Experimental Demonstration of Dual Recycling for Interferometric Gravitational-Wave Detectors

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We describe the first experimental demonstration of dual recycling, an optical system which should improve considerably the performance of proposed laser-interferometric gravitational-wave detectors. The results were in excellent agreement with predictions: An enhancement of the signal-to-noise ratio by a factor of 7 was observed.

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One of the most exciting developments in science in the next few years may be the observation of gravitational waves from sources such as supernovae, coalescing neutron stars or black holes, pulsars, or even the big bang (see Ref. 1 for a review). There are several current proposals for the construction of gravitational-wave observatories[2–4] that use laser interferometry to detect the changing curvature of space-time induced by the passage of a gravitational wave.

Laser-interferometric gravitational-wave detectors work by sensing the differential phase shift imposed on the light in the two orthogonal arms of a Michelson interferometer by a gravitational wave. This phase shift is converted into an observable intensity change by interference, the smallest detectable signal being limited by photon-counting statistics. The signal is greatest if the time the light spends in the arms of the interferometer is equal to half a gravitational-wave period. For this reason, most detector designs employ multiple bounces of the light in each arm, using either resonant cavities or optical delay lines to achieve this. Practical constraints on mirror size mean that simple delay-line interferometers cannot achieve long enough light storage times to be optimized for low gravitational-wave frequencies (≤ 500 Hz). However, if dual recycling[5] is incorporated into such a detector, the signal sidebands may be stored for sufficiently long times to allow optimum photon-noise-limited sensitivity to be achieved at arbitrary low frequency. Furthermore, dual recycling is both a flexible and an efficient method for enhancing the sensitivity of either type of interferometer within a restricted bandwidth.[5,6] Dual recycling will therefore allow better performance from laser-interferometric gravitational-wave detectors when searching for continuous radiation from pulsars, for a stochastic background from cosmic strings or the early stages of the big bang, or even for the chirp of gravitational radiation emitted by coalescing compact binaries.[7] In view of these potential benefits, it is important that the operation of an interferometer using dual recycling be demonstrated.

The optical system for dual recycling is shown in simplified form in Fig. 1. In addition to the interferometer mirrors (M_1,M_2) and beam splitter, the "power-recycling" (M_0) and "signal-recycling" (M_3) mirrors are shown. Power recycling[8] makes the whole system into a cavity in which the input laser light is resonant, allowing it to be coupled in efficiently. The interferometer is operated with its output maintained at an interference minimum and the power-recycling mirror is chosen to have a transmission equal to the losses in the interferometer to maximize the light amplitude in the arms and hence the potential signal-to-noise ratio for gravitational waves.

Dual recycling requires the placement of the (partially transmitting) signal-recycling mirror at the output from the interferometer to form the "signal-recycling cavity" (see Fig. 1). In a perfect interferometer the only light emerging from the output would be the sidebands produced by differential phase shifts in the arms. These sidebands are reflected by M_3 and can then resonate within the signal-recycling cavity. The round-trip phase shift of the sidebands within this cavity depends on the position of M_3. If one or more sidebands are made resonant within the signal-recycling cavity, their amplitude emerging through M_3 is increased. Note the rather counterintuitive nature of this system: The signal is enhanced by placing a mirror in front of the photodetector. This is all the more motivation for an experimental demonstration.

Dual recycling has two modes of operation: the

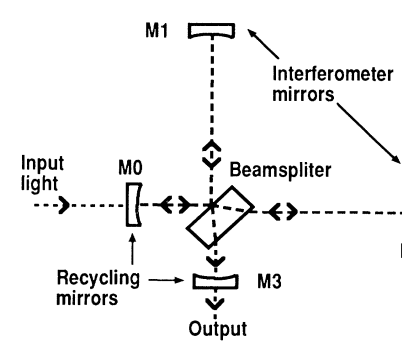

FIG. 1. Simplified optical arrangement of an interferometer with dual recycling. M_0 resonates the laser power while M_3 resonates the signal sidebands.

"broad-band" mode where the signal-recycling cavity is tuned to the original laser frequency (zero-signal frequency) and the low-frequency performance of the detector is enhanced, and the "narrow-band" mode where this cavity is tuned to a particular signal sideband frequency. The latter gives a response which is peaked at the chosen signal frequency. A detailed derivation of the frequency responses which can be expected from an interferometer with dual recycling appears in Ref. 6.

This first test of dual recycling was carried out on a rigid system with fixed mirrors in air to reduce the overall complexity. This required that measurement of fundamental noise properties were made at frequencies above about 10 kHz where the influence of ambient vibrational and acoustic noise became sufficiently small. The aim was to measure the signal and signal-to-noise-ratio enhancement produced by broad-band dual recycling, and to demonstrate that the control systems were workable. (Realistic measurement of the signal properties of narrow-band dual recycling can only be made on systems large enough to have the linewidth of the signal-recycling cavity comparable to the signal frequency.)

The optical system is indicated in Fig. 2. A single-bounce Michelson interferometer with an arm length of 0.50 m was used. The recycling mirrors were similar to each other, with radius of curvature of 0.7 m, 10% intensity transmission, and spaced 0.09 m from the main beam splitter. All of the mirrors which had to have position control were mounted on piezoelectric transducers. A single-mode argon-ion laser (Spectra-Physics model 165, wavelength 514.5 nm) was used to illuminate the apparatus.

The usual rf reflection-locking technique[9] was used both to stabilize the frequency of the laser (via an intracavity Pockels cell) to a reference cavity (length 46 cm, finesse 6000) and to control the positions of the recycling mirrors. Phase modulation at 12 MHz was applied by a Pockels cell in front of the laser. The position of M_3, and hence the resonant (or tuning) frequency of the signal-recycling cavity, was monitored using a control beam (a few percent of the light from the laser) to illuminate this cavity via M_3. This control beam was, however, frequency shifted by an amount adjustable about two free spectral ranges ($\sim$500 MHz) of the signal-recycling cavity using a double-passed acousto-optic modulator. The purpose of this was to ensure that no light was injected at the same frequency as the signal sidebands, while still generating the correct error signal. As an additional safety measure, the sensing light was injected in the orthogonal polarization to the main light; this also allowed easy separation of the beams. Any offset in the resonant frequencies of the two polarization states does not matter as long as it does not change quickly. Note that the tuning frequency can be changed easily by altering the drive frequency to the acousto-optic modulator. Double passing the modulator avoids problems with beam deflection. A longer system would have a much smaller free spectral range and it might then be convenient to use an electro-optic modulator and lock on a modulation sideband.

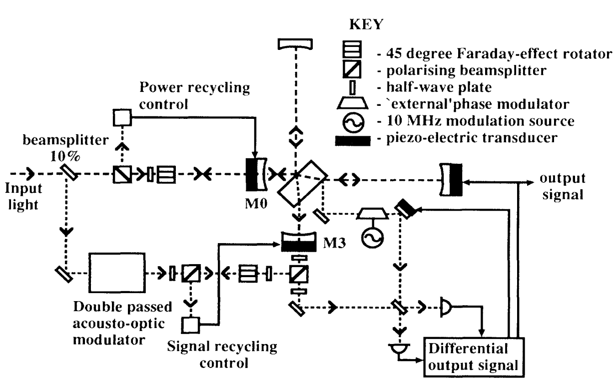

FIG. 2. The essential elements of the test system for dual recycling. The signal paths of the control systems are indicated.

The output signal from the interferometer was sensed using an external modulation technique.[3,10,11] The signal sidebands are detected by beating them with a phase-modulated reference beam, derived here from the antireflection coating (reflectance $\approx 10^{-3}$) on the back face of the beam splitter. External modulation allows measurements to be transferred up to high frequency (10 MHz in this case), where the laser intensity is limited by quantum noise, while avoiding the situation of modulators at places where the power is high or the losses are required to be low. A reference beam generated at the beam splitter gains the full benefit of the filtering action of the recycling cavity. (In a real gravitational-wave detector, the sensing beam for the signal-recycling cavity would probably be derived in a similar way.) The output signal was used to hold the Michelson interferometer on a dark fringe by feeding back to mirror M_2. The phase of the reference beam was controlled so that the signal was maximized: A gravitational wave was mimicked by modulating the position of one of the mirrors (M_2) of the interferometer by a small amount at 6 kHz, the resultant signal was detected, and the optimum reference phase found by dithering the external path length at 95 Hz. Because the modulation applied to interferometer mirror M_2 only controls the reference phase, its magnitude can be small: The fractional power loss from the interferometer due to the modulation was $\sim 7\times10^{-6}$. These servos also benefited from the incorporation of an automatic gain control system, which tried to adjust the rf gain to keep the apparent size of our simulated gravitational wave constant. By increasing the servo gain by as much as 60 dB when *any* part of the interferometer was not at its correct operating point, the range of start-up configurations which gave easy acquisition was considerably increased. Indeed, this combination of control systems worked remarkably well. Upon switching on the servos, the whole interferometer would jump into lock from essentially any initial state.

The 6-kHz arm-length modulation was used to measure the frequency response and signal enhancement of dual recycling. (The signal was measured before the automatic gain control system.) 6 kHz represents a very low frequency compared to the linewidth of the signal-recycling cavity, so the two sidebands produced by this modulation will resonate equally, seeing effectively the same phase shift δ within the cavity. If we define a function G to describe the enhancement of the signal in dual recycling compared to power recycling, the predictions[6] for the response reduce to

$$G(\delta)=\frac{t}{1-r\rho}\left[1+F'\sin^2\left(\frac{\delta}{2}\right)\right]^{-1/2}, \qquad (1)$$

where t and r are the (amplitude) transmission and reflection coefficients of M_3, ρ is the amplitude reflectivity of the arms of the interferometer (in practice, this is close to unity compared to r), and $F'=4r\rho/(1-r\rho)^2$ is the coefficient of finesse of the signal-recycling cavity. With the optical and geometrical parameters of the test system [$F'=1440\pm60$, $t/(1-r\rho)=6.2\pm0.2$], this leads to the predicted frequency response shown in Fig. 3, where it is compared to the normalized amplitude of the 6-kHz signal as a function of the acousto-optic modulator drive frequency. (A change of this frequency by one free spectral range of the signal-recycling cavity, calculated to be 253 ± 1 MHz, corresponds to a change of δ by 2π.) With no signal-recycling mirror the signal size was 0.15 ± 0.03 of the maximum. It can be seen that the agreement between the theoretical predictions and the observations is excellent.

It is important to demonstrate that not only is the signal size increased by dual recycling, but also the signal-to-noise ratio is improved. That this is indeed so can be seen in Fig. 4, which shows the spectra of the output signals of the interferometer with and without signal recycling. The observed improvement in signal-to-noise ratio was 17 dB at high frequency, a factor of 7. Note that this is slightly more than the increase in signal, a factor of 6. The difference is accounted for by the better fringe contrast possible with dual recycling. (We will discuss the improvement of fringe contrast in dual recycling in a future publication.[12]) With power recycling, the fraction of the circulating power which was lost out of the beam splitter was 4×10^{-4}. This contributed about 40% of the power on the final photodiodes, with a consequent increase in the photon noise of about 20%. But with dual recycling, the corresponding fractional power loss was only 2.5×10^{-5} and this increased the shot noise by only 1%. Not only does the reduced power loss decrease the detected noise, it can, when power recycling is optimized, enhance the signal by allowing a higher power buildup within the inteferometer. Another advantage of dual recycling is evident.

While at low frequency the interferometer noise (as seen in Fig. 4) is limited by mechanical vibration, at sufficiently high frequency (≥ 20 kHz) the level approaches that set by photon noise. This is an equivalent displacement-noise spectral density of 1.6×10^{-16} m/$\sqrt{\text{Hz}}$. There was 0.2 W of light in the power-recycling cavity, which represents an increase over the incident light by a factor of 32. This compares with a gain of 37 predicted from the transmission of the power-recycling mirror. The difference is consistent with being due to imperfect mode matching and the presence of the rf modulation.

Dual recycling may be a very important element of the interferometers used for gravitational-wave detection.

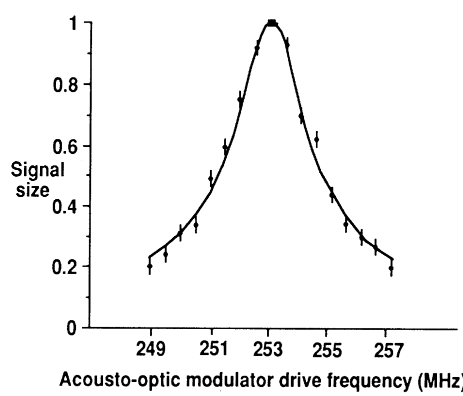

FIG. 3. The tuning curve of broad-band dual recycling. The points plotted with error bars are the experimental measurements of the signal size. The curve indicates the expected line shape.

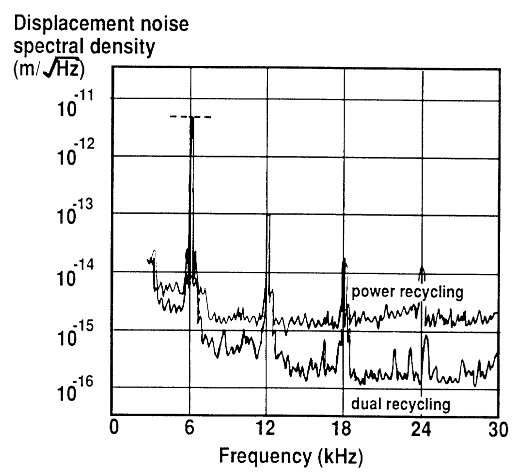

FIG. 4. The equivalent displacement of the noise at the output of the power- and dual-recycling systems. The 6-kHz peak was used as calibration.

Control systems for dual recycling, using principles that should be applicable to the final detectors, have now been developed and tested on a small-scale system. These results strongly suggest that a dual-recycling interferometer with external modulation will, indeed, be a practical proposition. Our experiment has confirmed that signal recycling produces the expected frequency response and signal-to-noise-ratio enhancement, a factor of 7 in our case. It also improves the fringe contrast. Recycling the dark fringe really does work.

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