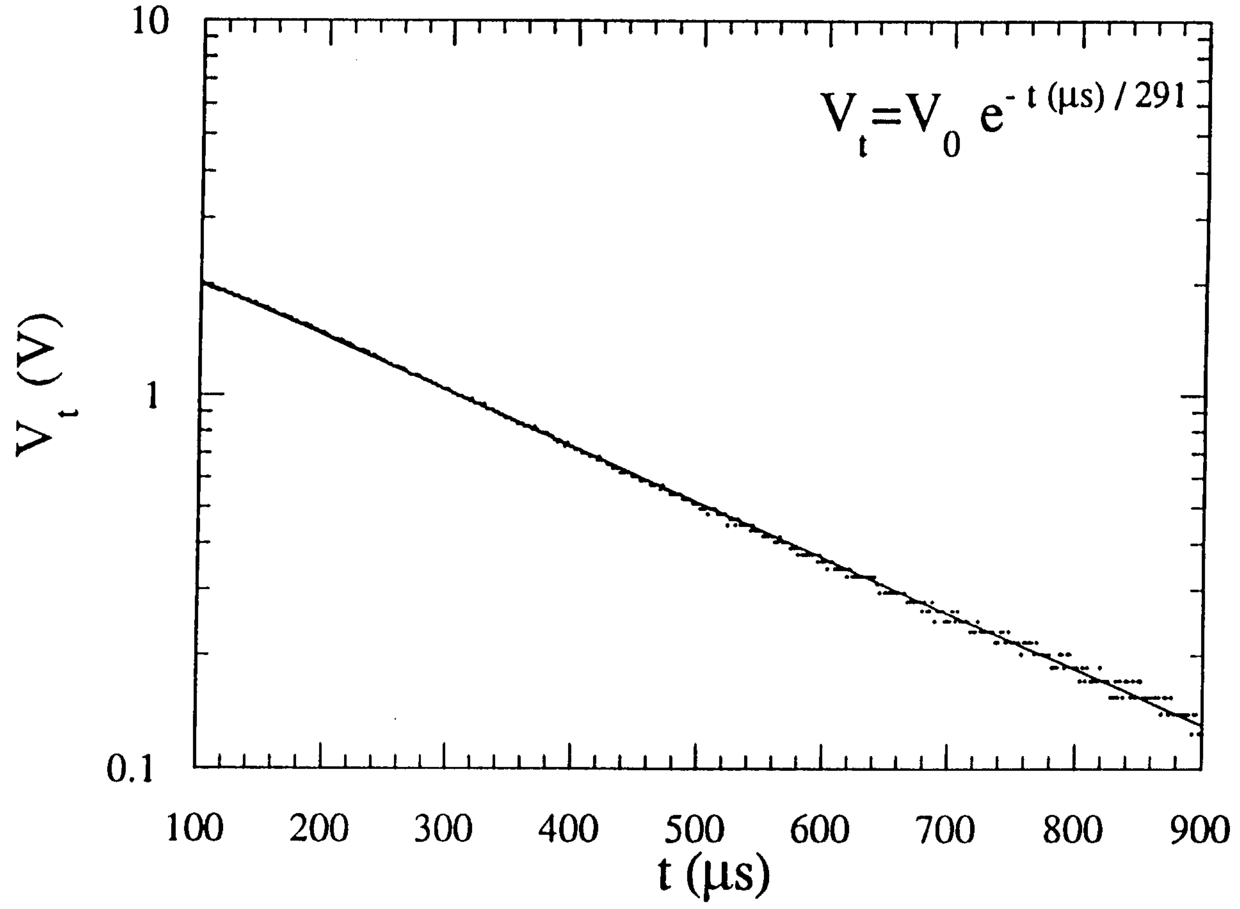
0
200
400
600
800
1000
t(μs)


$V_t = V_0\, e^{-t\,(\mu s)/291}$
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0.1
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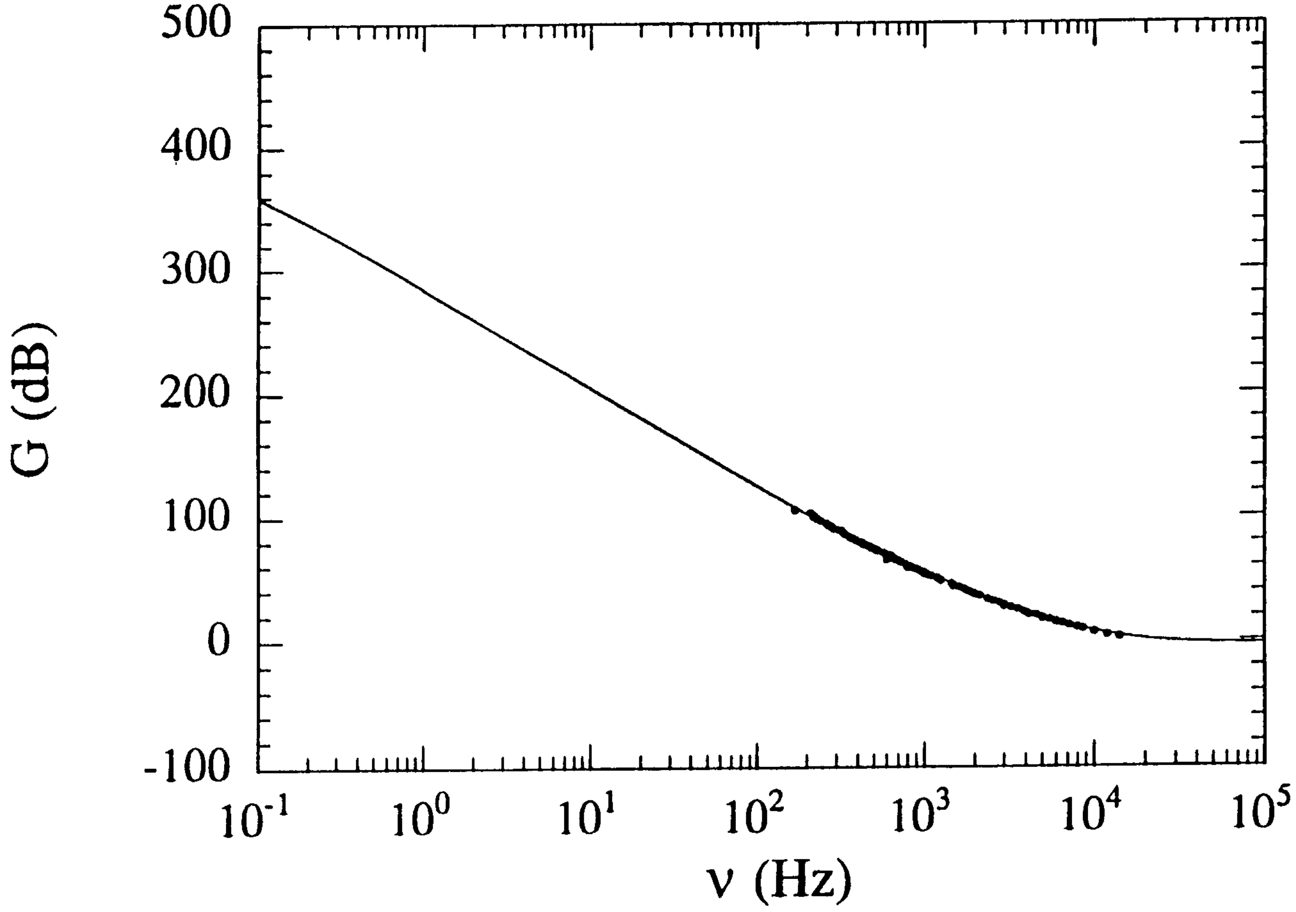
200
300
400
500
600
700
800
900
t (μs)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400
300
200
100
0
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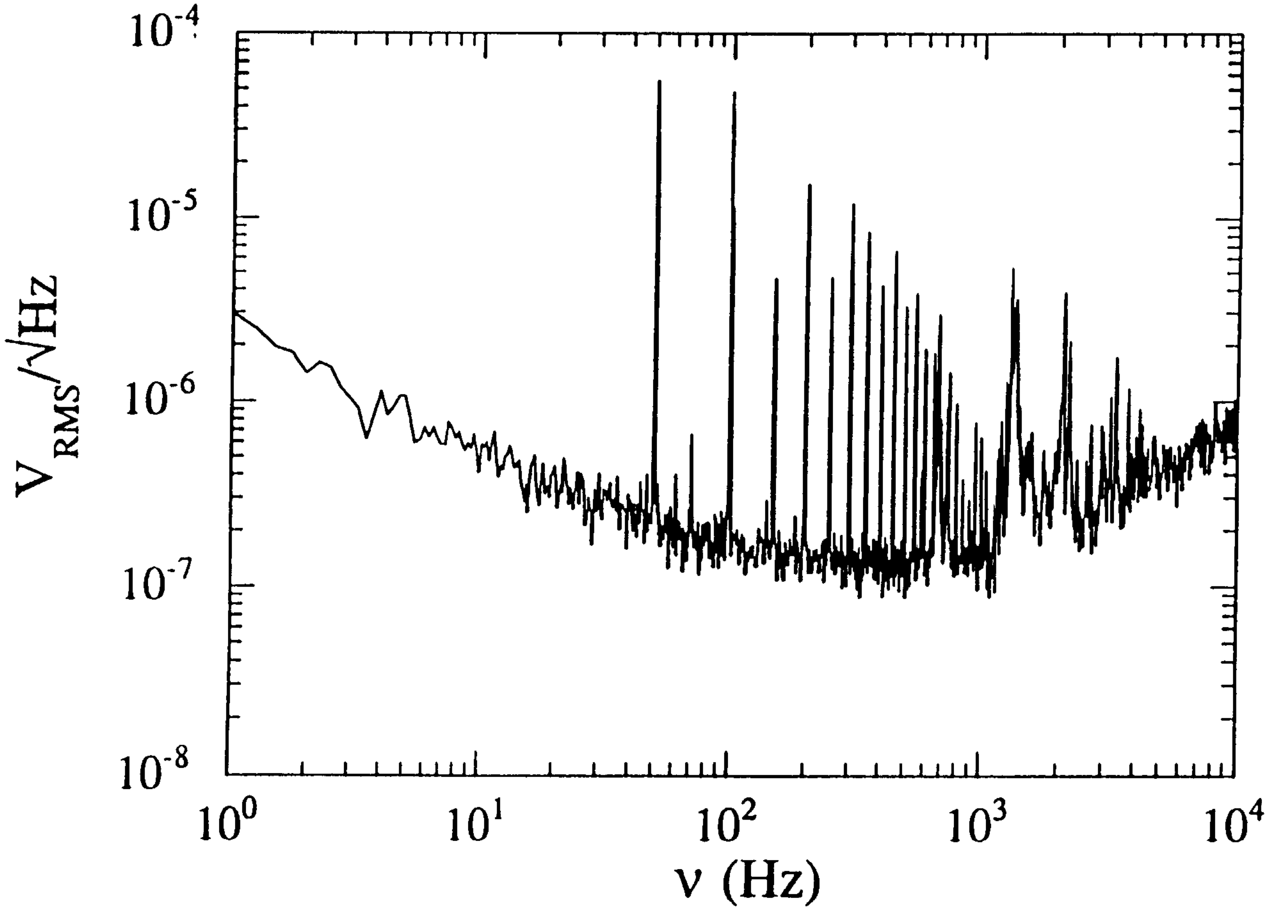
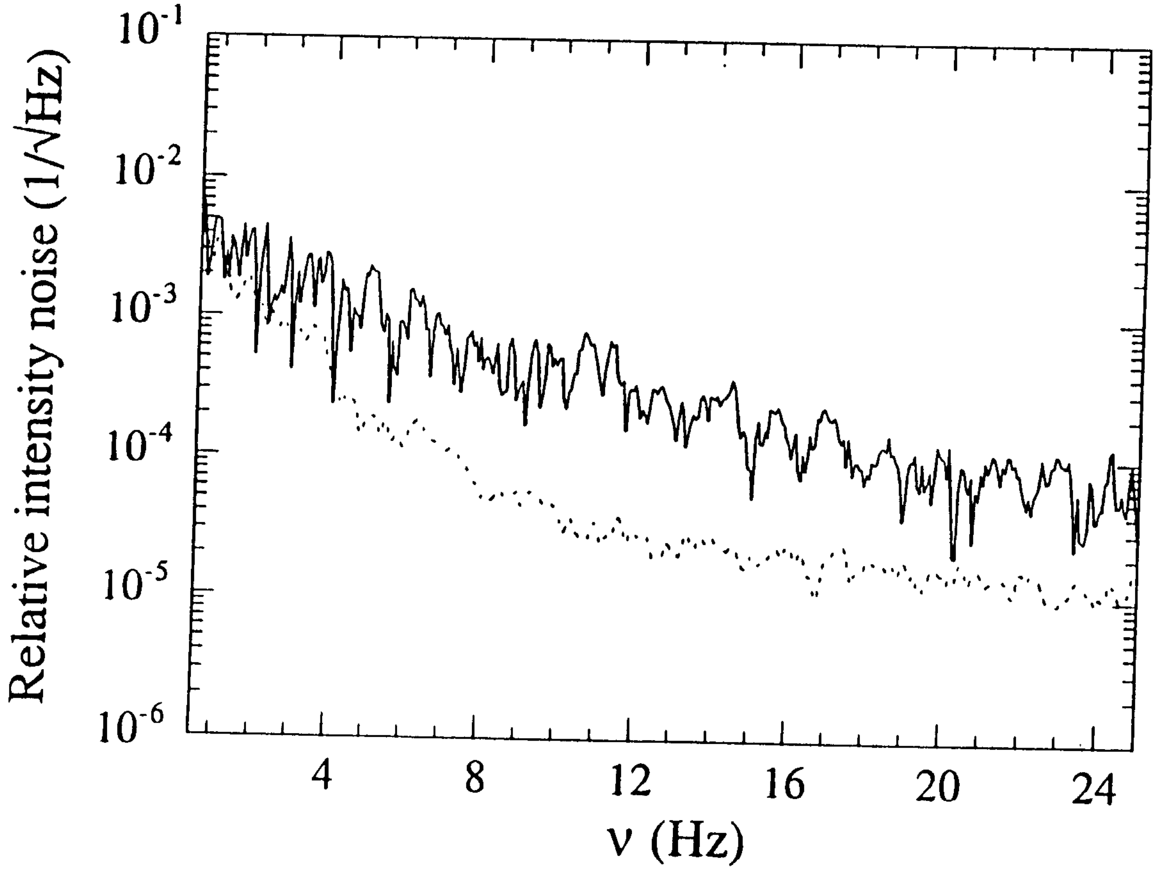
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
ν (Hz)



$V_{RMS}/\sqrt{Hz}$
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
ν (Hz)


Relative intensity noise (1/√Hz)
10-1
10-2
10-3
10-4
10-5
10-6
4
8
12
16
20
24
ν (Hz)