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# Proposal for a table-top prototype resonant sideband extraction interferometer (A graduate thesis proposal)

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# 1 INTRODUCTION

LIGO will commence gravitational wave research with an initial set of interferometers, following achievement of design sensitivity at the end of the year 2001. The designs of these interferometers rely upon results of a research and development program carried out during the early phases of the LIGO Project. It is a basic program assumption that detector advances will be required to reach the ultimate sensitivity for which the LIGO facility has been constructed.

The program of advanced detector research and development will consist of two major thrusts. Research leading to *advanced subsystems to enhance* the initial interferometers will be carried out by addressing each of the major mechanisms limiting the initial design sensitivity. Reaching beyond the research on initial detector subsystem improvements, the second thrust will explore other more ambitious topics intended to define the designs of completely new *advanced detectors* to replace the initial LIGO instrumentation.

The initial interferometer optical configuration, a power recycled Fabry-Perot/Michelson interferometer has been under development in the LIGO project for many years. It is a good compromise for the initial detector since it is one of the simplest configurations that can provide astrophysically interesting sensitivity and has an extensive heritage in smaller test interferometers. This configuration provides good broad band sensitivity with current technology and it can readily be adapted as technology improves. Nonetheless, future technological or scientific developments may favor other interferometer configurations. Anticipating this need, we propose an experimental program to investigate one of these configurations, resonant sideband extraction.

# 2 RESONANT SIDEBAND EXTRACTION

Signal recycling (SR) and resonant sideband extraction (RSE) are considered to be two of the more promising optical configurations for the enhanced LIGO. Both configurations could provide better practical shot noise limited sensitivity than the standard power recycling, depending on practical considerations of loss distribution. Moreover they can be operated both in broad band and narrow band mode; the switch between the two modes can be done without interruption of operation.

Resonant sideband extraction, originally proposed by Mizuno[1], employs the optical layout shown in Figure 1. It is the same as a power recycled Fabry-Perot/Michelson interferometer with an additional mirror placed at the anti-symmetric port of the interferometer. In a standard power recycled interferometer, the position of the beamsplitter is set up such that the carrier returning to the beamsplitter from the arms is directed back to the laser, whereas light that has been modulated differentially in the arms by a signal is directed to the anti-symmetric port of the beamsplitter. The purpose of the power recycling mirror is to then redirect the light heading toward the laser back into the interferometer. It is noted that the carrier spends a much longer time in the interferometer than the signal, because it’s been recycled. The storage time of the carrier is defined by both the arm cavities and the power recycled cavity, whereas the signal is only affected by the arm cavity.

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[1] J. Mizuno et al., Phys. Lett. **A175** (1993) p.273; J. Mizuno, Max-Planck Institut for Quantenoptik, Technical report **203** July 1995

The storage time for the signal in the arms is set such that it defines a bandwidth useful for signal detection, and the storage time of the carrier is set such that it is limited purely by losses in the interferometer, by choosing the appropriate optical parameters. RSE uses high finesse Fabry-Perot cavities in the arms, which have longer storage times than that of a power recycled interferometer. The signal extraction mirror is used to create a cavity that is resonant at the carrier frequency (in broadband operation), or at a signal frequency (in narrow-band operation) with the input coupling mirrors of the arm Fabry-Perots[1]. This signal extraction cavity is equivalent to a "compound mirror" to signals which have been differentially produced in the arm cavities. This compound mirror's reflectivity is a function of the mirrors comprising the cavity and the round trip phase of the cavity. For signals which are resonant with this signal extraction cavity, this compound mirror has a lower reflectivity than the physical input coupling mirror. This lower reflectivity lowers the storage time and broadens the bandwidth of the detector for differentially induced signals. The carrier, on the other hand, is not affected by this signal extraction cavity, and so retains the same high storage times in the arms[2]. One significant advantage of this scheme is that the amount of light power at the beamsplitter is much smaller compared with standard power recycling; thus the beamsplitter has much less thermal distortion. RSE can be also operated in a narrow band mode by changing the position of the signal extraction mirror by a fraction of a wavelength. This tunes the signal extraction cavity to be resonant with one of the signal sidebands on either side of the carrier frequency. This increases the sensitivity of the detector at that frequency while decreasing it outside the bandwidth set by the parameters of the coupled cavity.

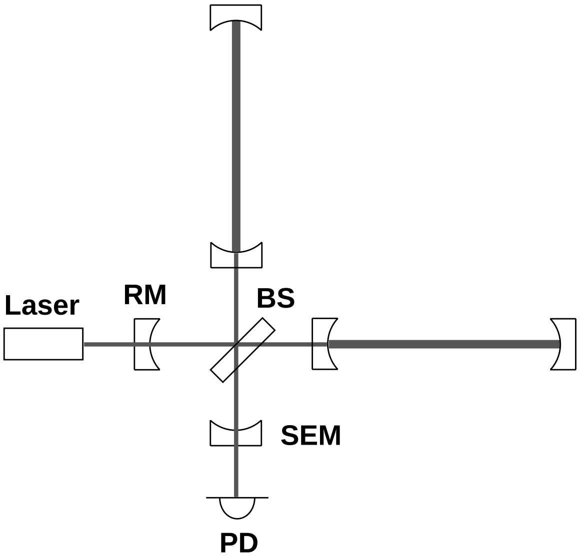

Figure 1: Optical configuration of signal recycling and resonant sideband extraction; PD: photodetector, BS: beamsplitter, RM: power recycling mirror, SEM: signal extraction mirror.

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[1] "Input coupling mirrors" or "input couplers" refer to the first mirrors of the Fabry-Perot cavities in the light path after the beamsplitter.

[2] It should be noted that this scheme could allow a design of arm cavities such that the storage time for the carrier is loss limited, and hence power recycling is not needed. It's not clear at this time whether this is a desirable design for LIGO.

# 3 OBJECTIVES

Both SR and RSE have been implemented in table top experiments[1], and their response to the signal was verified to agree with the model. It is not clear, however, which method will offer the best sensitivity in practice and is most amenable to adaptation in an advanced LIGO, since the methods used to demonstrate the principles in the table top experiments were not methods that will be used in LIGO. For example, LIGO has adopted a method known as Schnupp asymmetry modulation to introduce the local oscillators used for signal extraction, but both table top prototypes used External modulation. The simplicity of Schnupp modulation makes it a much more favorable scheme than External modulation, since External modulation requires the optics and controls of a second interferometer. We propose to do a table top implementation of RSE, while the collaboration at the University of Florida does an SR prototype, in order to do a more detailed comparison. This proposal for a table top implementation of RSE has the following objectives:

- Analytical and numerical models with which to design the control systems and investigate and optimize the cross couplings between the d.o.f.'s[2] (degrees of freedom) of the system. The cross coupling has a form in a "matrix of discriminants" shown below, where the $v_j$ 's are the signals accessible at the signal extraction points, and the $\phi_i$ 's are the d.o.f.'s. Ideally, this matrix would be diagonal, such that each signal extraction point was sensitive to one and only one degree of freedom. However, a real interferometer has cross couplings of all d.o.f.'s at all signal extraction points, the level of which decides how the control systems are designed and the signal extraction points chosen, and possibly to how parameters are chosen.

  $$M_{ij} = \frac{\partial}{\partial \phi_j} v_i(\phi_1, \phi_2, \phi_3, \phi_4, \phi_5)$$

- A tabletop prototype will be used to investigate possible control schemes and d.o.f., or signal extraction points (not to be confused with the signal extraction mirror), which is necessary for implementation into a long baseline LIGO interferometer, since the signal extraction schemes used in the previous table top experiments were not extensible to a LIGO gravitational wave detector (i.e. external rather than Schnupp modulation was used).
- RSE allows for "narrow-banding", or "detuning" about a frequency of interest. This frequency tuning is done by controlling the position of the signal extraction mirror. The ease of control and tunability of the signal extraction mirror will be investigated. Also the effect of detuning on the bandwidth of the detector will be analyzed and optimized.
- The issue of lock acquisition will be investigated. Questions regarding locking sequences[3], sign flips, and gain changes in servos when various d.o.f.'s acquire lock will be answered by using a time domain model to predict the behavior of the interferometer. Model validation will be done by comparison with experiment, and the resulting model and characterization of the

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[1] K. A. Strain et al., Phys. Rev. Lett. **66** (1991) p.1391; G. Heinzel et al., Phys. Lett. **A217** (1996) P.305

[2] The degrees of freedom of the RSE system are the round trip phases of the 4 coupled cavities of the interferometer plus the frequency of the laser light which defines the round trip phases, or linear combinations thereof.

[3] "Locking sequence" refers to the time order in which the degrees of freedom are able to acquire lock, resulting in a final acquisition of lock in all degrees of freedom.

behavior of the device will be useful in the design of a LIGO scale interferometer.

# 4 WORK PLAN

We propose the following working plan to implement RSE.

## 4.1. Optical parameters and configuration

### 4.1.1. Mathematics and modeling

A reasonable set of parameters, such as mirror reflectivities and cavity lengths will be determined first. This involves analytical calculation and modeling, with a view to developing general formulas applicable to a LIGO design. Other specifications, such as allowable rms phase fluctuations of the various degrees of freedom will also be worked out in order to properly design the control system. Another subtle point will be to determine the usefulness of power recycling, since in RSE, it's possible to design an interferometer with arm cavities whose finesse is loss-limited, and hence there would be no power returning to the laser to be recycled.

### 4.1.2. Control system configuration

A reasonable control system configuration will be determined. In order to do that, models will be built which can be used to investigate and optimize points of signal extraction and their sensitivity to the various degrees of freedom in the system. RSE is a 5 degree of freedom system which is linear on resonance, so a linear systems control strategy can be used. Optimization of the transfer functions for each degree of freedom will be done.

## 4.2. Table top implementation

### 4.2.1. Purchasing and lab setup

The first step towards actual implementation of the prototype will be acquiring the necessary equipment and supplies for the new lab space in 38 Lauritsen. Some supplies, such as the laser, optical table, and much of the diagnostic equipment will need to be purchased up front in order to begin work. Some of these items have long lead times and will need to be ordered as soon as possible. Questions regarding whether to implement the electronics in VME or NIM need to be answered before electronics supplies can be purchased. Optics and other supplies will be ordered as necessary.

### 4.2.2. Mirror mount fabrication

Dynamic range, sensitivity, and frequency response requirements for control of the positions of the mirrors requires that the mirror mounts be built in-house. Two designs for mirror mounts that have been used in table tops are readily available for use, namely the mirror mounts used in Martin Regehr's table top power recycled interferometer, and the mirror mounts in the FMI at MIT. These designs will be investigated to determine which is most desirable for this experiment.

### 4.2.3. Control system design and fabrication

Electronic control systems will be designed and built as a result of the modeling and calculations. Factors influencing the design of the controls systems are the allowable rms fluctuations in the d.o.f. being controlled, the free-running noise of the laser, the levels of seismic and acoustic noise, and characteristics of the physical components (transfer functions of the mirror mounts, etc.). Consultation with CDS will be carried out to determine the most useful format of the electronics, i.e. NIM vs. VME.

## 4.3. Locking

The process of acquiring lock in the interferometer will evolve with the layout of optical components. Lock will be acquired in the interferometer subsystems as these subsystems are physically laid out on the table (i.e., lock will be acquired in a simple Michelson before Fabry-Perot cavities are put in its arms, etc.). This will allow careful characterization and optimization of the subsystems of the interferometer as they are built. Questions regarding cavity response, mirror mount frequency response and characterization, sensitivity to external disturbances, and general troubleshooting will be accomplished in this phase. The goal, of course, is to demonstrate robust lock simultaneously in all five d.o.f. of the system.

## 4.4. Analysis and Characterization

### 4.4.1. Transfer functions and cross coupling

Transfer functions of system response (voltages) to fluctuations in the d.o.f.'s will be measured in order to validate the numerical model used to design the control systems. Related to this are the cross coupling of the degrees of freedom, or the “matrix of discriminants” mentioned earlier. Essentially these are the DC values of the transfer functions being measured.

### 4.4.2. Lock acquisition

Locking characteristics will be investigated. Specifically, locking sequences will be analyzed and compared with a time domain model to both predict and verify. We will also analyze the gain changes and sign flipping during the transient responses of the interferometer while attempting to acquire lock. Large time scale differences between a table top and a full LIGO sized interferometer may not allow for a direct extrapolation from the prototype behavior, but a verified model and characterization of transient behavior in a table top will aid in the design of a full sized interferometer.

### 4.4.3. Narrow-banding

Control of the signal extraction mirror allows tunability of the signal extraction cavity from broadband to a narrow band improved sensitivity at variable frequency. The ability and ease of the control of this mirror needs also to be characterized. Again, issues regarding lock acquisition and transfer functions while operating in narrow band mode will be analyzed.

## 4.5. Documentation

Documentation of the results of this experiment will be done. It is expected that this will mostly be in the form of a graduate thesis.

# 5 SCHEDULE

| TASK | | 1997 | | | | | | | | | | 1998 | | 1999 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | M | A | M | J | J | A | S | O | N | D | Jan. - June | July - Dec. | Jan.- June |
| Optical parameters and configuration | Math & Modeling | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | |
| | Control system configuration | | | ■ | ■ | ■ | | | | | | | | |
| Table-top implementation | Purchasing and lab setup | | ■ | ■ | ■ | ■ | ■ | | | | | | | |
| | Mirror mount fabrication | | | | ■ | ■ | ■ | | | | | | | |
| | Control system design and fab | | | | | | ■ | ■ | ■ | ■ | ■ | | | |
| Locking | | | | | | | | | ■ | ■ | ■ | ■ | | |
| Characterization and Analysis | | | | | | | | | | | | ■ | ■ | |
| Documentation | | | | | | | | | | | | | | ■ |

Table 1: 1997 / 1998 RSE work schedule

# 6 MANPOWER

We propose that the experiment is conducted using 100% of J. Mason’s time, who will do the bulk of the work and research with the goal of a Ph.D. thesis. S. Kawamura (research advisor to JM) shall spend 20% of his time on the project assisting. R. Vogt will act as faculty supervisor to J. Mason. It is expected that some time will be requested from CDS for consultation purposes.

# 7 BUDGET

| ITEMS | AMOUNT | Source |
|---|---:|:---:|
| **Optical table and supplies** | | |
| Optical table and legs | 20,000 | Quote |
| Compressor for pneumatic legs | 1,000 | Catalog |
| Table cover and clean air blower | 1,000 | Estimate |
| **Laser (Lightwave 126-1064-100)**[a] | 21,000 | Catalog |
| **Diagnostic and gen'l electronics** | | |
| Spectrum analyzer (HP 3563A) | 19,000 | Catalog |
| Digital storage oscilloscope | 5,000 | Catalog |
| Analog scopes (2) | 6,000 | Catalog |
| SR560 pre-amps (4) | 8,000 | Catalog |
| Ithaco bandpass filter | 2,000 | Catalog |
| Power supplies (2) | 1,000 | Catalog |
| Function generator | 1,000 | Catalog |
| BNC cables, connectors, etc. | 2,000 | Estimate |
| **Miscellaneous (Tools, bolts, etc.)** | 2,000 | Estimate |
| **Optical supplies (hardware)** | | |
| Mirror mounts (10) (manufactured) | 10,000 | Estimate |
| General supplies (lens holders, etc.) | 3,000 | Estimate |
| **Optics (mirrors and lenses)** | 30,000 | Estimate |
| **Optical electronics** | | |
| Pockels cells (2) | 8,000 | Catalog |
| Faraday isolator | 3,000 | Catalog |
| Photodiodes (manufactured) | 3,000 | Estimate |
| Acousto-optic modulator and driver | 2,000 | Catalog |

Table 2: Proposed budget for RSE table top prototype

**Spending profile**

Start-up supplies
(April through
June '97)
89,000

June '97
through
December '97
71,000
,000

| | | |
|---|---|---|
| **Electronics** | 5,000 | Estimate |
| **Computer** | 7,000 | Catalog |
| **Contingency** | 15,000 | Estimate |
| **TOTAL** | 175,000 | |

Table 2: Proposed budget for RSE table top prototype

a. For this particular experiment, a 100 mW IR laser would be sufficient. However, it might be desirable to purchase the higher power 700 mW laser for use in future experiments, for an additional $15,000.

J. Mason's graduate research assitantship will need to be maintained. S. Kawamura's salary commensurate with the 20% of his time to be spent on this project should also be factored in.