Stanford
Gravitational Wave
Program

LIGO

Advanced Interferometer Considerations

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ABSTRACT

The first generation LIGO-I interferometer illuminated by a 10W solid state laser source operates in static thermally stable regime. The proposed LIGO II interferometer, with a 170W laser and some crystalline optics operates at the edge of stability and may require active control to suppress dynamic instabilities.

An advanced interferometer of the Fabry-Perot Michelson topography will require cooled crystalline optics and active wavefront control to suppress dynamic instabilities inherent in coupled Fabry-Perot interferometers with thermally modulated coupling.

The proposed Polarization-Sagnac interferometer with 50 bounce delay lines can operate in the static stability limit using crystal silicon optics. The common path Polarization-Sagnac interferometer requires 4.4kW of frequency doubled laser power to reach $h = 2.0 \times 10^{-24}$.

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Future Prospects

Introduction

System Design Considerations

Select an architecture that allows scaling in sensitivity.
Avoid an architecture that leads to instabilities

Crystal optics
- High acoustic Q
- Excellent thermo-optic properties
- Cryogenic cooling advantageous

Laser Source
- Laser Diode Pumped Solid State Laser
- Master Oscillator Power Amplifier
  - Power scaling
  - Coherence control
  - Soft failure mode
  - Repair while operate
- Harmonic conversion to 532nm possible

Suspension, Isolation and Control
- Active system at first stage
  - Allows alignment
  - Provides reduction in ground noise
- Pendulum system as follow-on stages
  - Heritage in development
  - Allows cryogenic cooling

Leveraging on commercial progress in laser and crystals

Select key components with commercial push & ride the wave of commercial development

Silicon Crystals
- increased diameter
- reduced defects

Laser Diode Pumped Solid State Lasers
- high average power
- high reliability
- harmonic conversion

Introduction

Advanced Interferometer considerations

QUESTION: **What do a 4.4kW laser and a 170Wlaser have in common?**

ANSWER: $h = 2.0 \times 10^{-24}$

EXAMPLE

	sensitivity (at 180Hz)	Power recycling	Finesse (FP cav)	Laser Power
LIGO I		*Fabry-Perot Michelson*		
	2.5×10^{-22}	x 30	200	10W
LIGO II		*Fabry-Perot Michelson*		
	2.0×10^{-24}	x 90	200	170W
Advanced LIGO		*Delay-Line Polarization Sagnac*		
	2.0×10^{-24}	none	N = 50 (delay line)	4.4kW (532nm)

BOTTOM LINE: **LIGO II** requires the development of crystalline test masses that have low absorption loss, low scatter loss and high optical quality in transmission.

ADVANCED LIGO requires the development of a 5kW laser but can utilize the best crystal available for the test mass:

SILICON.

The System Design Approach

The Stanford Program

RESEARCH ELEMENTS

Advanced Interferometers

Laser Sources for LIGO

Suspensions, Isolation and Control

MATERIALS MATERIALS MATERIALS

The LIGO I receiver was developed over the past decade in an era of low power (~5Watts) laser sources. It is an excellent first generation design.

The LIGO II receiver will require substantially more laser power (~170Watts) and may reach the thermally induced stability limits.

The Advanced LIGO receiver will require high power lasers (>1000 Watts) that will require substantial changes in the interferometer architecture if thermally induced instabilities are to be avoided.

The System Design Approach

The Stanford Program

Technological Innovations

Precision Interferometry

- **Photon limited designs**
  - Michelson-Fabry Perot
  - Recycling
- **Thermally limited designs**
- **The polarization Sagnac Interferometer**
  - Response and Sensitivity
  - Delay Line Configuration
- **Signal Extraction**
  - Polarization generated local oscillator
  - Low frequency signal extraction
- **Future Design Considerations**
  - All reflective interferometer
  - Crystalline optics and test masses

Lasers and Optics

- **Precision laser oscillators**
  - The nonplanar ring oscillator
  - Injection locked power oscillators
- **Power scaling with coherence**
- **The master oscillator power amplifier**
  - Pre-mode cleaner
  - The Precision Stabilized Laser
- **Advanced Amplifier Module**
  - 125 W edge – pumped slab laser
  - Active mirror control

Suspension, Isolation and Control

- **Actively stabilized strut base**
  - Factor of 30 isolation by feed-back/feed-forward control
  - Direct control of offset alignment
- **Control reallocation**
  - Double to triple pendulum suspension
- **Silicate bonded suspension**
  - Crystalline test masses
  - Ribbon suspension
  - Crycooling

The Stanford program has been guided by a **system design approach** to an advanced interferometer. All elements of research to date are congruent with this long-range goal.

The System Design Approach

Interferometer Design Choices

Fabry-Perot Michelson	**Polarization - Sagnac**
Low laser power	**High laser power**
Recycle laser pump power	**Single pass laser pump**
Fabry-Perot storage	**Delay-Line storage**
Resonant Cavities	**Non-resonant cavities**
Transmissive Optics	All reflective Optics
Fused silica Optics	Crystalline Optics
Room Temperature	Cryogenic Temperature
Low incident laser power (~ 170 Watts)	Very high incident laser power (~ 4 kW)

Design Trade-offs

Not common path	**Common Path**
Single frequency laser	Broad band laser
Amplitude stable laser	wide amplitude noise
Precise length control (~ λ/1000)	no length control
De-polarization sensitive	**De-polarization sensitive**
Tilt alignment sensitive	**Tilt alignment sensitive**

The Polarization-Sagnac Interferometer allows longitudinal motion of the test masses thus making tilt and alignment control easier.

The Polarization-Sagnac Interferometer allows broad band laser input thus making power scaling and scattered light control possible.

The System Design Approach

WHY CRYSTAL OPTICS?

Glass optics	Crystal Optics
Optical Properties	
optical quality (in transmission)	
(1/10 wave per 30cm)	**(1/4 wave per 3cm)**
optical quality (in absorption)	
(ppm per cm absorption)	**(10-100ppm per cm)**
optical quality (in reflection)	
(super polish)	(super polish)*
Thermal properties	
thermal expansion	
(low for SiO_2)	(zero for Si at 20K)*
thermal conductivity	
(low for SiO_2)	(very high for Si)*
thermal time constant	
(~ 5 sec SiO_2)	(~μsec (20K) to ~msec (270K))

A System Design Approach

Interferometer Design Choices

The Polarization-Sagnac interferometer

- **Common path interferometer**
  - No length control required
  - Laser frequency and amplitude bandwidth opened
  - Common path reference oscillator
- **Polarization beamsplitter**
  - Adjustable beamsplitter ratio to 50%
  - Symmetrical beamsplitter port
  - Diffractive, all reflective beamsplitter
- **Delay line for storage**
  - Nonresonant interferometer
  - Response is zero at zero frequency
  - Alignment sensitivity same as FP-Michelson
  - Scatter controlled by optical coherence
  - 50 pass delay at 532nm for 180Hz peak response
- **Post modulation with heterodyne reference**
  - Modulator in low power beam
  - Balanced heterodyne detector
  - 30 to 40 db dark port
  - high tolerance for laser amplitude noise
- **Spatial mode filtering**
  - Input and output spatial mode filter
  - >30dB dark port contrast
- **Sensitivity Scaling**
  - Sensitivity meets LIGO II at 4.4kW 532nm
  - Sensitivity peaks at 180Hz and is broadband
  - Sensitiviy scales with laser power
  - Crystalline Silicon Optics allowed
  - Cryo-cooling allowed for power scaling & high-Q

The Polarization–Sagnac interferometer allows

***use of crystalline optics in reflection (Silicon)**

***cryo-cooled optics for low noise (Silicon)**

***increased sensitivity via increased laser power without thermally induced instabilities (non-resonant)**

***control of scattered light via optical coherence.**

Motivation for considering a Delay-Line Sagnac for gravitational wave detection

- Sensitivity goal of LIGO II requires an increased storage time of interferometer light
- Delay Lines offer simpler control than resonant cavities
  - A Delay-Line Sagnac is a common path interferometer with no resonances to be maintained
- Delay Lines work with broadband laser sources
  - Can use short coherence length source to reduce sensitivity to scattered light

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A Polarization Sagnac Interferometer with Common-Path Local Oscillator for Heterodyne Detection

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A Polarization Sagnac Interferometer with Post Modulation for Gravitational Wave Detection

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We describe a polarization Sagnac interferometer that uses an in-loop half-waveplate to allow signal detection on the reciprocal port of the beamsplitter while maintaining the ability to detect at a dark fringe. Post modulation and balanced heterodyne detection are used to recover the signal. This topology is simple to control because of its common-path characteristics and its collinear signal and local oscillator. The robustness of this scheme to amplitude and frequency fluctuations of the laser is demonstrated. Intra-loop birefringence in this interferometer acts only as a loss, the magnitude of which is discussed and experimentally verified.

Sagnac interferometers[1,2] have been proposed[3] and are being experimentally investigated[4,5] for gravitational wave detectors. An attractive aspect of the Sagnac interferometer is that both interfering beams sample the same optical path with the same elements, so that distortions of the optics have a minimal effect on the sensitivity of the differential signal.

In previously proposed Sagnac configurations, the photodetector was placed at the asymmetric port of the beamsplitter, where interference is destructive, to avoid photodetector saturation. At the asymmetric port one beam is reflected twice from the beamsplitter while the other is transmitted twice, the contrast of the resulting interference, and hence the interferometer sensitivity, is limited by the ability of the beamsplitter to split the amplitude of the beam equally.

Here we present a polarization Sagnac interferometer that allows detection of the interference minimum on the symmetric port of the beamsplitter[6]. The interferometer topology includes a signal extraction scheme that uses a common path local oscillator for balanced heterodyne detection. Unlike many signal extraction schemes, in the scheme described here the modulator used to generate the heterodyne frequency sidebands can be placed at an interference minimum away from the high circulating power, which minimizes the thermal loading of the modulator crystal.

By controlling the polarization state of the light as it circulates in the interferometer the polarization of the signal can be made orthogonal to that of the

the practical advantages offered by this topology. The sensitivity of the polarization Sagnac interferometer is similar to that of previously investigated topologies and is therefore not investigated.

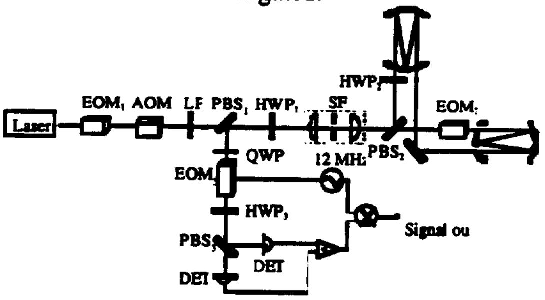
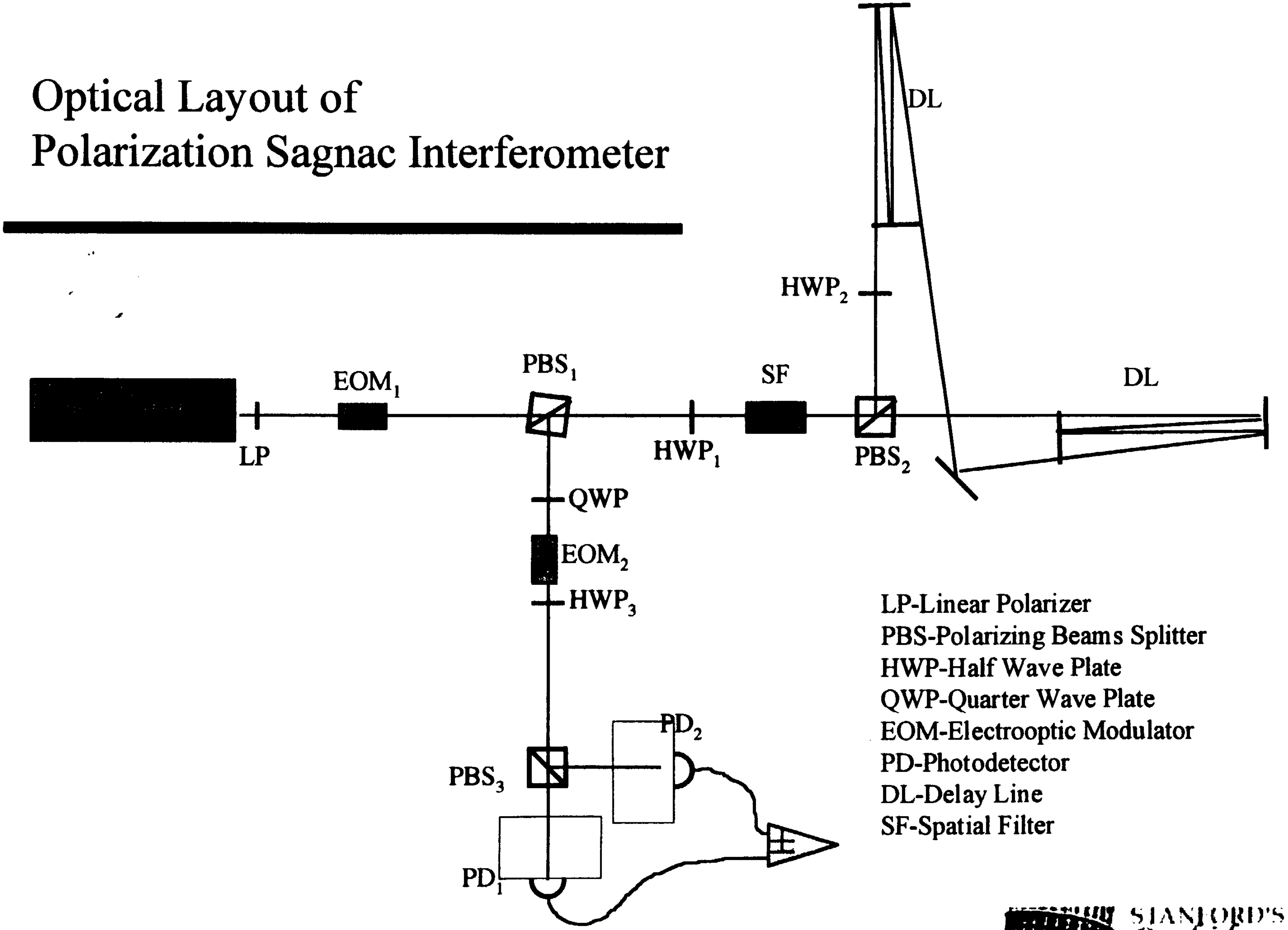


Figure 1 The optical layout of the polarization Sagnac interferometer with acousto-optic modulator (AOM), polarizing beamsplitters (PBS), half waveplates (HWP), quarter waveplate (QWP), spatial filter (SF), electro-optic modulators (EOM) and photodetectors (DET). Each arm contains a 75 bounce, 2m long delay line. The beamsplitter PBS_1 is slightly tilted to leak 0.3% of the cross polarization. Not shown is the resonant ring cavity[11] immediately after the laser used as a spatial and temporal mode cleaner.

The optical layout of the polarization Sagnac is shown in Figure 1. This interferometer topology offers many practical advantages over conventional Sagnac or Michelson topologies. Because the signal and carrier light are orthogonal polarization

Optical Layout of Polarization Sagnac Interferometer



LP-Linear Polarizer
PBS-Polarizing Beams Splitter
HWP-Half Wave Plate
QWP-Quarter Wave Plate
EOM-Electrooptic Modulator
PD-Photodetector
DL-Delay Line
SF-Spatial Filter

STANFORD'S *Galileo* PROJECT

Comparison with fused silica, sapphire and silicon

	Fused Silica	Silicon	Sapphire	YAG
↑ Density, r (*kgm^{-3}*)	2.2×10^3	2.33×10^3	3.98×10^3	4.55×10^3
↑ Speed of sound, c (*ms^{-1}*)	5720	8415	10025	7887
↓ dn/dT (*K^{-1}*)	8.7×10^{-6} *	-	1.36×10^{-5} *	7.3×10^{-6} *
↓ Coeff. Therm. Exp. α (*K^{-1}*)	5.1×10^{-7}	2.62×10^{-6}	7.15×10^{-6}	7.7×10^{-6}
↑ Spec. Heat Cap., C_m (*$J\,kg^{-1}K^{-1}$*)	746	713.9	777	625
↑ Thermal Cond., K (*$Wm^{-1}K^{-1}$*)	1.38	140	25-35	13
Youngs Modulus, E (Nm^{-2})	7.2×10^{10}	16.5×10^{10}	40×10^{10}	28.3×10^{10}

All data taken from "Electro- optics handbook", Eds. R. Waynant, M. Ediger, Pub. McGraw Hill apart form
* "Optical materials" S. Musikant, Pub. Marcel Dekker Inc (1985)
Properties specified at 300K

A System Design Approach

The Laser

The Challenge - **Design the laser to meet LIGO I, LIGO II and Advanced LIGO requirements**

Laser properties

Power scaling from 10W to 10kW in one decade

- Harmonic conversion to 532nm
- Frequency and amplitude noise control

Master Oscillator – Power Amplifier (MOPA)

- Maintain LIGO pre-stabilized laser oscillator
- Add amplifiers as needed to increase power
- Active spatial mode control
- Pre-mode cleaner and mode cleaner as needed

Laser Diode pumped for 10% electrical efficiency

Conduction cooled for low noise improved reliability

The Laser design should be congruent with commercial needs to leverage NSF funds for the development of the LIGO laser.

A System Design Approach

The Laser

LIGO I 10W Nd:YAG laser

FP-Michelson **glass optics**

A Photon limited design
Operation below the onset of thermal instability

LIGO II 170W Nd:YAG laser

FP-Michelson **some crystal optics**

Power recycled, FP-Michelson coupled interferometer
Operation at the thermal instability limit
Crystalline optics of low loss used in transmission

Advanced LIGO 4.4kW 532nm Yb:YAG

Polarization-SAGNAC **Crystal Optics**

All reflective, common path interferometer
Cryo-cooled crystal Silicon optics
No power recycling, no FP resonances, thermally stable

The Laser source

***has minimum requirements on frequency and amplitude stability**

***can be designed to reduce scattered light by coherence control**

***can be power-scaled to meet sensitivity needs without the onset of thermally induced instabilities.**

A System Design Approach

Prospects for LD pumped Solid State Lasers

The edge-pumped Nd:YAG Slab laser amplifier

125W cw power, 55% slope efficiency

Projected >100W Nd:YAG amplifier output

The edge-pumped Yb:YAG Slab laser

>200W at 50% optical to optical efficiency

Power scaling to >10kW

Discussion

When will 1kW cw lasers be available?

1kW lasers were demonstrated at the Munich Laser show in June,1999 and announced in Japan by two companies.

When will 1kW of 532nm be available?

Second harmonic generation follows the fundamental laser by approximately two years. To date >200W of 532nm has been demonstrated in the laboratory.

BOTTOM LINE

It is less costly and less risky to engineer a 4kW laser source, in parallel with industry, than to develop and grow a high optical quality single-crystal test mass.

The commercial market is driving toward kilowatt class LD-pumped solid-state lasers. Similarly, the semiconductor market is driving the development of 30cm diameter **SILICON** crystals.

Future Prospects

Crystalline Test Masses
    All reflective Interferometer
    Cryogenic operation

LD Pumped Solid State Lasers
    Current Status
    Power Scaling

An Upgrade Path: is it possible?

Paraphrasing Edwin Land

Don't undertake a project unless it is

scientifically compelling

and nearly impossible.

LIGO is compelling!

Note 1, Linda Turner, 08/17/99 08:05:41 PM
LIGO-G990079-21-M