New Folder Name Recycling Interferometer Light

Gravitational Waves

Recycling Interferometer Light

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Observation of gravitational waves, the ripples in space-time emitted by violent cosmic events such as the deaths of stars and the births of black holes, will likely revolutionize our understanding of astrophysics. Several groups worldwide are engaged in efforts to build gravitational-wave observatories using advanced laser interferometers to detect the waves. Efforts at this measurement frontier have spawned new techniques, such as light recycling and the use of squeezed light. A new tool, called dual recycling, has recently been demonstrated[1] which allows more efficient use of laser light and provides an elegant method of tailoring the bandwidths of these detectors.

A passing gravitational wave causes distances between inertial masses, as measured by the transit time of light, to change by some fractional amount. This effect is measured in an interferometer (see box) by bouncing light beams from a common laser between mirrored test masses in each of two perpendicular interferometer arms, then interfering the beams as they emerge from the arms. If the distances between the masses in both arms are exactly equal, the light recombining at the beam splitter returns toward the laser, leaving a strategically placed photodetector in darkness. The absence of light at this photodetector is referred to as a dark fringe, in contrast to the bright fringe returned toward the laser by the beam splitter. A gravitational wave incident on the detector upsets the balance of arm lengths thereby switching some light from the bright fringe onto the photodetector. Because gravitational waves interact weakly with matter, the rich information they carry is preserved as they propagate through space but their influence on detectors is feeble. Predicted signals for the gravitational-wave observatories correspond to fractional displacements of $h = \Delta L/L \approx 10^{-21}$, where ΔL is the difference between the two arm lengths, and L is their average length. Test masses separated by several kilometers will move much less than a nuclear diameter. Laser interferometer prototypes with resolutions of a few percent of a nuclear diameter over tens of meters operate today, but further progress is needed.

Once the test masses are sufficiently isolated from disturbances due to seismic noise and other random forces, the ability to detect a change in the dark fringe sets the detector's sensitivity. In the shot-noise limit, fundamental fluctuations in photon number inherent in the quantum nature of light make the smallest detectable signal from the interferometer inversely proportional to the square root of the power in the bright fringe.

Light recycling[2] increases the bright fringe power obtained with a given laser, in principle achieving the equivalent of a thousandfold increase in laser power. In broadband recycling, a mirror inserted between the laser and the beam splitter reflects the bright fringe light back into the interferometer, recycling the photons for another measurement. An alternate technique, resonant recycling, uses a combination of mirrors to switch photons between the two arms in synchrony with the oscillations of a given gravitational wave, allowing the signal to build up over many cycles. In addition to increasing the bright fringe

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power, this technique converts the interferometer into a more sensitive tuned instrument for detecting periodic signals. Dual recycling[3] involves recycling both the bright fringe and any signal that would appear at the photodiode, allowing it to build in strength. Although it is conceptually similar to resonant recycling, dual recycling can operate over a wide range of bandwidths.

The recent work by K. A. Strain and B. J. Meers[1] demonstrates that dual recycling can improve the broadband low frequency performance of a particular interferometer configuration which uses optical delay lines to store light in its arms. With this improvement the delay-line interferometer should be as sensitive as a Fabry-Perot interferometer. (Practical constraints on mirror size had previously favored the more compact Fabry-Perot configuration for detecting gravitational waves at frequencies below a few hundred Hertz because the maximum storage time for light in a delay line was too short.) For their demonstration, Strain and Meers built a small scale broadband recycled interferometer in which the light made a single bounce in each arm. Since the mirrors were not suspended as in a real gravitational-wave detector but were held in rigid mounts, vibrations dominated the displacement noise below 20 kHz. Above this frequency, the displacement noise was shot noise limited at a level determined by the available bright fringe power and the very short storage time of light in the arms. When the signal recycling mirror was added a sevenfold increase in signal to noise ratio was observed. This was slightly better than the expected sixfold improvement, a fact which the authors attributed to the improved wavefront quality inside the interferometer with dual recycling.

Dual recycling also looks promising to those of us who favor the Fabry-Perot interferometer design. Dual recycling can adapt a broadband recycled interferometer to narrowband operation by adding a single mirror to the output side of the instrument. Adjusting the position of the signal recycling mirror tunes the interferometer to a particular frequency, which might be chosen to correlate with the rotation frequency of a known pulsar. The detector's bandwidth can be varied by adjusting the transmission of the signal recycling mirror. In some cases an intermediate bandwidth may be desirable, trading off some bandwidth for improvements in mode quality within the interferometer.

A very different method for improving interferometer sensitivity in the shot-noise limit is to inject squeezed light into the interferometer at the beam splitter[4]. The presence of squeezed light can alter the stochastic nature of the beam splitting process, reducing quantum fluctuations in the output beam at the cost of increased fluctuations in radiation pressure on the test masses. Although squeezing cannot violate the uncertainty principle, it may allow the quantum limit to be reached with less bright fringe power. The improvement in precision has been demonstrated in a simple interferometer[5] and evaluation of squeezing techniques in practical gravitational-wave detectors has begun[6]. For squeezed light to be effective, interferometer losses must be minimized, a situation which also enhances recycling efficiency.

Where will this lead? Gravitational-waves from sources that can be predicted with confidence, such as coalescing neutron star binaries, should be detectable with long baseline interferometers using modest broadband recycling factors (about 100), and laser powers (about 60W) that should become available in the near future, even without squeezing. The use of squeezed light with broadband recycling configurations should either relax demands for bright fringe power or further extend detector sensitivity. The relative weighting of these techniques in future detectors will hinge on developments in optics, lasers, and materials – technologies which are moving significantly on timescales of a few years. As we look to a new frontier in astronomy we should remember a lesson learned from the opening of a previous frontier, radio astronomy. The universe was far richer in sources than could previously have been imagined and nobody ever complained that their instruments were too sensitive.

References:

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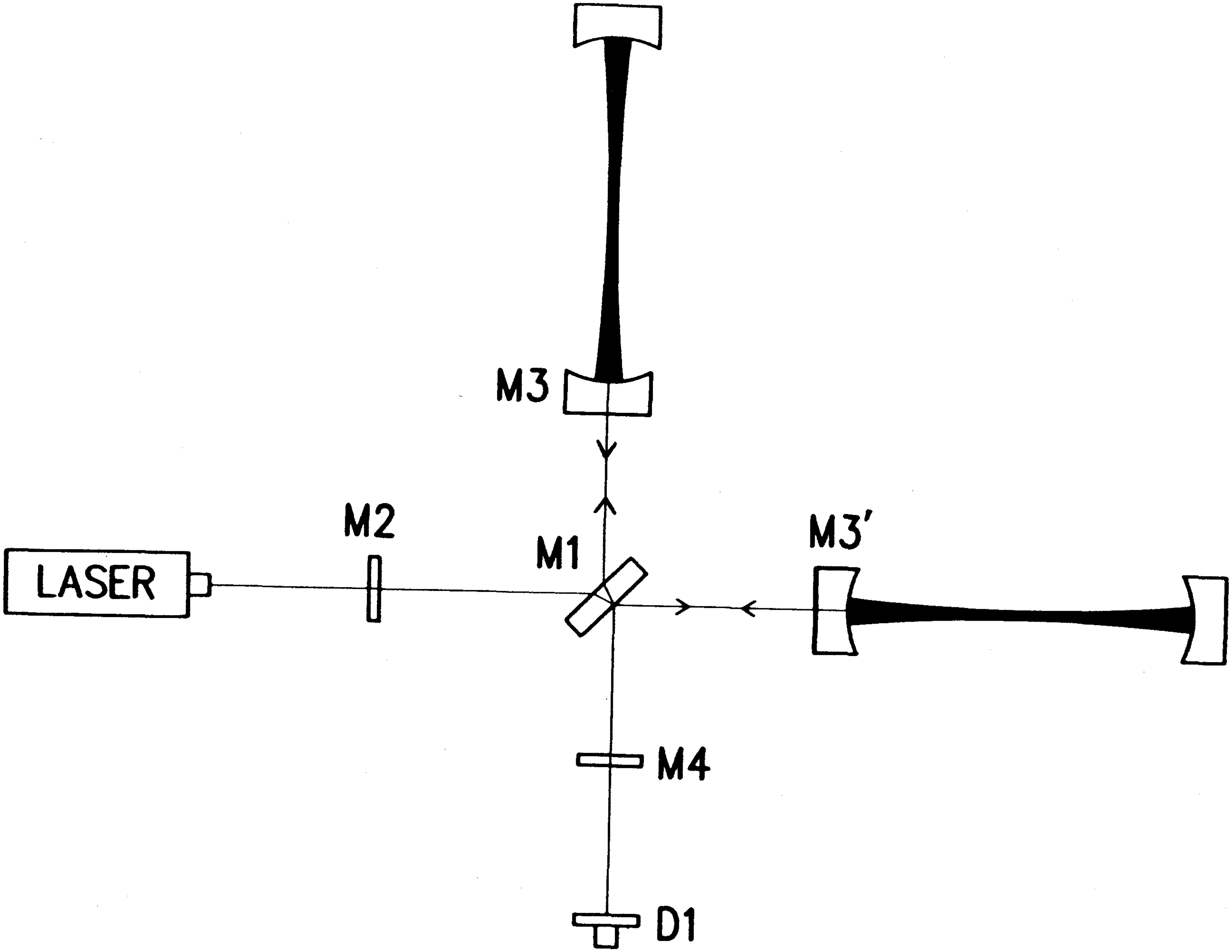
Figure caption

Schematic diagram of a laser interferometer with dual recycling.

Laser light illuminates the beam splitter (M1) after passing through the power recycling mirror (M2). The beam splitter directs light into two perpendicular interferometer arms where the light is stored between an input mirror (M3 or M3') and an end mirror (unlabeled), bouncing many times between these mirrors (denoted by thick lines). In the delay-line configuration, this light illuminates different spots on these mirrors on each pass; in the Fabry-Perot configuration the same spots are illuminated on each pass, thereby forming an optically resonant cavity with these mirrors. Light returning from the arms interferes at the beam splitter. If both beams have traveled exactly the same distance, all of the light is returned toward the laser; any slight imbalance in the arm lengths causes some light to propagate towards the photodetector (D1). This light is the interferometer output signal. The power recycling mirror reflects light returned by the beam splitter back into the interferometer, thereby increasing the circulating power. The signal recycling mirror (M4) allows the signal to build up in the interferometer in a similar manner before detection at D1.


M3
M2
M1
M3′
LASER
M4
D1

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