Demonstration of a power-recycled Michelson interferometer with Fabry–Perot arms by frontal modulation

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Large-scale gravitational-wave detectors currently under construction such as the LIGO detectors use multiple-mirror resonant optical systems containing several surfaces at which the relative phase of interfering light beams must be controlled. We describe a tabletop experiment that demonstrates a scheme for extracting signals in such an interferometer corresponding to deviations from perfect interference.

Gravitational radiation from astrophysical sources produces a strain in space transverse to its direction of propagation. Because this strain has opposite sign along orthogonal axes, variants of the Michelson interferometer are well suited for detection of these waves. Such interferometers with kilometer-scale arm lengths are now under construction by the LIGO[1] and VIRGO[2] collaborations.

Each LIGO interferometer will be a Michelson interferometer with partially transmitting mirrors interposed in the arms between the beam splitter and the end mirrors, forming long Fabry–Perot cavities, and with a recycling mirror between the laser and the beam splitter[3,4] (see Fig. 1). The Fabry–Perot cavities amplify the change in phase of the light returning to the beam splitter for a given displacement of the end mirrors. Optimum sensitivity is obtained when light returning from the cavities interferes constructively at the beam splitter in the direction toward the laser. The recycling mirror improves the signal-to-shot-noise ratio by reflecting this beam back into the interferometer, thus increasing the power incident upon the beam splitter. Antisymmetric motions of the cavity end mirrors (such as those produced by a gravitational wave) alter the interference and cause light to exit the interferometer through the beam splitter.

High-sensitivity operation of such an interferometer requires that light beams interfering at each of the four partially transmitting surfaces have the correct relative phase. Errors in the relative phases must be sensed and corrected by a control system that adjusts the mirror positions and the laser wavelength. A simple technique that uses phase-modulated light has been developed to solve this problem for a single cavity[5] and serves as a basis for the work described here. Previously constructed recycled interferometers[6,7] have relied on an external modulation technique[8] to generate one or more of the necessary signals. This technique requires the introduction of one additional optical surface whose position needs to be controlled.

In this Letter we describe the demonstration of a signal extraction scheme that does not increase the number of degrees of freedom requiring control. This scheme is a variant of an idea proposed by Schnupp (Ref. 9); Drever[10] has proposed a similar scheme.

As shown in Fig. 2, the laser light is phase modulated at frequency f_{mod} (typically a few tens of megahertz) with a Pockels cell (PM). The Fabry–Perot cavities in the arms of the interferometer are located at distances l_I and $l_P = l_I + \delta$ from the recycling mirror. The nominal arm length is $L = (L_I + L_P)/2$ (note that $L_I \simeq L_P$). Light is extracted in three places and detected with photodiodes (PD's). The signal from each photodiode is demodulated with a reference signal that is either in phase (I) or 90° out of phase (Q) with the applied phase modulation. The nominal cavity lengths were chosen such that, when the carrier resonates in both the arms and the recycling cavity, the phase-modulation sidebands resonate in the recycling cavity but are nearly antiresonant in the arms. This is achieved when $L \simeq (k + 1/2)c/(2f_{\mathrm{mod}})$ and $(l_I + l_P) \simeq (n + 1/2)c/(2f_{\mathrm{mod}})$ (where k and n are integers).

We calculated the response of the interferometer configuration of Fig. 2 to small changes in the positions of the mirrors, using the approximation that the position changes are slow compared to the equilibration time for the light in the cavities. According to this quasi-static model, the dependence of the outputs on the distances between the mirrors and the laser wavelength is, near resonance (see Fig. 2),

$$V_1 \propto (\delta L_I + \delta L_P) + \varepsilon_1(\delta l_I + \delta l_P),$$

$$V_2 \propto (\delta L_I + \delta L_P) + \varepsilon_2(\delta l_I + \delta l_P),$$

$$V_3 \propto (\delta L_I - \delta L_P) + \varepsilon_3(\delta l_I - \delta l_P),$$

$$V_4 \propto (\delta l_I - \delta l_P) + \varepsilon_4(\delta L_I - \delta L_P).$$

Seismic noise drives l_I, l_P, L_I, and L_P so that they have comparable deviations from perfect resonance. The ϵ_k are small coefficients with absolute values typically between 0.1 and 0.001, depending on the mirror

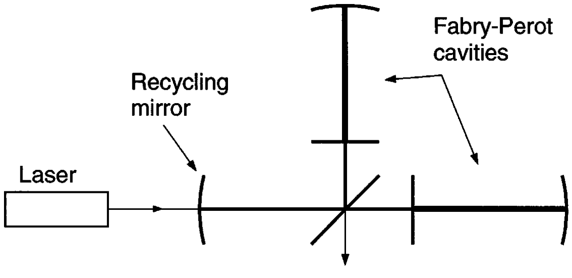

Fig. 1. Simplified diagram of a LIGO interferometer. Light beams are depicted with line thicknesses that indicate relative optical power levels.

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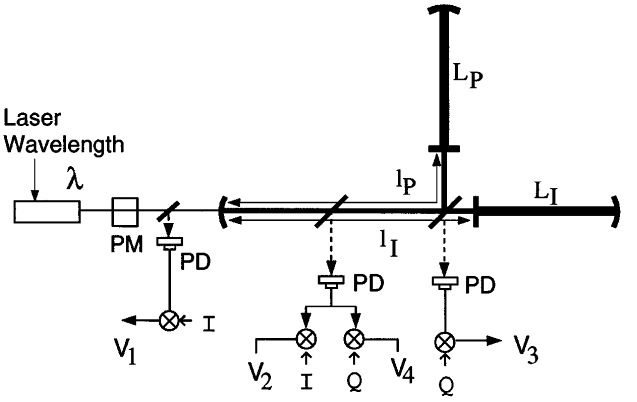

Fig. 2. Signal extraction scheme for a power-recycled interferometer that uses frontal modulation.

parameters. A computer program based on the quasi-static model solves for the complex amplitude of each of the three frequency components of the light (the carrier and the two nearest rf sidebands produced by the phase modulation) everywhere in the interferometer, finds the corresponding demodulator outputs, and differentiates these with respect to mirror positions.

The control system must be designed to accommodate the coupling of the different lengths in the output signals. Ideally, linear combinations of these four signals could be formed to adjust the four controllable degrees of freedom independently. One potential difficulty is immediately apparent from expressions (1). Of the common-mode and differential combinations of l_I, l_P, L_I, and L_P, the dependence on the recycling cavity length $(l_I + l_P)/2$ is not dominant in any output, and the performance of the servo depends on the accuracy of the coefficients of this linear combination. An alternative technique, used in this experiment, is to operate the servo loop feeding back to the laser wavelength with much higher gain than the others.[11] Using V_1 to generate feedback to the laser then drives $\delta L_I + \delta L_P \simeq 2L(\delta\lambda/\lambda)$ sufficiently close to zero that V_2 is nearly proportional to $(\varepsilon_2 - \varepsilon_1)(\delta l_I + \delta l_P)/2$. In most cases of interest, the absolute value of $(\varepsilon_2 - \varepsilon_1)$ is of the same order of magnitude as ε_1 and ε_2 themselves, so this factor does not significantly degrade the sensitivity to $(\delta l_I + \delta l_P)$.

A tabletop interferometer was assembled and its response was compared to the model's predictions. Light from an argon-ion laser (Coherent Innova 100) was phase modulated, spatially filtered, and power stabilized before entering the interferometer. A 12.33-MHz phase modulation was used. We satisfied the resulting requirement for cavity lengths of approximately 6 m ($k = n = 0$) on our 3.7-m table by folding the recycling cavity and both arm cavities in half. An asymmetry δ of 30 cm was used. The Fabry–Perot cavity input mirrors had reflectivities of 91%. Round-trip losses in the arm cavities were measured to be between 0.2% and 0.25% and were caused mainly by dust in the air and on the mirrors. The recycling mirror reflectivity was 82%, and the ratio of optical power in the recycling cavity to the incident laser power was 4, corresponding to round-trip losses in the recycling cavity (including power deflected by the pickoff and loss in the Fabry–Perot cavities) of 16%.

The length control system is shown schematically in Fig. 3. Interferometer mirror positions were adjusted with piezoelectric transducers; the laser frequency was adjusted with piezoelectric transducers on the laser mirrors and an extracavity Pockels cell for fast correction of the phase of the light. The demodulator phases and amplifier gains were adjusted empirically by optimization of the stability of the locked state.

When servo loop 4 was disabled and the perpendicular Michelson arm length l_P was varied slowly back and forth, the remaining three servo loops occasionally acquired lock until continued motion disrupted the resonance. This served as the basis for an automatic lock-acquisition circuit. When the circulating power in either arm cavity fell below a preset threshold, this circuit disabled the feedback to loop 4 and swept l_P with a triangle wave. Once the power in both arms was again above threshold, the triangle wave sweep was removed and the loop 4 servo was reengaged. An example of this process is shown in Fig. 4.

The closed-loop response of the interferometer was measured for loops 2, 3, and 4 of Fig. 3 and compared with that of the quasi-static model. We took each measurement by injecting a swept-frequency sine wave into a summing node in one of the high-voltage amplifiers driving a piezoelectric actuator. A dynamic

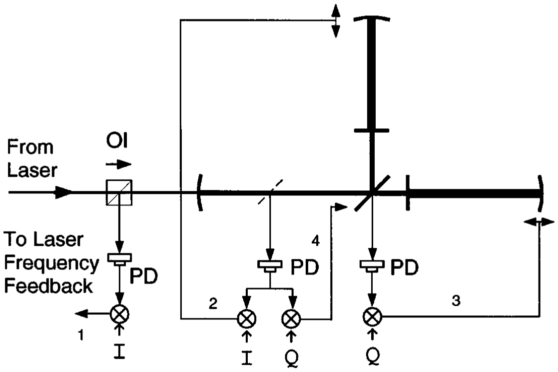

Fig. 3. Control loop configuration used for this experiment. An optical isolator (OI) is used to extract the beam reflected from the recycling mirror. The feedback signal shown schematically as driving the beam splitter actually drove a folding mirror on the in-line arm.

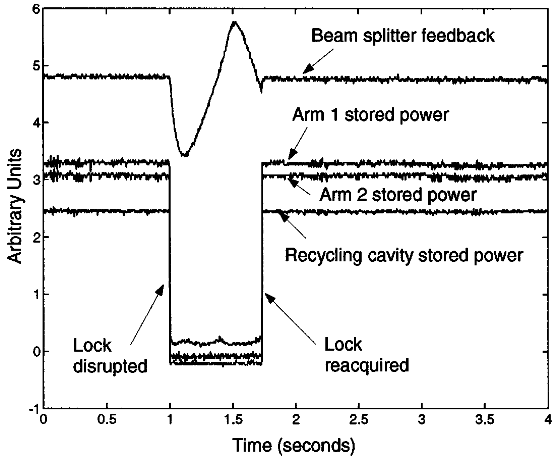

Fig. 4. Time record of acquisition transient. The traces showing stored power levels have been offset for clarity.

Table 1. Sampled Values (in decibels) of Experimental and Calculated In-Resonance Responses[a]

	Loop Measured					
Loop Driven	2		3		4	
2	**19.0**	22.1	**26.9**	24.6	**23.6**	23.4
3	**9.86**	16.4	**38.3**	37.7	**15.4**	17.8
4	**27.3**	31.8	**24.6**	25.8	**36.3**	36.9

[a] The experimental values are in boldface type; the calculated values are in regular type. In all cases the driving signal was a 2-kHz sine wave.

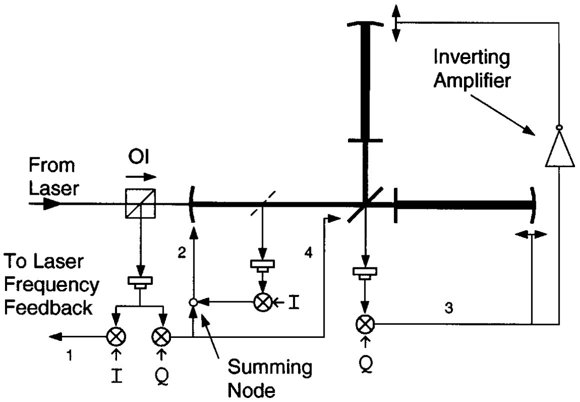

Fig. 5. Possible LIGO control configuration.

signal analyzer (Hewlett-Packard 3562A) was used to measure the transfer function from the output of the amplifier to the (amplified) output of the mixer. We calculated the expected response by incorporating the quasi-static optical model into a closed-loop control model, using standard multivariable servo modeling software.[12] In addition to mirror reflectivities and positions, the interferometer response depends on a number of factors such as the optical power, the efficiency of the photodiodes, and the response of the piezoelectric transducers. For each of the loops we measured the product of these factors by misaligning mirrors within the interferometer so that only a single Fabry–Perot cavity was resonating. The response of this cavity together with the factors to be calibrated was then measured and divided by the known response of a Fabry–Perot cavity. The experimental and calculated responses of the interferometer at a test frequency of 2 kHz are tabulated in Table 1. The agreement is reasonable given the estimated experimental uncertainty of ±3 dB.

The control loop configuration (Fig. 3) that was used in the prototype interferometer was adequate for proof-of-principle tests and model verification. In fact, a more balanced control configuration, shown schematically in Fig. 5, is better suited for use in a gravitational-wave detector. The quadrature phase output from the isolator is used instead of the quadrature signal from the pickoff, since the signal at the isolator is larger relative to the shot noise. The gravitational wave signal is taken directly from control loop 3. Additional modulation frequencies may also be used to obtain further decoupling of the individual feedback loops.[13]

In summary, we have demonstrated a means of extracting signals from a power-recycled Fabry-Perot interferometer by introducing phase modulation of the laser light and an asymmetry in the positions of the arm cavities. The response of a tabletop prototype incorporating this scheme agrees well with the predictions of a simple model.

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