Optical mode cleaner with suspended mirrors

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We report on the development of a new type of mode cleaner that reduces any geometric noise of the laser beam in an interferometric gravitational-wave detector. The mode cleaner is a Fabry–Perot cavity that comprises independently suspended mirrors and works as a frequency-stabilization reference as well as a mode selector; the length of the cavity is 1 m. Stand-alone tests have shown at least a 30-dB reduction in the geometric fluctuation of the beam and a 60-dB reduction of the frequency noise of the laser. We have also succeeded in operating a 20-m Fabry–Perot prototype detector (at the National Astronomical Observatory, Tokyo, Japan) by using this mode cleaner. © 1997 Optical Society of America

Key words: Gravitational-wave detector, mode cleaner, Fabry–Perot cavity, interferometer.

1. Introduction

The investigation of interferometric gravitational-wave detectors is currently moving from studies of prototype detectors with ~10-m baselines to the construction of full-scale interferometers with kilometer-length baselines[1,2] for actual detection. Therefore each part of the detector should be improved so as to be applicable to long-baseline interferometers.

The geometric stability of the light source is in particular need of improvement. The deformation of the laser beam that is due to spurious higher modes degrades the efficiency of the interference, resulting in an insufficient common-mode noise rejection ratio (CMRR) and in a poor recycling gain of the detector. The beam jitter, that is, angular or lateral beam fluctuation caused by the vibration of the laser cavity or by other optical components, couples to the asymmetry of the interferometer and may be among the serious noise sources.[3] To reduce the beam deformation and beam jitter, mode cleaners have been incorporated into most prototypes between the laser and the main interferometer.

Single-mode optical fibers[4] or rigid Fabry–Perot cavities[5] formed by mirrors attached to each end of a rod have been used as mode cleaners. However, the current mode-cleaner designs cannot be applied in the future because optical fibers cannot sustain these high-power lasers being used; also, a rigid short Fabry–Perot cavity has insufficient angular stability for detectors with long baselines. Therefore the mode cleaner for a full-scale interferometer will inevitably comprise separately suspended mirrors on long baselines to give sufficient stability and to allow its use with a high-power laser.

We have thus developed a new type of mode cleaner, a Fabry–Perot cavity with its two mirrors suspended independently as pendulums, and have incorporated it into a prototype gravitational-wave detector to estimate the performance of the combined system. An independently suspended Fabry–Perot cavity also enables us to use it as a reference for frequency stabilization of the laser. Henceforth, for convenience, the term mode cleaner will occasionally encompass the entire input system, including the light source (a laser), the mode-cleaner cavity proper, and the frequency-stabilization system.

2. Principle

The name mode cleaner comes from its function, a mode selector that excludes any spurious beam deformation.[3] This function can be realized with a Fabry–Perot cavity, which has mode selectivity by virtue of a difference in the resonant frequency between the higher-order transverse modes and the

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fundamental mode. Here, the function of the Fabry–Perot cavity as a mode selector is described.[3,6]

Assuming a laser beam incident to a Fabry–Perot cavity with two mirrors having curvature radii of R_1, R_2 and separated by a length L, the resonant modes can be expressed as Hermite–Gaussian modes. Because the Hermite–Gaussian modes form a complete system, the incident beam can be expanded in terms of the cavity eigenmodes (ψ_{lm}) as

$$\psi_{\text{incident}} = \sum_{l,m} c_{lm}\psi_{lm}, \tag{1}$$

where c_{lm} are expansion coefficients and l and m are integers related to the transverse modes.

Their resonant frequencies are given by

$$\nu_{lm;n} = \frac{c}{2L}\left[n + (l + m + 1)\gamma\right], \tag{2}$$

$$\gamma = \frac{1}{\pi}\cos^{-1}(g_1 g_2)^{1/2}, \tag{3}$$

$$g_{1,2} = 1 - \frac{L}{R_{1,2}}, \tag{4}$$

where c is the speed of light and n is an integer that characterizes the longitudinal modes.

In Eq. (2), the resonant frequencies of the cavity eigenmodes are different from each other when they are not degenerate.[7] Therefore, if the incident light is resonant with the fundamental mode of the cavity, the transmitted light contains predominantly the fundamental mode, and the other higher-modes are reflected by the cavity; the incident beam is reduced to the fundamental mode. If we use such a beam for the interferometric detector, a high contrast can be realized.

Another advantage of using the mode cleaner is a reduction in the beam-jitter noise, because any fluctuation of the beam direction is equivalent to a fluctuation in the contribution of the higher transverse modes.[3] The most significant contributions are the first- and the second-order transverse modes. If the incident beam tilts by a small angle of $\delta\alpha$ from the cavity axis and shifts by a small displacement of δa, measured at the beam-waist position, the resulting incident beam (ψ'_{00}) can be expressed with the fundamental (ψ_{00}) and first-order (ψ_{10}) cavity modes, as[3]

$$\psi'_{00} \simeq \psi_{00} + \left(\frac{\delta a}{w_0} + i\,\frac{k w_0 \delta\alpha}{2}\right)\psi_{10}, \tag{5}$$

where w_0 is the beam-waist radius and k is the wave number. The variation in the beam size (δw) or the waist position (δb) causes second-order modes, as

$$\psi'_{00} \simeq \psi_{00} + \left(i\,\frac{\delta b}{k w_0^2} + \frac{\delta w}{w_0}\right)\frac{\sqrt{2}}{2}\,(\psi_{20} + \psi_{02}). \tag{6}$$

The suppression ratio of the higher modes relative to the fundamental mode is dependent on the difference in the resonant frequency between the fundamental mode and the higher modes, as well as on the reflectivity of the mirrors (r_1, r_2). The suppression ratio of the TEM_{lm} modes to the fundamental mode is

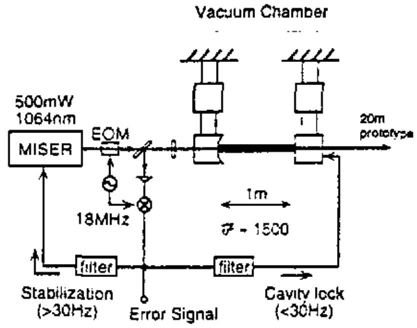

Fig. 1. Schematic diagram of the 1-m mode cleaner. A laser-diode-pumped Nd:YAG laser (Miser) was stabilized in frequency by reference to a suspended Fabry–Perot cavity housed in a vacuum. The reflected light from the cavity was used to lock the cavity on the resonance at lower frequencies and to stabilize the laser frequency at higher frequencies. EOM, electro-optic modulator.

$$S_{lm} = \frac{1}{\{1 + (2\mathcal{F}/\pi)^2 \sin^2[(l + m)\cos^{-1}(g_1 g_2)^{1/2}]\}^{1/2}}, \tag{7}$$

where $\mathcal{F}\,[= \pi(r_1 r_2)^{1/2}/(1 - r_1 r_2)]$ is the finesse of the cavity.

From Eqs. (5) and (7), we can expect a reduction in the beam jitter by a factor of S_{10} for either the angular or the lateral jitter.

3. 1-m Mode Cleaner

A. Setup

Figure 1 shows a schematic diagram of the mode cleaner. A 500-mW laser-diode-pumped Nd:YAG laser (Miser, Model 122-1064-500-F, Lightwave Electronics Corp., λ = 1064 nm) was stabilized in frequency by reference to a Fabry–Perot cavity.[9] We used a Miser, not only because it is tunable in frequency when a piezoelectric transducer (PZT) attached to the laser resonator is used, but also because it has a good noise performance owing to its monolithic ring resonator.

The incident light was modulated in phase by an electro-optic modulator (EOM) at 18 MHz. The reflected light from the cavity was detected and demodulated to obtain a signal, which was used to lock the cavity on the resonance at lower frequencies and to stabilize the laser frequency at higher frequencies.

The parameters of the cavity are summarized in Table 1. In our design, we chose γ = 0.3, using a combination of a flat mirror and a concave one in order to isolate the resonant frequencies of the first- and the second-order transverse modes from those of the fundamental mode. The cavity length was set at 1 m for this study, but it can be extended for future large-scale detectors.

Because the power loss of the mirrors must be extremely small, we used dielectric multilayer coating mirrors made with the ion-beam-sputtering method[10]

Table 1. Parameters of the Mode-Cleaner Cavity[a]

Nominal	
Curvature radius (front)	$R_1 = 1.5$ m
Curvature radius (end)	$R_2 = \infty$
Measured	
Cavity length	$L = 0.993$ m
Finesse	$\mathcal{F} = 1.5 \times 10^3$
Cavity transmittance	$T_{cav} = 0.91$
Calculated	
Free spectral range	$\nu_{FSR} = c/2L = 151$ MHz
Cutoff frequency	$\nu_{FWHM}/2 = 50.4$ kHz
Mirror reflectivity	$r^2 = 0.9979$
Mirror loss	$a^2 = 9.6 \times 10^{-5}$
Beam-waist radius	$w_0 = 490$ μm
Geometric factor	$g_1g_2 = 0.338$
Higher-mode interval	$\gamma = 0.30$
Suppression ratio	$S_{10} = 1.3 \times 10^{-3}$

[a]Calculated parameters are derived from nominal or measured parameters.

(fabricated by Japan Aviation Electronics Industry, Ltd.). These mirrors, 20 mm in diameter, were attached to a silica bar by optical contact. The finesse of the cavity was measured to be 1.5×10^3, which was derived from both the resonant width of the cavity and from the frequency response of the cavity in operation. The loss of each mirror (96 parts in 10^6) was calculated from the transmittance of the cavity on resonance (T_{cav} = 91%), assuming that the two mirrors were identical.

The mirrors were suspended independently as double pendulums with 100-μm-diameter tungsten wires (Fig. 2) and housed in a vacuum. The double pendulum consisted of an aluminum upper mass and a lower mass that comprised a fused silica bar with a mirror; eddy-current damping[11] was applied to the upper mass in order to suppress any large motion of the pendulum. Two magnets (2-mm diameter) were attached to the end of the bar for noncontact control of the cavity length with coil-magnet actuators. To isolate the vertical vibration, which may easily couple to the horizontal mirror motion, rectangular blade springs were inserted at the upper and the lower suspension points of the upper mass, resulting in two-stage vertical isolation, which we observed reduces up to 50 dB of the vertical ground vibration at 30–100 Hz. An alignment control from outside the vacuum chamber was realized by controlling the position of the uppermost suspension points of the pendulum with both motorized drives (for coarse control ≳1 μm) and PZT actuators (for fine control ≲10 μm).

Owing to losses in the input optics, the incident power of the laser beam to the cavity diminished from 500 mW at the laser down to 240 mW. The resulting power transmitted from the cavity was ~220 mW.

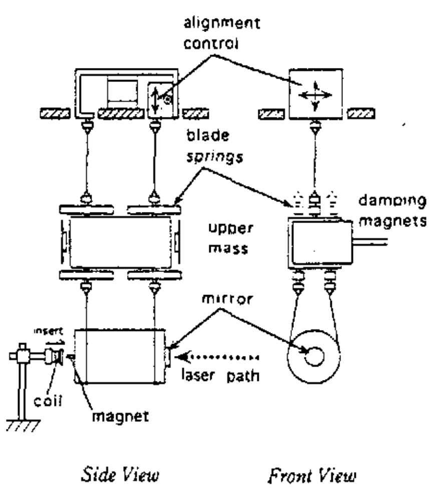

Fig. 2. Suspension system of a mode-cleaner mirror, which consisted of the aluminum upper mass and the lower mass of the fused-silica bar with the mirror. Eddy-current damping was applied to the upper mass in order to suppress the large pendulum motion. To isolate the vertical vibration, rectangular blade springs were inserted at the suspension points of the upper mass. The alignment control was realized by controlling the position of the uppermost suspension points of the pendulum.

B. Servodesign

The frequency-stabilization system contained two servoloops: the signal at low frequencies was fed back to the cavity, whereas at higher frequencies the laser frequency was locked to the cavity. Such a servoloop at low frequencies was necessary because of the instability of the cavity length, which was due to the pendulum motion's being excited by seismic noise. We chose the crossover frequency between these loops to be ~30 Hz, considering the cavity stability. Because a low crossover frequency causes the reference for the frequency stabilization to be unstable, whereas a higher crossover frequency limits the frequency stabilization gain, we chose 30 Hz as a tradeoff in this experiment. In the full-scale detector, frequency stabilization at lower frequencies (from dc) will be necessary both to keep long cavities on a stable resonance and to observe various events, such as coalescing binary neutron stars in the low-frequency band[12] (10–100 Hz). Therefore another low-frequency reference, such as a thermally controlled rigid cavity or an absorption molecular cell, will be used for frequency stabilization in addition to the suspended reference cavity.

Figure 3 shows the calculated transfer function of the two loops: the pendulum loop to lock the Fabry–Perot cavity [transfer function $F(\omega)$] and the PZT loop for frequency stabilization [transfer function $G(\omega)$]. The unity gain frequency (~20 kHz) was limited by a PZT resonance at ~100 kHz. The stabilized frequency noise (ν_{stab}) can be expressed as

$$\nu_{stab} = \frac{1 + F(\omega)}{1 + F(\omega) + G(\omega)}\, \nu_n, \qquad (8)$$

where ν_n is the original frequency noise of the laser. Therefore approximately an 80-dB frequency stabilization would be realized at 1 kHz.

In this servosystem, we checked for continuous operation for periods of up to 3 h, but saw no failures of the locking in the absence of external vibration.

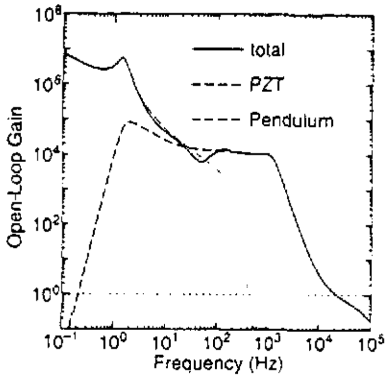

Fig. 3. Calculated transfer function of the frequency-stabilization system: the pendulum loop to lock the Fabry–Perot cavity and the PZT loop for the frequency stabilization. Approximately 80-dB frequency stabilization would be realized at 1 kHz.

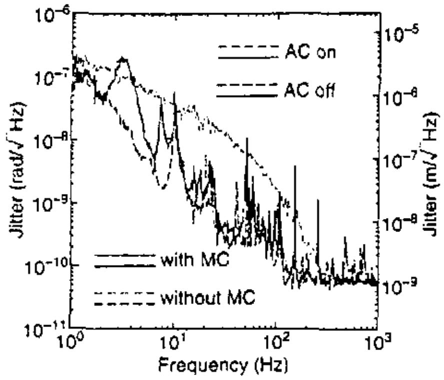

Fig. 5. Horizontal beam jitter in four cases: with the mode cleaner (MC) installed when the air conditioner (AC) was turned on (thin solid curve) or off (thick solid curve) and without the mode cleaner when the air conditioner was turned on (thin dashed curve) or off (thick dashed curve). By comparing the two curves when the AC was turned on (both thin curves), we can see approximately a 30-dB reduction with the mode cleaner near ~30 Hz, where the detection is limited by background noise, such as vibration of the position sensor.

4. Performance

A. Measurements of the Beam Jitter

To estimate the performance of the mode cleaner as a mode selector, we measured the reduction in the beam jitter by the mode cleaner, using the 20-m vacuum chamber as a stable optical path (Fig. 4). The angular fluctuation is magnified by the length of the arm. The position of the transmitted beam from the end chamber was detected by a knife-edge position sensor, which blocks half of the light horizontally or vertically. The effects of the intensity noise were cancelled out when the intensity of the sampled light was subtracted from the output of the position sensor.

1. *Effects of the Mode Cleaner*

First we measured the horizontal beam jitter without the mode-cleaner cavity. The thick dashed curve in Fig. 5 is the lowest measured level, which was limited mainly by the vibration of the position sensor as well as the electric noise of the sensor. Unfortunately, because of the large path length between the laser and the chamber, we found that the relatively large beam jitter originated from a fluctuation in the air.

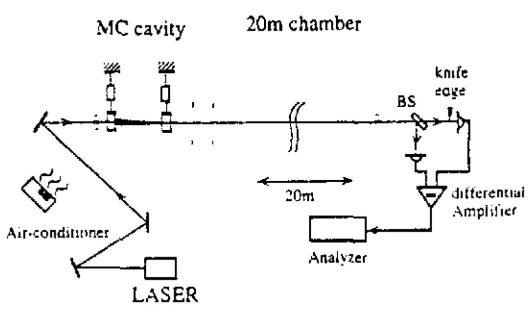

Fig. 4. Measurement of the beam jitter; the angular fluctuation is magnified by the 20-m vacuum path. The position of the transmitted beam from the end chamber was detected by a knife-edge position sensor, which blocks half of the light horizontally or vertically. We compared four cases, with or without the mode cleaner, when the air conditioner was turned on or off. MC, mode cleaner; BS, beam splitter.

When the air conditioner near the path was turned on, the beam jitter at low frequencies increased to the thin dashed curve in Fig. 5. Although we are interested in the beam jitter of the Miser itself,[13] we could not estimate it because of the above-mentioned background noise. We therefore estimated the total beam jitter, including the air fluctuation, and observed such a reduction of beam jitter that was due to the mode cleaner.

We then measured the beam jitter again in the same way after the mode-cleaner cavity had been installed (as shown by the figure in Fig. 4). The measured horizontal beam jitter is shown in Fig. 5 as two solid curves: the solid thick (thin) curve with the air conditioner turned off (on).

By comparing the two curves when the air conditioner was turned on (both thin curves), we could see approximately a 30-dB reduction with the mode cleaner near ~30 Hz. Although approximately a 60-dB reduction is expected from the parameters given in Table 1, the detection is limited by the background noise, such as vibration of the position sensor (shown as a thick dashed curve).

It can be seen that the beam jitters with the mode cleaner (both solid curves) below ~10 Hz are almost identical, regardless of the status of the air conditioner. The remarkable increase in the beam jitter near ~3 Hz is due to the instability of the mode-cleaner cavity; this can be clearly understood by a comparison of the horizontal and the vertical beam jitter, as shown in Fig. 6. Some of the peaks are resonances of the vibration isolation system: the horizontal pendulum motion at ~3 Hz and the vertical resonances of the blade springs at ~10 Hz. Hence the beam jitter at low frequencies may be enhanced because of resonances of the vibration isolation of the mode-cleaner cavity.

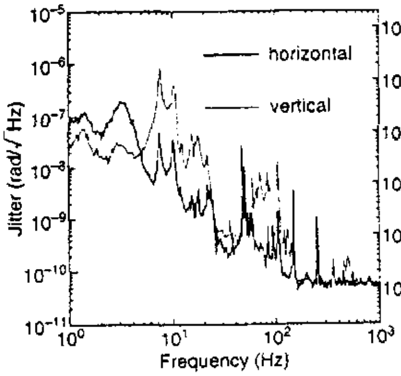

Fig. 6. Horizontal or vertical beam jitter with the mode cleaner installed. Horizontal pendulum motion appeared at ~3 Hz and vertical resonances of blade springs at ~10 Hz. Hence the beam jitter at low frequencies may be enhanced because of resonances of the vibration isolation of the mode-cleaner cavity.

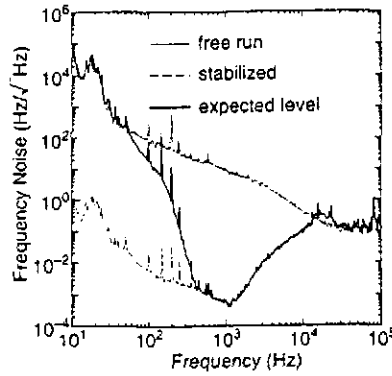

Fig. 8. Expected frequency noise of the mode cleaner. The thin curve indicates the free-running spectrum of the laser. With the stabilization, the error signal fell to the dashed curve. The expected frequency noise of the output light was calculated from the stabilized error signal with the feedback loop to the pendulum at low frequencies, level, taken into account.

2. *Beam Jitter by Frequency Control*

Another component of beam jitter of particular interest is that which is due to the PZT attached to the laser crystal for controlling the resonant frequency by deforming the laser crystal. When a swept sinusoidal voltage was applied to the PZT, the frequency dependence of the beam jitter was measured (without the mode cleaner). As shown in Fig. 7, extra beam jitter from controlling the laser frequency does exist at similar levels horizontally and vertically. Such jitter will also be reduced by the mode cleaner. Although the voltage to the PZT produces an extra intensity change, we showed that this effect is negligible compared with the result from repeated measurements without the knife edge (dashed curve in Fig. 7).

B. Estimation of the Frequency Stability

The frequency stability of the mode-cleaner system was estimated. Although it can be calculated from the error signal of the servosystem to some degree, the instability that is due to any deficiencies of the mode-cleaner cavity as a reference or to the detector noise cannot be estimated in this way. Another reference cavity with the same or higher stability is needed. For this reason we used a reference cavity, which is an independently suspended Fabry–Perot cavity that has a length of 20 m and a finesse of ~350.

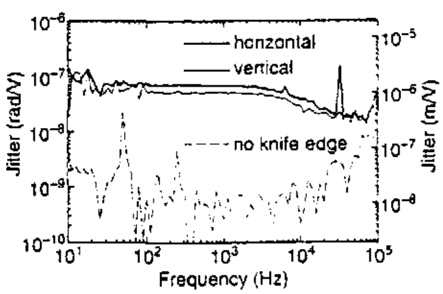

Fig. 7. Extra beam jitter that is due to the frequency control of the Miser when a PZT attached to the laser crystal is used. Repeated measurements without the knife edge (dashed curve) showed that an extra intensity change by frequency control was negligible to the result.

1. *Expected Frequency Noise*

Before an estimation, for which a 20-m Fabry–Perot cavity was used, the frequency noise level expected from the original frequency noise of the laser and the servogain was evaluated. The thin curve in Fig. 8 indicates the free-running spectrum of the laser obtained from the error signal without stabilization. Above 30 Hz the spectrum shows the trend of the frequency noise of the Miser, which is inversely proportional to the Fourier frequency, whereas vibration of the pendulum motion can be seen below 30 Hz. With stabilization, the error signal fell to the dashed curve. This level agrees well with the theoretical level calculated from the thin line and the servogain (Fig. 3). We calculated the expected frequency noise of the output light from the stabilized error signal while taking into account the feedback loop to the pendulum at low frequencies [Eq. (8)], which appears in Fig. 8, labeled expected level.

2. *Estimation with the 20-m Fabry–Perot Cavity*

Figure 9 shows the setup for estimating the frequency noise of the mode cleaner by use of a 20-m Fabry–Perot cavity. The beam from the mode cleaner illuminated the 20-m reference cavity housed in the vacuum chamber. To obtain a signal, the transmitted beam from the mode cleaner was modulated in phase at 40 MHz, and the reflected beam from the 20-m Fabry–Perot cavity was extracted by an optical circulator. The signal was demodulated in the same way for the mode cleaner and then fed back to the end mass in order to keep the cavity on resonance.

Figure 10 shows the calibrated spectra from the 20-m Fabry–Perot cavity as well as that from the mode cleaner. The two dashed curves, which represent runs without stabilization, agree well with each other, except below 30 Hz. The difference comes