Detection of Gravitational Waves: Advanced Research and Development for LIGO

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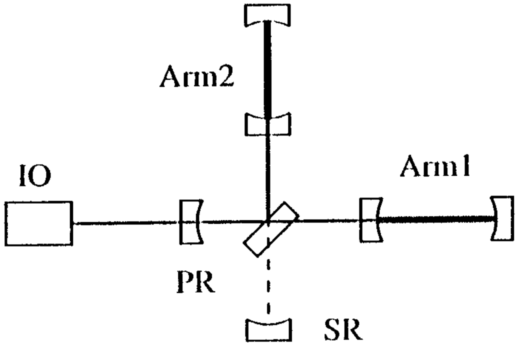
LIGO-G990143-00-Z

Suspended, signal-recycled interferometer

- Signal recycling: planned upgrade of LIGO
  - SR mirror placed in dark port, between beamsplitter and photodetector, adding another resonant length to the detector



  - May either decrease (dual recycling) or increase (resonant sideband extraction) detector bandwidth
- DR and RSE improve stability against thermal distortions
- RSE has lower power at the beamsplitter, desirable if thermal instabilities affect detector performance.
- Upgrade will probably occur in the form of RSE, though details will be settled only after it has been demonstrated (tabletop experiments) that a robust locking scheme exists and satisfactory lock acquisition can be expected

Signal Recycling Experiments

- 10-m, suspended, in vacuum, signal and power-recycled, Fabry-Perot Michelson testbed, jointly with Glasgow University. Realistic tests of:
  - Locking method
  - Readout scheme
  - Modulation method
  - Alignment control
  - Evaluation of optical distortion (e.g., thermal lensing) tolerance
  - Sensitivity to coupling of laser and other noise to the detector
- Personnel: David Tanner, David Reitze, graduate student and two postdoctoral students (the latter resident at Glasgow during the critical two-year period of this research)

SR tasks:

1. Optical parameters (mirror reflectivities, optical cavity parameters, cavity lengths, modulation methods, readout scheme, installation in the LIGO vacuum envelope, etc)
2. Control system (length and alignment) and lock acquisition.
   - Complexity of these issues requires a testbed configured as close as practical to LIGO II
   - Testbed uses GEO-type triple-pendulum suspensions, similar to LIGO II suspensions
3. Noise studies. The suspended, in-vacuum IFO provides quiet system for measuring noise performance
4. Evaluation of optical distortions
   - 10 W Nd:YAG laser will be part of the Glasgow facility.
   - Issue: is signal-recycled/power-recycled interferometer less susceptible to optical defects than a power-recycled instrument, such as the original LIGO?

Input optics for LIGO II

- Critical components of any advanced gravitational wave detector
  - Faraday isolators, electro-optic modulators (EOMs), a mode cleane and beam-expanding telescopes
  - Must handle 180 W of continuous power, (20 × LIGO I)
- Personnel: David Reitze, David Tanner, two half-time research scientists, one postdoc, and one graduate student. Work will be performed jointly with the LIGO Laboratory (both research scientists based at the Livingston site).
- Studies involving 160 W or higher-power lasers will be performed jointly with Stanford University, through collaboration with E. Gustafs and R. Byer.

Faraday isolators

- Isolate the mode cleaner and laser from back-reflected light
- deliver signal to instrument control systems

Issues: thermal lensing and isolation ratio

With TGG and 100 W, only 40% of the light in the TEM_{00} mode

1. Focus error: Measure thermal distortions using a Shack-Hartmann wavefront sensor.
2. Suitability of polishing a negative radius of curvature on the crystal
3. Automatic temperature control with a heating beam and a wavefront sensor, much as in the core optics compensation
4. Depolarization effects compensated by using two Faraday rotators with a waveplate between them.

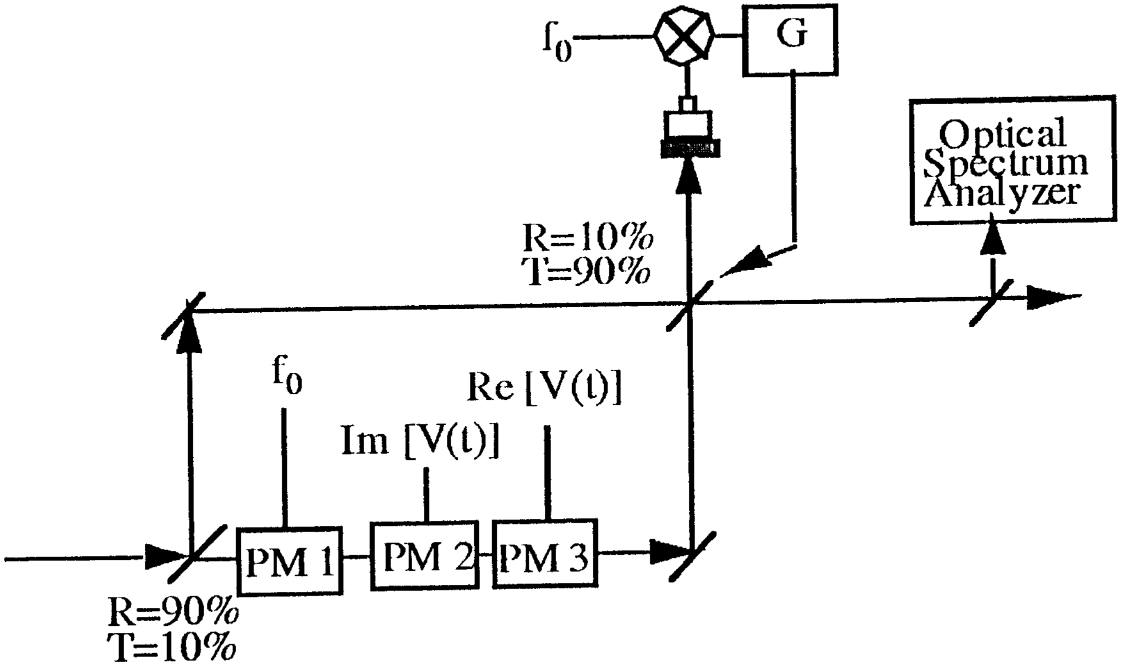
Electro-optic modulators

- EOMs fail at $I \sim 80$ kW/cm^2.
- Need large crystals ($\sim$ cm) and these need to be evaluated.

1. Thermal lensing: At 100 W, each EOM has a 1-m thermal lens.
    - Also redistribution of TEM$_{00}$ power into higher order cylindrical modes
    - Measure wavefront distortion (Shack-Hartmann detector) to assess modal degradation
2. Amplitude fluctuations from second harmonic generation (SHG) and RF amplitude modulation
    - must be reduced to meet intensity noise requirements of LIGO II.
    - Characterize SHG fluctuations directly in LiNbO$_3$.
    - Determine the amplitude modulation

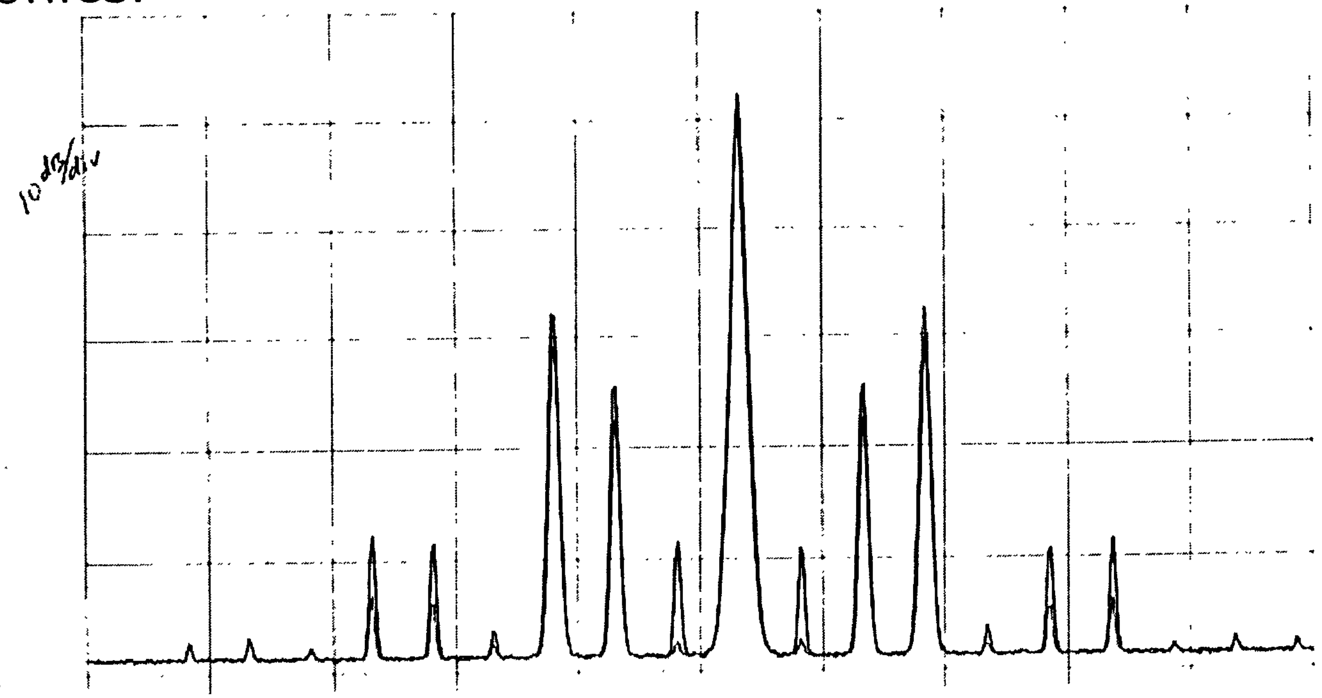
Alternative modulation schemes

- Modulate ∼ 10% of the laser light, using Mach-Zehnder interferometer with modulation placed in one arm.



- Combine in phase at the second beam splitter.
- We have previously developed a benchtop Mach-Zehnder using an NPRO YAG laser locked to a reference cavity. Results were encouraging.

- Phase modulation in the Mach-Zehnder: only $\sim 10\%$ of the power travels through the EOM
  - Requires modulation indices of $\Gamma > 5$
  - most of the power in higher order harmonics
  - Remove unwanted harmonics by combining both phase and amplitude modulation with a judicious choice of modulation signals.
  - With "complex modulation," we can synthesize any desired frequency spectrum and, in particular, eliminate the higher order harmonics.



Blue: phase modulation at two frequencies. Red: Phase and amplitude modulation. (Qi-ze Shu, 1998)

Mode cleaner

Noise sources in LIGO II mode cleaner:

- Thermal noise → frequency noise: larger mirrors
- Shot noise → frequency noise: higher MC lock modulation, 4–5×
- PSL amplitude fluctuations → frequency noise: Larger test masses and improved PSL intensity stabilization

Advanced mode matching diagnostics

- "Bullseye" mode matching diagnostic
- Extend method to the power-recycling cavity
- Includes detailed modeling

LIGO data analysis

- LSC White Paper—plan of work on
  - detector characterization
  - development of detection algorithms
  - provision of reduced data sets
- Personnel: S. Klimenko, G. Mitselmakher, B. Whiting, Bob Coldwell and one or two graduate students
- The UF group commitments (assigned by LSC):
  Wavelet Analysis Tool for:
  - transient signal characterization
  - unmodeled GW sources detection
  - data compression/reduction
  - will be part of LIGO/LSC Algorithm Library (LLAL)

Detector simulations

- As providers of the input optics system, the UF group has an essential duty in providing *and maintaining* IO e2e model.
  - first version of IO simulation module completed
  - modifications and upgrades of the IO modules
  - comparison of the IO simulation with data
  - detector noise simulation with e2e model

Wavelet transformations

- Successfully used in image and signal processing
- Many wavelets and methods available
- Very promising technique for LIGO data analysis
- UF has been assigned the task of developing wavelet data analyses tools by the data analysis working group of the LSC

Why wavelets?

- Basis functions local in time and frequency domains
- Sort and reconstruct transients
- Detect arbitrary pulses
- Whiten, de-noise, compress data

Plans

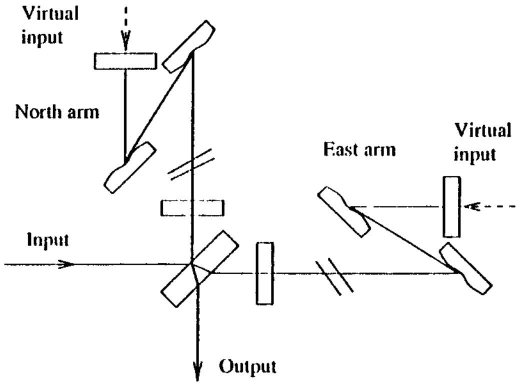
- 2000–01 — initial Wavelet Analysis Tool
  - Implement lifted wavelets in LLAL (Fast WT)
  - Include commonly used wavelets (Std. WT)
- 2001–03
  - Develop wavelets specifically for LIGO
  - Use wavelets to analyze LIGO data

Noise characterization

1. Algorithmically identify "good" data (in progress for 40-m data)
2. Catalog and quantify amplitude distribution at each frequency
   - Use likelihood and chi-squared tests for Gaussian distribution ("noise" evaluation)
   - Fisher f test on variance (power) controls freq.-averaging domains
3. Investigate line-removal techniques
   - 60-Hz (and harmonics)
     - Quantify long-term phase coherence at each harmonic (up to 80th in 40-m data)
     - Evaluate correlations between frequencies
   - "Violin" wire resonances
     - Test for "whiteness" at nearby freqs. before/after removal
     - Develop excitation model for amplitude of (non-decaying) lines
     - Quantify correlations with low-frequency spectrum (viewed as effective "source" for mode excitations).
     - Evaluate tracking (non-linear) Kahlman filtering
4. Apply statistical tools to data analysis

New technologies for LIGO III

- We propose to study, model, and (if modeling works out) test on a tabletop novel configurations for LIGO III.
- For example, a carefully designed cavity including two gratings in a compressor configuration is in principle a "white light cavity," allowing build-up of signal sidebands over a wide frequency range.



Two different configurations in detail:

1. A "LIGO I extension" in which the arm cavities are "white" and no power recycling and no signal recycling is used
2. A "GEO extension" in which the signal-recycling cavity is "white" and no arm cavities are used

- Personnel: Guido Mueller, David Reitze, David Tanner, and possibly a graduate student