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Dual recycling for GEO 600

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Abstract

Dual recycling is the combination of power recycling and signal recycling. GEO 600, a German–British interferometric gravitational wave detector being built in Germany, has no arm cavities and needs to use dual recycling from the beginning, while the other interferometric detectors may use it at a later stage to enhance their sensitivity. The control scheme to be used in GEO 600 has been demonstrated at the Garching 30 m prototype. This paper summarizes those results and the adaptions necessary in order to apply the scheme for GEO 600.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

In a laser-interferometric gravitational wave detector, the sensitivity fundamentally depends on two parameters of the system: the amount of light energy stored in the arms and the storage time of the gravitational wave-induced optical signal in the arms. These can be changed by implementing the techniques of *power recycling* and *signal recycling*, respectively. The combination of signal recycling and power recycling is called *dual recycling*.

In all currently operated prototype interferometers and proposed large-scale detectors, the detection system is based on a Michelson interferometer operated in the dark fringe condition. The term 'Michelson interferometer' in this paper is intended to represent the combination of a beamsplitter and suspended mirrors at the end of two long orthogonal arms. The directions north, east, west and south, as shown in figure 1, will be used to identify directions as seen from the beamsplitter.

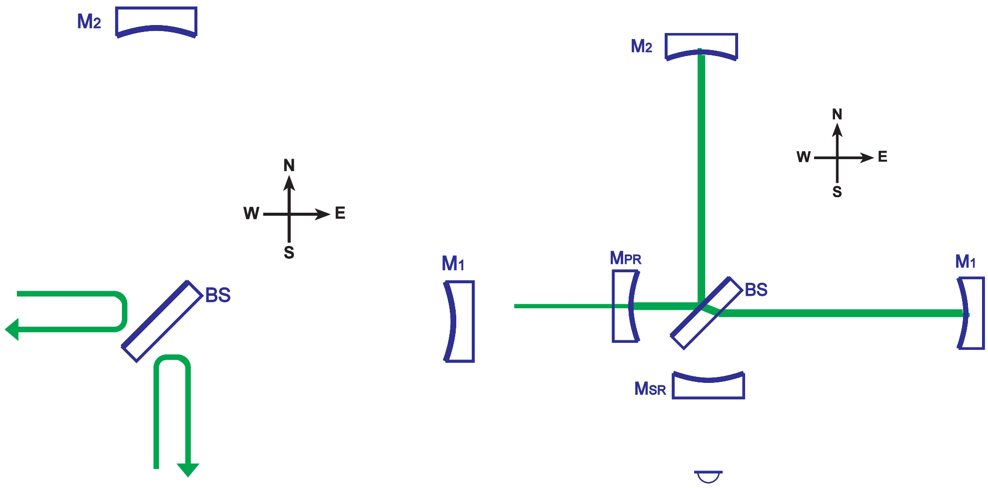

Figure 1. Left image: a Michelson interferometer in the dark fringe condition will essentially look like a mirror from both ports. Right image: power recycling resonantly enhances the light power circulating in the arms.

In the dark fringe condition, all light incident on the beamsplitter will be reflected back to where it came from, as shown in figure 1. This is true for light coming from either the west or the south directions.

If all other parameters remain constant, the shot-noise limited sensitivity of the detector will improve in proportion to the square root of the light power in the arms. All planned detectors will use *power recycling* to increase this power: As seen from the laser, the Michelson in the dark fringe state looks like a highly reflective mirror for the incident light. By placing another mirror, the *power recycling mirror* M_{PR}, between the laser and Michelson, a Fabry–Perot cavity is formed, the *power recycling cavity* (*PR cavity*, see figure 1). This cavity must be kept resonant with the laser light, usually using the Pound–Drever–Hall scheme [1].

The second fundamental parameter influencing the sensitivity of the detector is the interaction time of the gravitational wave with the light.

One way to describe the effect of a gravitational wave is to say that it induces a phase modulation on light travelling in a given direction in the arms (with respect to the propagation of the gravitational wave). The effect is the same as if the index of refraction of the traversed medium were to be modulated. Consequently, modulation sidebands appear on the light, and the light can now be regarded as consisting of a high power carrier with much weaker sidebands imposed by the gravitational wave (see figure 2).

For this simplified discussion, we assume optimal orientation of the Michelson and polarization of the gravitational waves. Due to the quadrupole nature of the gravitational waves, the modulation sidebands are generated with opposite signs in the two arms, and upon their first encounter with the beamsplitter they interfere constructively towards the south port. In the absence of any signal recycling, the modulation sidebands produced by the gravitational wave immediately leave the interferometer (see figure 2).

Their interaction time with the gravitational wave is thus given by the roundtrip travel time in the arms, $2L/c$. For a signal frequency of 1000 Hz, the optimal armlength would be of the order of 100 km—impossible to realize on Earth. In the Michelson without arm cavities, the signal storage time can be increased with a signal recycling mirror (M_{SR} in figure 2). This configuration was chosen for GEO 600 and investigated in the 30 m prototype.

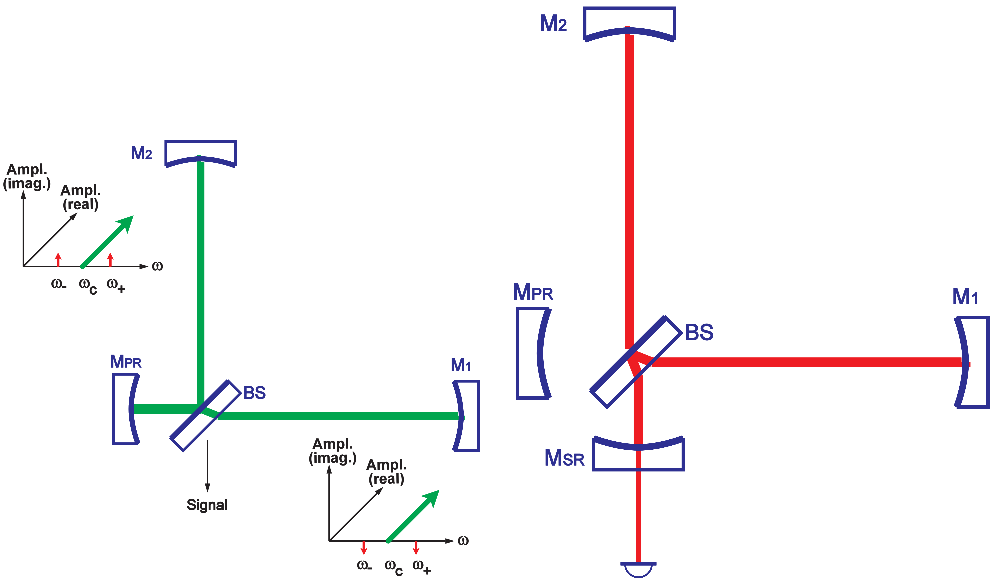

Figure 2. Left image: a gravitational wave produces phase modulation sidebands of opposite sign in the two arms. They are separated from the carrier by the beamsplitter. Right image: the signal sidebands can be resonantly enhanced in the signal recycling cavity, thus increasing the signal storage time.

Signal recycling and dual recycling were first proposed and demonstrated by the Glasgow group around ten years ago [2–4]. Dual recycling in a suspended interferometer with both broadband and detuned operating modes was demonstrated on the Garching 30 m prototype [5–7].

The partially reflecting signal recycling mirror M_{SR} reflects the signal sidebands back into the interferometer. Again, the Michelson looks like a mirror and reflects the signal sidebands back towards M_{SR} after each roundtrip in the arms. A cavity is formed for the signal sidebands, the *signal recycling cavity* (*SR cavity*). Thus the time during which the gravitational wave can coherently interact with its induced signal sidebands can be optimized and the sensitvity thus be enhanced, at the cost of reduced bandwidth.

2. Transfer function of the interferometer with signal recycling

We assume the macroscopic armlength to be fixed by the construction. The finesse of the SR cavity (and hence the signal storage time) can be chosen independently of the carrier storage time, which is determined by the PR cavity finesse. This gives great flexibility in the design of the detector.

There are two possible modes of operation of signal recycling, which we call *broadband* and *detuned*. In 'broadband' mode, the SR cavity is controlled such that the carrier frequency is resonant. This corresponds to a maximum in the frequency response at zero signal frequency. The frequency response behaves like a one-pole low-pass filter with a corner frequency of $\mathrm{FWHM_{SR}}/2$, where $\mathrm{FWHM_{SR}} = cT_{SR}/(4\pi L)$ is the bandwidth of the signal recycling cavity, T_{SR} the power transmission of M_{SR} and L the effective armlength, $L = 1200$ m for GEO 600 with its once-folded arms. All other operating points are called 'detuned' (i.e. the SR cavity is not tuned to the carrier). The frequency response typically has a maximum at some other

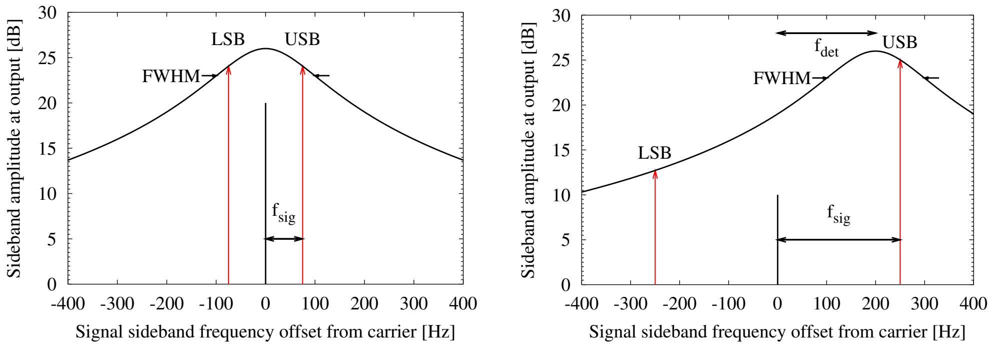

Figure 3. Schematic diagram of the SR cavity resonance for broadband (left) and detuned (right) signal recycling. LSB and USB are the signal sidebands for a gravitational wave of frequency f_{sig}.

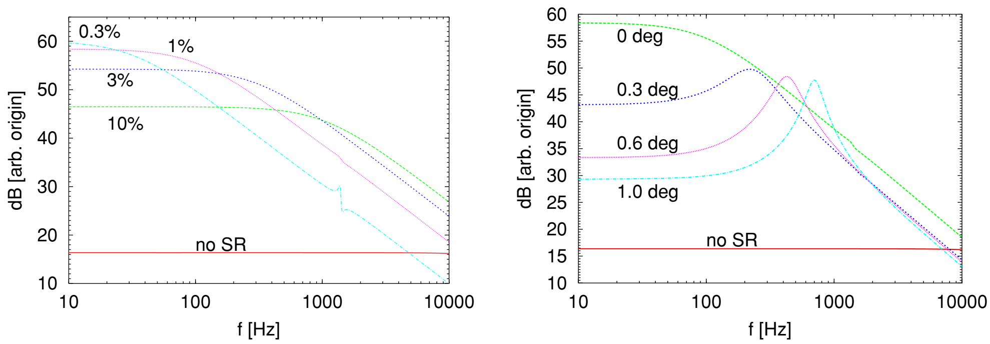

Figure 4. Transfer function of GEO 600 for gravitation wave signals for different power transmissions of the signal recycling mirror in broadband mode (left), and for different tunings with a 1% mirror in detuned mode (right).

signal frequency $\neq 0$. The bandwidth of that sensitivity peak is typically $FWHM_{SR}$. Figure 3 shows the resonance of the SR cavity and the position of the signal sidebands. Figure 4 shows some transfer functions for GEO 600 that can be obtained in the two modes of operation.

3. Control of signal recycling

Of course, all mirrors must be controlled by appropriate servo loops to reach and maintain their desired position. There are three degrees of freedom:

Michelson The Michelson interferometer must be in the dark fringe condition. The relevant degree of freedom is the (microscopic) armlength difference. A differential motion of both end mirrors is used as actuator.

PR cavity The incoming carrier light must be resonant in the PR cavity. The length of the PR cavity is equal to the distance from M_{PR} to the 'average' of the two end mirrors. Possible actuators are M_{PR} and a common mode motion of the two end mirrors. Another possibility to ensure resonance is to change the laser frequency.

SR mirror Finally the microscopic position (tuning) of M_{SR} must be controlled. The control signal is fed directly to M_{SR}.

The control scheme to be used in GEO 600 has been demonstrated on the Garching 30 m prototype [5–7]. It consists of the following elements:

PR lock. The loop to lock the PR cavity and the frequency of the incoming laser light to each other is designed to have a very high bandwidth and a huge gain margin, such that it can remain in lock during a wide variety of conditions of the Michelson interferometer. In the prototype, it remained locked for essentially all conditions, i.e. large deviation from the dark fringe and arbitrary position of M_{SR}. By doing so we reduce the effective number of degrees of freedom to two.

Schnupp modulation. The error signals for the two remaining degrees of freedom are obtained by employing a Schnupp modulation, i.e. a phase modulation of the incoming beam in combination with a small armlength difference of the Michelson. The armlength difference causes a fraction of the modulation sidebands to cross-couple between PR and SR cavities every time they pass the beamsplitter, such that the sidebands resonate in the whole interferometer. Generally, PR and SR cavities will have slightly different lengths and the system hence behaves like coupled resonators and has a complicated resonance structure.

Because of this complicated resonance structure, error signals cannot be accurately predicted by simple intuitive models. Hence a program has been developed in our group to compute error signals (among other things) numerically for arbitrary interferometers and modulations [8]. Using this program we can find useful sets of parameters for the locking of GEO 600. The models have been successfully verified by comparing their predictions to the experimental results of the 30 m prototype.

Michelson lock. The error signal for the Michelson (i.e. the differential armlength of the two long arms) can be obtained at the south port by coherent demodulation at the Schnupp modulation frequency in a standard fashion. Any deviation of the Michelson condition from the dark fringe will cause some carrier light to arrive at the south port, where it beats with the Schnupp modulation sidebands. The parameters to be optimized are the armlength difference and the modulation frequency to ensure a sufficient coupling of the sidebands to the south port. In detuned operation, this coupling slightly changes such that the modulation frequency needs to be adjusted by a tiny amount (some tens of Hz). Demodulation will take place with both quadratures of the Schnupp modulation frequency anyway, because the gravitational wave signal is contained in this signal and no loss of signal-to-noise ratio is tolerable here. The optimal phase for obtaining the error signal will also slightly depend on the detuning frequency in detuned mode.

Error signal for the signal recycling mirror. The error signal for the signal recycling mirror M_{SR} can also be obtained by Schnupp modulation. While in the Garching 30 m prototype the same frequency was used as for the Michelson, for GEO 600 we use two different frequencies for more flexibility in the parameter optimization. Since the Schnupp modulation sidebands are present everywhere in the interferometer, they also hit M_{SR}, and their phase everywhere in the interferometer is affected by the position of M_{SR}. In the south port, however, there is no carrier present in the nominal dark fringe operating point, and hence the phase shift cannot be detected there. Everywhere else in the interferometer, however, there is carrier present and a beat signal can be obtained. We use a fraction from the light circulating in the east arm which is sampled by a stray reflection at the beamsplitter.

Lock acquisition. Our experience in the Garching 30 m prototype has shown that the dual-recycled interferometer falls in lock by itself, if all cavities are properly aligned and all gains, phases, etc are set to their correct values. The system which has effectively

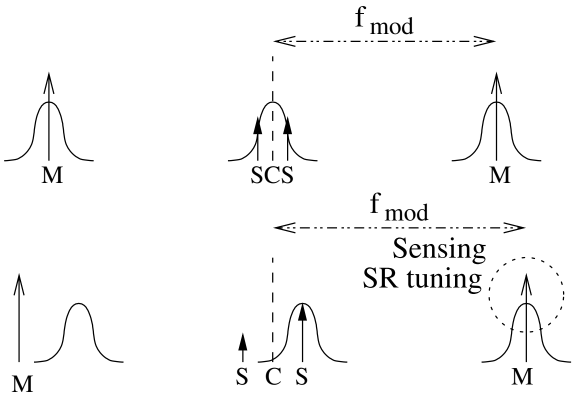

Figure 5. Schematic diagram of the SR cavity resonances for broadband (top) and detuned (bottom) signal recycling. *C* is the carrier frequency, *S* are the signal sidebands and *M* the Schnupp modulation sidebands.

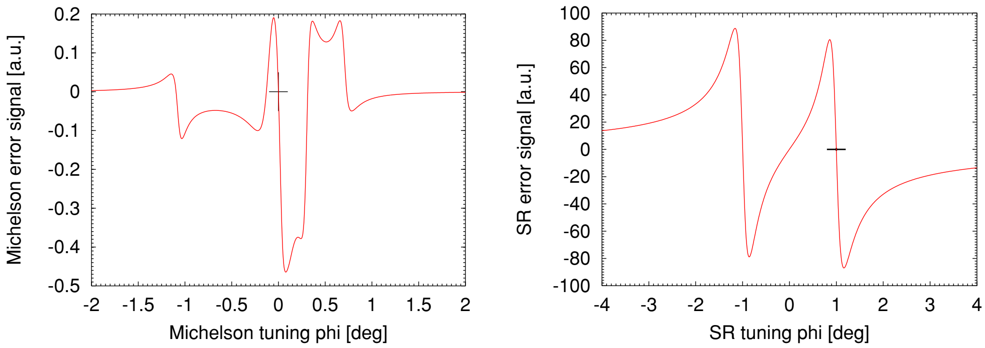

Figure 6. Computed error signals for the Michelson (left) and SR mirror (right) for a detuned operating point ($T_{SR} = 1\%$, detuning 1°, $f_{det} = 690$ Hz).

two degrees of freedom swings through this two-dimensional parameter space, eventually approaches its operating point, enters into a converging nonlinear oscillation for a fraction of a second and falls into lock. All this usually happens in less than one minute.

Detuned operation. The error signal for M_{SR} in the detuned operating point is obtained in the same way as for the broadband case. By shifting the Schnupp modulation frequency by an amount close to the desired detuning frequency, the resonance of the SR cavity is probed (see figure 5). In order to move from broadband operation to detuned operation, that frequency is slowly changed, together with incremental adjustments of demodulation phases and loop gains. In that way it is possible to reach any desired detuned operating point starting from the broadband mode without losing lock. Once the system has been calibrated, it is even possible to sweep the sensitivity maximum during operation, e.g. in order to track a coalescing binary. Once the frequencies and phases have been set for the detuned mode, the system re-acquires lock as easily as in the broadband mode. This has been demonstrated at the Garching 30 m prototype. In GEO 600 cavity finesses will be higher and lock acquisition might be more difficult. On the other hand we have the additional flexibility of having two different modulation frequencies for the Michelson and M_{SR} which will make operation easier than in the prototype. Figure 6 shows the computed error signals for both degrees of freedom for the detuned case. The Schnupp modulation frequencies for the Michelson and M_{SR} were shifted by 60 Hz and −520 Hz, respectively, in order to achieve a sensitivity maximum at $f_{det} = 690$ Hz. Fine-tuning of the sensitivity maximum is possible with adjustments of the demodulation phase for the M_{SR} error signal.

4. Conclusion

Based on our experiments on the 30 m prototype and numerical simulations we are confident of having a practical scheme to lock GEO 600 in both broadband and detuned modes of operation, and to be able to switch between these modes during operation without losing lock.

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