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DEMANDS ON LASER PURITY IN AN INTERFEROMETRIC GRAVITATIONAL WAVE DETECTOR

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Abstract

In the signal frequency window (500 to 3000 Hz) inside which the Michelson interferometer is to detect gravitational radiation, it must at least be able to resolve 10^{-9} of a fringe. This requires a laser illumination of extremely high purity. Noise contributions due to laser fluctuations in power and in beam geometry can be kept sufficiently small by proper control of the operating point, and by the use of a mode-selective resonator.

The strong demands on frequency stability arise from two deficiencies of the interferometer: (i) a residual path difference between the two arms requires $\delta v < 5 \cdot 10^{-2}$ Hz/ $\sqrt{\text{Hz}}$; (ii) the interference of scattered light with the main beam, with large path differences ΔL , may require $\delta v < 3 \cdot 10^{-3}$ Hz/ $\sqrt{\text{Hz}}$. A rather conventional frequency control (with feedback to the laser cavity) is expected to allow $\delta v < 3 \cdot 10^{-2}$ Hz/ $\sqrt{\text{Hz}}$. A totally independent second control loop uses the interferometer arms as reference, and corrects the light phase (and thus the frequency) with a Pockels cell, after the light has left the laser. A stability of $\delta v < 10^{-4}$ Hz/ $\sqrt{\text{Hz}}$ may eventually be possible. The noise due to scattered light may be reduced further by a scheme of breaking the coherence between scattered light and main beam.

1. LASER INTERFEROMETER AS GRAVITATIONAL WAVE DETECTOR

This conference is devoted to the measurement and standardization of frequencies, with accuracies that are almost unbelievable. I will talk about an application - a laser interferometer to detect gravitational waves - in which the prime emphasis is on sensitivity rather than on accuracy. But it will soon become clear that in order to achieve the desired sensitivity, the laser illumination must have a degree of purity that is quite comparable to the demands in frequency metrology, and we may benefit tremendously from the progress achieved there.

Laser interferometers to detect gravitational waves are now being investigated in several laboratories. After pioneering work at Hughes Laboratories [1] and at MIT [2], similar activities were started by groups in Munich [3, 4] and Glasgow [5], and recently at Caltech [6]; related investigations are under way at Novosibirsk [7].

1.1 Gravitational Waves

Gravitational radiation would manifest itself as an alternating strain in space, with opposite signs in the two orthogonal directions transverse to the direction of propagation. A Michelson interferometer (Fig. 1), with its two orthogonal arms, is an ideal antenna for such radiation. The expected strains are, however, extremely small. Typical estimates [8] (perhaps even somewhat on the optimistic side, [9]) are strains $\delta L/L$ of the order 10^{-18} for supernovae events in our galaxy, which, however, occur only a few times per century. Event rates of, say, one a week could be expected if supernovae in the Virgo cluster could be detected, but they would have strains of as little as 10^{-21} or less.

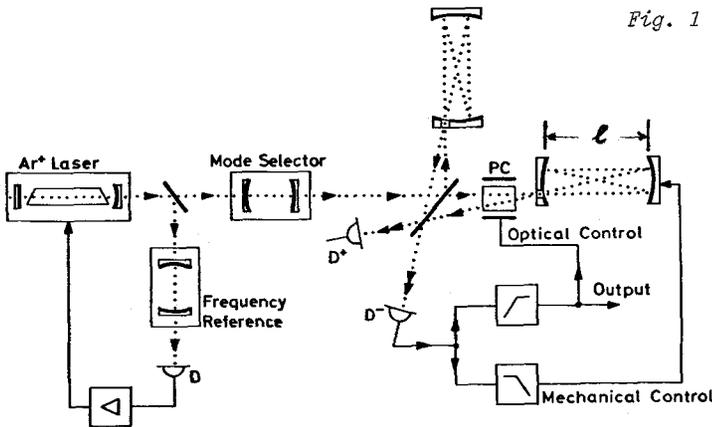


Fig. 1 Michelson interferometer, with multiple reflections in optical delay lines. Optical and mechanical controls to stabilize operating point.

The mere detection of gravitational waves would be a goal worth striving for, as a further verification of general relativity. But even more valuable would be the chance to observe the millisecond processes during stellar collapse, forever hidden to visual observation.

1.2 Signal Frequencies of Gravitational Waves

Our search for gravitational waves has chances of success only in a limited frequency range in the kHz region, say from 500 to 3000 Hz: gravitational radiation is expected to decrease rapidly at frequencies above a few kHz, and towards low frequencies the steep rise of almost all noise contributions sets a limit at a few hundred Hz.

As our interest is centered mainly on a frequency range not including zero and slow drifts, we prefer to express the noise contributions by their spectral densities rather than by integral measures such as Allan variance or line width. We will represent a stochastic variable $q(t)$ by the linear measure $\hat{q}(f)$, related to the (two-sided) power spectral density $S_q(f)$ by $\hat{q}(f) = \sqrt{2 \cdot S_q(f)}$. If $q(t)$ has the dimension m , then $\hat{q}(f)$ has the dimension $m/\sqrt{\text{Hz}}$.

1.3 Length of Optical Path

The strain sensitivity of the interferometer increases with increasing optical path L , up to an optimum length L of half the wavelength of the gravitational wave, for instance 150 km for a 1 kHz signal. Even with such extremely long paths L in the interferometer, the variation δL due to a gravitational strain of 10^{-21} would be only $1.5 \cdot 10^{-16}$ m. Our interferometer, illuminated with the green line of an argon laser ($\lambda = 0.514 \cdot 10^{-6}$ m), would have to be able to detect phase differences $\delta\phi = 2\pi\delta L/\lambda$ of as little as $2 \cdot 10^{-9}$ rad, or $3 \cdot 10^{-10}$ of a fringe.

The required long total paths L can be realized with multi-reflection schemes, for instance with optical delay-lines, as indicated in Fig. 1. The number N of reflections is limited to a few hundred by considerations of reflectance losses and mirror size. With $N = 300$, we would need a mirror distance (= arm length) of $\ell = 500$ m to arrive at $L = N \cdot \ell = 150$ km. In our present prototype, the mirror distance is $\ell = 3.05$ m, and with $N = 138$ bounces we have a total path of 420 m.

In an alternative approach [6], using Fabry-Perot resonators instead of the delay-lines, the integer N would have to be replaced by N_F , a factor closely related to the finesse $F = \pi\rho/(1-\rho^2)$ of the cavity, with ρ^2 the reflectance of the cavity mirrors. Typical values for N_F would range from 50 to several hundred.

1.4 Shot Noise Limit

A quantum theoretical limit for the sensitivity is given by the shot noise of the photo current, equivalent to fluctuations in phase difference $\delta\phi$ that can be expressed by the (linear) spectral density

$$\delta\tilde{\phi}_{sh} = \sqrt{\frac{2hc}{\lambda\eta P}}$$

where h is the Planck constant, c the speed of light, P the light power available at the interferometer output, and η the quantum efficiency of the photodiode(s). The best combinations of λ and ηP are provided by argon ion lasers. With commercially available single mode powers of 2 W, and an overall loss of 0.4, one would have $\delta\tilde{\phi}_{sh} = 1 \cdot 10^{-9}$ rad/ $\sqrt{\text{Hz}}$. We will take this as our realistic sensitivity goal.

With our signal band width of 2.5 kHz, this is about a factor of 25 above our eventual goal (Virgo cluster). More powerful lasers are one hope for the future, and there are other proposals aiming at a better utilization of the available laser power ("squeezed states" [10]; "recycling" [11]). At any rate, the shot noise limits for today's lasers would easily allow the detection of supernovae in our own galaxy.

2. LASER NOISE

The natural purity of a laser is by far not sufficient to allow the desired sensitivity $\delta\tilde{\phi}_{sh}$ of our interferometer. What the demands are in our particular application will be discussed in this chapter. The non-ideal behavior of a laser can manifest itself as fluctuation in laser power, in beam geometry, and in laser frequency. These three noise sources have in common that they become apparent only when accompanied by appropriate asymmetries in the interferometer. The frequency noise will turn out to be the toughest problem, and the most relevant at this conference, and so a further chapter will be devoted to the techniques of controlling it.

2.1 Power Fluctuations

Fluctuations in the incident light power P will, of course, become apparent in the output currents of the photo diodes (Fig. 1). A plot of the relative power fluctuations $\delta\tilde{P}/P$ is shown in Fig. 2. They are typically of the order $10^{-5}/\sqrt{\text{Hz}}$ in our frequency range of interest.

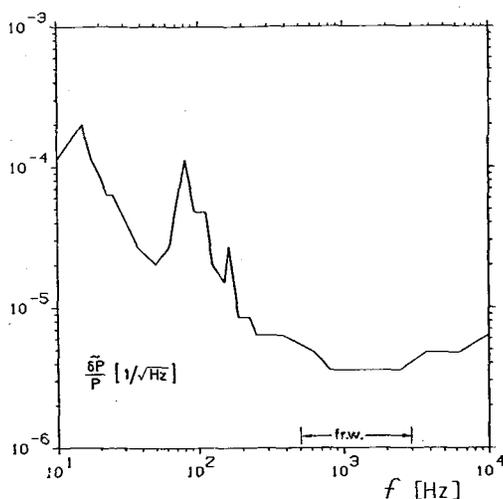


Fig. 2 Power fluctuations $\delta\tilde{P}/P$.

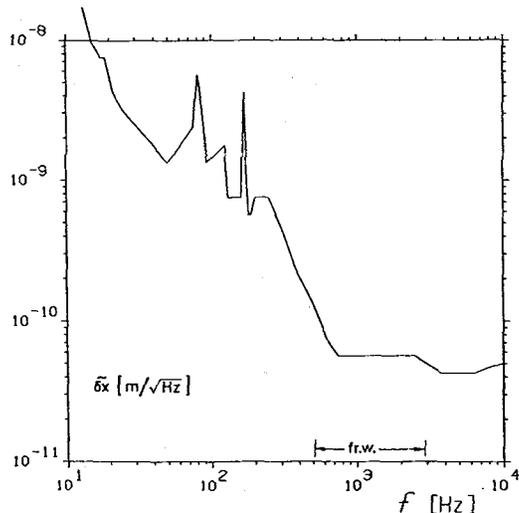


Fig. 3 Lateral beam jitter $\delta\tilde{x}$.

The Michelson interferometer lends itself to applying a nulling technique, by which the effects of power fluctuations can be strongly suppressed. One common method is to measure the difference in the photo currents, and one has to operate near a point of equal currents in the two diodes D^+ and D^- . The other method, the one we have implemented, is to use a phase modulation in one arm and operate near the interference minimum, monitoring it with only one diode (D^-). In both cases, fluctuations $\delta\dot{P}/P$ in the laser power enter only according to the quasistatic deviation $\delta L_{Op}/\lambda$ from the ideal operating point.

A mechanical servo loop, acting on the distant mirrors, controls the slow variations in path length difference (up to, say, 30 Hz), and the high frequency deviations are corrected optically with a Pockels cell. The Pockels cell voltage also represents the signal to be analyzed for gravitational events. The mechanical and the optical servo loops reduce the deviations δL_{Op} to something like 10^{-5} of a wave length, and so the effect of power fluctuations is sufficiently suppressed.

2.2 Fluctuations in Beam Geometry

Fluctuations in the geometry of the illuminating laser beam will introduce spurious signals if the wavefronts of the two outgoing beams are not perfectly matched. It is easily seen, for instance, that a tilt, due to a misaligned beam splitter, would make the interferometer sensitive to a lateral jitter of the beam.

The lateral jitter x has been measured with position sensitive photo diodes [4]; Fig. 3 shows a plot of its spectral density $\dot{x}(f)$. The amplitudes are very small compared with the beam width $2w$ (of about 1 mm), and this allows a representation of the nearly gaussian beam by a fundamental mode TEM_{00} , contaminated with transverse modes TEM_{mn} of non-zero order $m+n$. The lateral jitter is described as an admixture of a mode of order 1, having a (time varying) amplitude $a(t) = 0.8 x(t)/w$. An admixture of modes of order 2 would represent pulsations δw in beam width, which also have been observed, and which lead to spurious interferometer signals if the two interfering wave fronts are mismatched in their curvatures.

The mode representation of the fluctuations in beam geometry already suggests the proper therapy: the beam is made to pass through an optical cavity that is tuned so it has maximum transmission of the fundamental mode, but suppresses the transverse modes, by a factor related to the finesse of the cavity [13]. By implementing such a "mode cleaner" we have been able to suppress the noise due to beam fluctuations.

2.3 Frequency Fluctuations

The upper trace of Fig. 4 shows the natural frequency jitter of our Ar^+ laser, after some mechanical improvements had been implemented [4]. Inside our frequency window we have spectral densities between 10 and 100 Hz/ \sqrt{Hz} .

There are several types of mismatches between the two interferometer arms by which frequency fluctuations $\delta\nu$ can be turned into spurious signals $\delta\phi$.

Path Difference: It is by no means impossible to operate the interferometer in the "white" fringe, i.e. with a residual path difference $\Delta L < \lambda/2$. Due, however, to inevitable differences in the mirror curvatures, a good matching of the two outgoing wave fronts may require operation with rather large path offsets ΔL . We do not know to what extent one can adjust the mirror curvatures, by applying appropriate bending forces to the mirrors.

To be on the safe side, let us assume that in a final configuration we have to live with a ΔL of as much as 1 m. To arrive at the desired sensitivity, the frequency fluctuations in our frequency range should not exceed $5 \cdot 10^{-2}$ Hz/ \sqrt{Hz} . When we compare this with the free-running noise of our Ar^+ laser (Fig. 4, upper trace), we see that an improvement in frequency stability by at least 3 powers of ten is required.

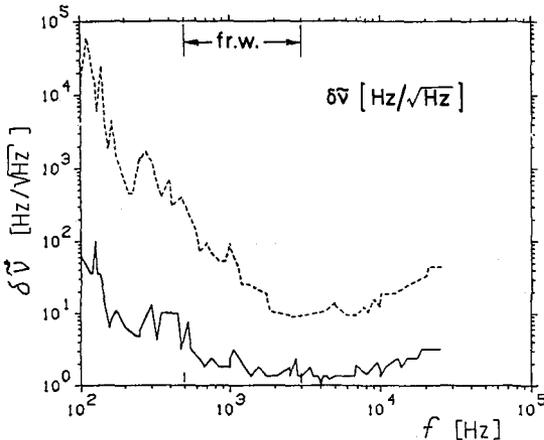


Fig. 4 Frequency jitter $\delta\nu$. Free-running (upper trace), and with first stage of frequency stabilization (lower trace).

Scattered Light: An even more stringent demand arises from the existence of scattered light, which, due to its nature, cannot be expected to show much correlation in the two arms. The scattering at our optical surfaces, particularly at the delay line mirrors, has been investigated recently by Walter Winkler [14]. One finds a whole series of "echoes", with different "delays" $\Delta L_{SC} = 2m \cdot \ell$ between the scattered light and the main beam, depending on how many return trips 2ℓ were skipped ($m < 0$), or repeated ($m > 0$), by the scattered light. A schematic diagram of these contributions is shown in Fig. 5.

The strong "echo" at $-N$ ($= -138$) results from scatter at the Pockels cell before the beam even enters the delay line; other major contributions (at N , $2N$, etc.) represent additional full round trips of the scattered light in the delay line. The fraction of light scattered, and then finding its way to the photo diode to interfere with the main beam, has been established to be in the order of 10^{-8} in power, or $\sigma = 10^{-4}$ in amplitude. The insert in Fig 5 shows how the vector $\vec{\sigma}$ superimposes on the main beam, with a phase $\vec{\Phi} = 2\pi\Delta L_{SC}/\lambda$ that is a very large number, and that changes very rapidly with a change in frequency:

$$\delta\vec{\Phi} = \frac{2\pi\Delta L_{SC}}{c} \cdot \delta\nu.$$

To keep the phase error $\delta\phi = \sigma \cdot \cos\vec{\Phi} \cdot \delta\vec{\Phi}$ in the resulting field vector below our shot noise limit, a 150-km interferometer would require the frequency to vary by no more than $\delta\nu = 3 \cdot 10^{-3} \text{ Hz}/\sqrt{\text{Hz}}$ (or $\delta\nu/\nu = 0.5 \cdot 10^{-17}/\sqrt{\text{Hz}}$). So here we want an improvement in frequency stability by at least 4 powers of ten.

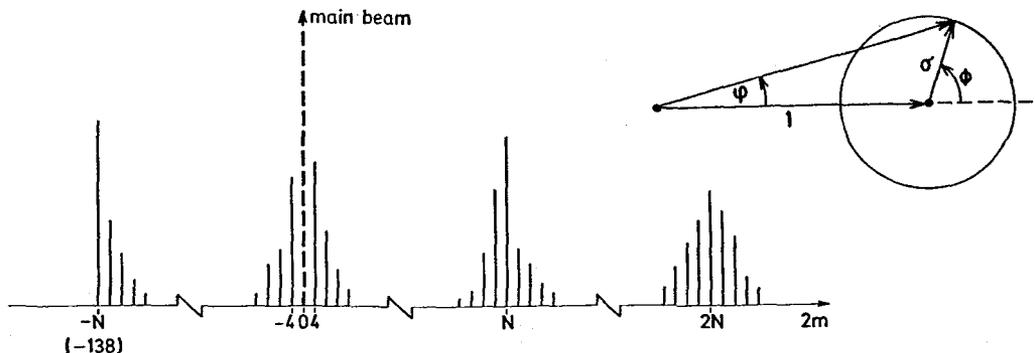


Fig. 5 Scattered light contributions in our interferometer, vs. "delay length" $2m\ell$ with respect to main beam. Insert: Scattered light of relative amplitude σ , and of phase Φ , superimposing on main beam.

Finesse: Before we discuss how such a frequency control might be accomplished, let us briefly look at the requirements in the alternative approach of using two orthogonal Fabry-Perot interferometers. To suppress noise due to power fluctuations, the interferometer has to be operated at equal photo currents. The sensitivity of each Fabry-Perot to frequency fluctuations is proportional to its finesse F , and the difference signal, expressed as a phase error, might be represented by

$$\delta\phi = \frac{2\pi L}{c} \cdot \frac{\Delta F}{F} \cdot \delta\nu$$

As one can see, the requirements are even higher than those due to scattered light, unless one succeeds in matching the finessees of the two arms to better than $\Delta F/F = 10^{-4}$, the value of σ .

3. FREQUENCY CONTROL

We have heard at this conference of several very powerful methods to stabilize the frequency of a laser. Again let me point out that in our application we are not so much concerned with long-term stability; however, inside our frequency window of interest (500...3000 Hz), we want a suppression of the frequency fluctuations down to such extremely small spectral densities as 10^{-3} Hz/ $\sqrt{\text{Hz}}$. The concept of our frequency control is, in some respects, modelled after these particular needs.

3.1 Feedback to the Laser Cavity

A first step toward the high noise suppression is a rather conventional feedback to the laser cavity (Fig. 6). An optical resonator, evacuated to reduce statistical pressure fluctuations, is used as frequency reference. The amplified error signal is fed back to the laser in two ways. The high frequency part is applied to an intracavity Pockels cell (PC), whereas the low frequency portion, with its large dynamic swings, can only be handled by the piezo (PZT) driving the output mirror.

With a commercial resonator (TROPEL), a reduction of the frequency noise down to 1 Hz/ $\sqrt{\text{Hz}}$ was achieved (Fig. 4, lower trace). Karl Maischberger has just implemented a new resonator having larger mirror spacing (25 cm), using a heavy Zerodur spacer for improved mechanical and thermal stability. This, together with an upgrading of the electronics, has reduced the frequency noise to $1.5 \cdot 10^{-1}$ Hz/ $\sqrt{\text{Hz}}$. With better mirror coatings, and perhaps a further extension of the length, values of 10^{-2} Hz/ $\sqrt{\text{Hz}}$ seem achievable. This is, however, still somewhat short of our goal of $3 \cdot 10^{-3}$ Hz/ $\sqrt{\text{Hz}}$.

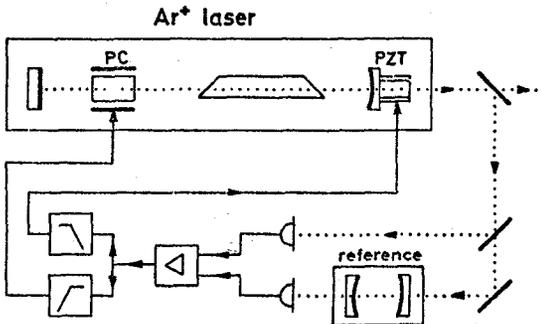


Fig. 6 Frequency control, by feedback to the laser cavity. High frequency part: to intracavity Pockels cell; low frequency part: to piezo drive of mirrors

3.2 Phase Control Loop

A decisive further improvement is expected from the second stage of feedback control that is currently being implemented by Roland Schilling [14]. The essential components can be found in Fig. 7. One utilizes the interferometer itself, with its long optical path L , as a very sensitive frequency measuring device, by letting one (or both) of the outgoing beams interfere with the undelayed light of the incoming beam. This is similar to a scheme proposed for the Fabry-Perot interferometer [6].

The decisively new feature is that the resulting error signal is not fed back to the laser, but is used to drive a Pockels cell that corrects the phase (and thus the frequency) after the light has left the laser cavity. The two stages of frequency control are thus completely decoupled, and each can be separately optimized. Their noise suppression factors are multiplied.

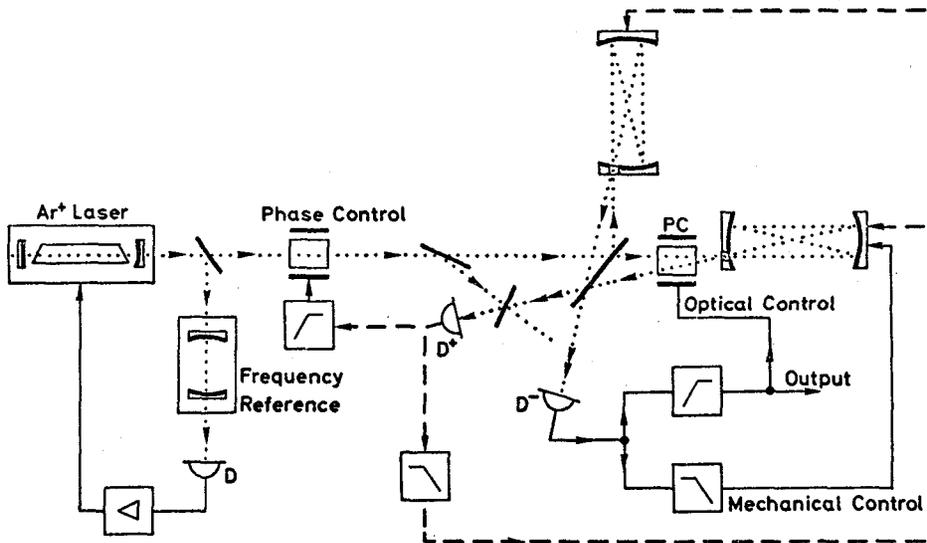


Fig. 7 Phase control loop (dashed lines). Interferometer arms used as frequency reference; high frequency part of error signal corrected by Pockels cell; low frequency part corrected mechanically (mirror distance).

As a Pockels cell allows only a limited phase swing, the low frequency portion of the error signal is used to correct mechanically the mirror positions. The result is that the mirror distances l , expressed in wavelengths λ , remain constant, and this is precisely what has to be done to suppress the noise due to scattered light. Therefore, we are justified to use the error signal for judging what we have accomplished (for our application).

With a rather crude preliminary set-up the feasibility of the concept has been proved. The error signal, with and without the second stage of control, is shown in Fig. 8. An artificially introduced modulation, at 4 kHz, exhibits the expected noise suppression by one power of ten. The suppression of the noise floor is not quite as good, for reasons yet to be analyzed. We have observed that driving the Pockels cell produces, as a side effect, rather strong variations in beam geometry. These, in turn, give a contribution to the error signal, which the feedback loop tries to compensate by a spurious shift in frequency. With a proper design, and by placing the mode cleaner after the Pockels cell, we hope to eliminate this difficulty.

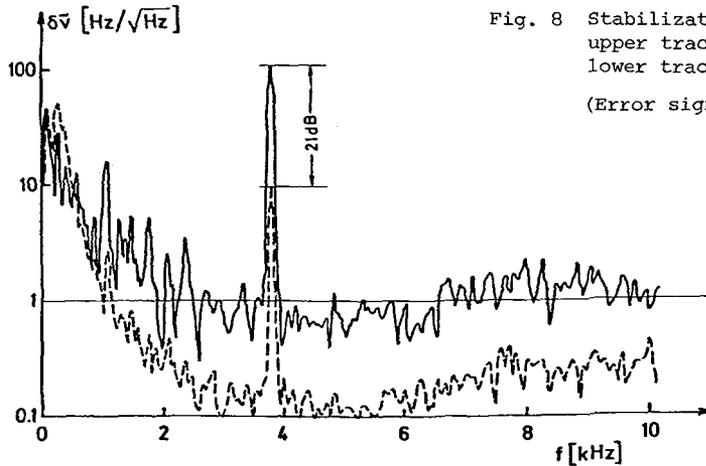


Fig. 8 Stabilization of laser frequency;
 upper trace: only first control loop,
 lower trace: both controls turned on.
 (Error signal)

3.3 Breaking the Coherence

At the end of the talk, I will mention a possibility to cope with our scattered light problem in a way that must seem like blasphemy at this conference. Do not all our difficulties with the scattered light stem from the fact that - despite its huge path difference - it is still coherent with the main beam? And does this not mean that the constancy of our frequency is too good? In a way this is really the case. By adding a frequency modulation (of course well outside our frequency window) one can break the coherence between main beam and scattered light, whereas the interference between the two main beams is practically unaffected.

One such method has been described and implemented by Roland Schilling [15], and only quite recently we have heard from Alain Brillet that they had used a similar method some years ago in a different context [16]. The difficulty in our application is that we want to suppress simultaneously the different "echoes" of Fig. 5.

A simple harmonic phase modulation $\Psi = \theta \cdot \sin \Omega t$ of the incoming beam allows us to cancel out the effects of a subset of these echoes, if the phase swing θ and the modulation frequency Ω are properly chosen. With the addition of further periodic components in the modulation, a larger number of the echoes can be suppressed, but the suppression will no longer be a full cancellation.

In a different approach, one could modulate the laser frequency with broad band noise (at high frequencies, say from 1 MHz upward). The suppression of the scattered light noise will be a function of the rms modulation phase swing and the modulation band width. Both must be very high to produce appreciable effects.

4. CONCLUSION

After this heretic digression on reducing our interferometer noise by adding noise to the laser frequency, let me remind you that this affects only the noise due to scattered light. For the main effect of a residual path difference ΔL between the two main beams, the rather stringent demand remains, of keeping the frequency jitter down to, say, $\delta\nu < 5 \cdot 10^{-2} \text{ Hz}/\sqrt{\text{Hz}}$, perhaps even $< 2 \cdot 10^{-3} \text{ Hz}/\sqrt{\text{Hz}}$ for experiments in the distant future. Again, it must be mentioned that this high purity is required only inside our frequency window between 500 and 3000 Hz. We are confident that such a high degree of frequency stabilization is within the realm of possibility, even with rather conventional techniques, but it will be an uphill battle, each improvement by another factor of ten becoming more difficult. This conference has not nourished any illusions that the desired purity of laser behaviour might fall into our laps.

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