New Folder Name Behavior Evaluation

Proposal to Evaluate Behavior of Gravitational-Wave Interferometer Optics at High Light Levels.

I. Initial Experiments

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Abstract

A series of experiments is proposed to study the mechanisms which determine the usable optical power levels obtainable in practical gravitational-wave interferometers. This program includes studies of optical components in transmission and reflection, and investigation of any changes of coating properties over time due to light exposure or surface contamination.

Introduction

LIGO interferometers will place higher demands on interferometer optics than are required in the 40-m prototype. Optics can limit the light level obtainable in a working interferometer by (1) limiting the duty cycle due to insufficient mean time between failures (MTBF); (2) limiting the circulating power obtainable in the main arm cavities; (3) distorting the input wavefronts and thus limiting contrast, fringe visibility, and recycling efficiency while providing a path for certain noise contributions (e.g. due to fluctuations in modal content) to be amplified. Power related problems typically result from heating of the optical component produced by light absorption, either in the bulk material or at surfaces. In both cases there are intrinsic and contamination-related contributions to the absorption. This heating produces three optical defects: thermal focussing, surface figure deformation due to thermal expansion, and thermally-induced stress birefringence.

Current State of Knowledge Regarding Optical Distortion

The 40-m prototype's operations provide some useful data. The input optics used on the 40-m prototype between the laser and the mode cleaner are routinely exposed to optical power levels of several Watts, comparable to exposure levels for similar optics in the initial LIGO interferometer. Table 1 gives power (P) and intensity ($I = P/\pi\omega^2$; ω is spot size) levels for the light inside cavities in the initial LIGO interferometer, and in the 40-m prototype mode-cleaner cavity (which has a much higher circulating power level than the main 40-m cavities). For purposes of comparison the upper bounds on power and intensity levels were calculated assuming perfect mode matching. Clearly the 1-m mode cleaner in the prototype could provide useful test data for intensity-dependent phenomena relevant to the initial LIGO. Unfortunately this data is somewhat corrupted since the

40-m prototype's vacuum system is not clean and surface contamination of optics in this environment is regularly observed.

Input Optics

The prototype's input optics have handled power levels of up to 3.5 Watts before serious thermal focussing was observed. So far the most seriously affected component is a Faraday isolator (and the problem may be specific to the method of construction used for the polarizers in this unit). Excessive scattering from Pockels cells has also been observed after more than one year of service, and this effect may be caused by water absorption or contamination instead of light exposure. From this experience we conclude that although further work is required, we are confident that the input optics can handle power levels comparable to that specified for the initial LIGO.

Mirrors: Power-Dependent Effects

The 1-m mode cleaner cavity has shown power-related difficulties. In 1989, a power-dependent loss of throughput (power output from mode cleaner divided by incident power) was observed. This led to a series of tests of various mirrors in a 9-m tube set up for power testing. Generally throughput degradation became serious at between 0.8 and 1.2 kW of circulating power in most cavities, although certain mirrors showed no degradation at 1.6 kW. The observations were consistent with a failure of mode-matching light into the cavities caused by thermal focussing in the input mirror substrate. Observed transients in fringe visibility upon locking the cavity onto the light implied that this problem was driven by light absorption in the mirror coating. A numerical model of this effect was developed by A. Cadez which "predicted" throughput saturation at 0.22 Watts of absorbed power. This corresponds to 200–250 ppm absorption loss, comparable to the losses of mirrors used in this study[1]. We have recently tested mirrors with total losses as low as 17 ppm. Since we expect scattering losses to account for at least 5—10 ppm, a reasonable absorption is $A \lesssim 10$ ppm. We estimate that circulating power levels of $\gtrsim 20$ kW are possible with scaled up (in size) versions of these mirrors.

Mirrors: Intensity Related Effects

Another problem experienced in mode cleaners on the prototype is light-exposure related degradation. This was observed in one mode cleaner shortly after installation,

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[1] It was later observed that mirrors were being contaminated by their storage boxes, and that repeated vigorous drag wiping with multiple solvents dramatically lowered measured losses. In this regard it is notable that the mirrors which showed no degradation at 1.6 kW were newly received from the manufacturer.

and was believed to come from a silver epoxy used to bond wires to the piezoelectric transducer (PZT). Recently a second mode cleaner exhibited a catastrophic failure mode in which losses accumulated rapidly during light exposure and only on the illuminated surface of the mirror[2]. In this case the mode cleaner had been operating for about six months before this sudden failure mode occurred. There is circumstantial evidence linking this failure to a vacuum system contamination problem.

Unanswered Questions

We have, as shown above, a theoretical and experimental basis to believe that we can expect to operate optical components at light powers comparable to the initial LIGO interferometer presented in the December, 1989 proposal. Some concerns remain.

A major reliability concern relates to degradation of components exposed to high light power for long periods of time. The 40-m prototype has a low duty cycle compared to a LIGO interferometer. For example some thin film coatings can change their optical properties under exposure to light or vacuum[3]. We have not yet run our mirrors very hard for a long time, either in vacuum or exposed to controlled, introduced contaminants.

An immediate concern is our lack of knowledge of input parameters for calculating the heating-related thermal distortion of the light, possibly the major cause of wavefront distortion in the initial LIGO interferometer.

For example, taking the mirror coating absorption to be A = 10 ppm, gives a large-signal mode-matching efficiency (for 4.5 kW circulating power) of $M_o \leq 0.95$, that is, thermal focussing will degrade the fringe visibility by an additional 5% as the power is increased. This would be tolerable, comparable to the contrast loss from a $\lambda/15$ optics chain. But if absorption were higher, say A = 20 ppm, the mode-matching efficiency would degrade to $M_o = 0.84$, comparable to a $\lambda/7$ wave front error across the spot. This level of distortion might seriously degrade contrast at the beam splitter. Clearly we need to establish the value of the mirror absorption and its variation from batch to batch.

Proposed Research

The proposed initial experiments fall into three broad categories: short-term power tests of optical components, short-term power tests of mirrors, and exposure (long-term) tests of mirrors. (This last experiment is complementary to the low-light-level contamination testing proposal.)

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[2] This was in sharp contrast to the normal surface contamination from exposure to the 40-m vacuum system's environment which produced increasing cavity losses at a rate of $\simeq$ 20 ppm/week independent of light exposure.

[3] See, for example, M. Commandre and E. Pelletier, Appl. Opt. **29**, 4276, (1990).

Apparatus

The Power Test Station shown in Figure 1 will be set up for these tests. This apparatus incorporates a large-frame Argon laser with appropriate optics and electronics for stable locking to optical cavities (for convenience the circulators and photodiodes will be duplicated). The exposure test station (labelled (1) in Figure 1) will be used for long-term exposure testing of rigid-spacer cavities. Exposure testing will be the normal background task in time-sharing use of the laser beam. The foreground tasks will be short-term tests such as mirror power testing (in the throughput/calorimetry station labelled (2) in Figure 1), and optical component power testing (by insertion in beam line labelled (3) in Figure 1). Three movable mirrors (labelled (A),(B), and (C) in Figure 1) allow switching among the various tasks.

Power Tests of Mirrors (short term)

These tests are designed to investigate the problem of thermal focussing in mirror substrates and to measure absorption coefficients for the mirror coatings. Calculations reveal that the power incident on the mirror coating (i.e. the circulating power) determines the amount of wave front distortion[4]. A cavity will be assembled in the 0.6-m tube with mirrors having the parameters given on the first row of Table 2. The laser will be switched into the 0.6-m tube using mirrors (A) and (B) in Figure 1. Reflected and transmitted power (P_r and P_o) will be monitored as a function of incident power (P_i) with the cavity resonating. From these we can calculate visibility (V_c), throughput (T_c), and circulating power P_c using the relations:

$$V_c = 1 - (P_r/P_i) \tag{1}$$

$$T_c = P_o/P_i \tag{2}$$

$$P_c = P_o/T_2 \tag{3}$$

where T_2 is the transmission of the output mirror. Both V_c and T_c depend linearly on M_o, the mode matching (power) efficiency which provides a sensitive measure of wave front distortion. For mirror absorption A = 10 ppm, we expect a fractional change in visibility of about 7% as the circulating power is varied over the range indicated in Table 2. The distortion of the output mode will be checked with a laser beam analyzer (LBA).

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[4] Intensity should be relevant to long-term degradation due to high light level exposure. To test for such degradation mirrors should be exposed to the highest intensities possible.

of about 7% as the circulating power is varied over the range indicated in Table 2. The distortion of the output mode will be checked with a laser beam analyzer (LBA).

To obtain the mirror-coating absorption coefficient the above experiment can be repeated[5] with the input mirror held in a special mount (calorimetry mount) to measure heating of the mirror substrate. The temperature at the edge of the substrate is recorded at a given (large) circulating power. The mirror is then replaced with a calibration blank (an identical substrate with an absorbing spot in center). The incident laser power is now adjusted to obtain the same edge temperature on the calibration blank as was obtained on the test mirror. The laser power is then measured. The ratio of this power to the circulating power in the test cavity is the absorption of the mirror coating. From earlier work with the calorimetry blank we expect repeatability of a few mW absorbed power, which would correspond to a fraction of 1 ppm in the absorption coefficient.

It is expected that the throughput measurements alone can establish the most relevant parameter for conceptual design purposes, namely the wave front distortion from thermal focussing. The absorption measurements provide both corroboration of the thermal focussing model, and provide a more precise diagnostic of mirror quality. They will become essential in developing optics for advanced interferometers.

If the absorption measurements and calculated throughput disagree significantly with the throughput data we can test for a spot-intensity dependence by making throughput measurements on cavities with the parameters given in lines 2 and 3 of Table 2.

Power Tests of Optical Components (short term)

Faraday Isolators, Pockels Cells, and Acoustooptic Modulators (AOM's) will be tested for thermal focussing effects by placing them in the beam line (at position (3) using mirror (A) in Figure 1) and directing the light into the laser beam analyzer (using mirror (C) with mirror (B) removed). One looks for a difference in the beam spot size measured with the LBA when a suitable attenuator is moved from the input to the output side of the component with the laser delivering maximum power. Thermally induced wave front distortions of $\lambda/10$ to $\lambda/20$ should be measureable[6].

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[5] Some silicone rubber was used in the prototype calorimetry mount. Because of concern about contamination the absorption test will await construction of a new, more vacuum compatible mount. Final tests of the prototype calorimetry mount will be completed before the first throughput tests are done.

[6] More precise and informative measurements will require a wave front measuring apparatus such as a Mach-Zender or Fizeau interferometer.

Exposure Tests of Mirrors (long term)

The first exposure tests will be studies of the mode cleaner (Mark V-A) that developed a serious light-exposure-related degradation. There is circumstantial evidence that this cavity was exposed to a contaminant in the 40-m vacuum system. A second possibility is that a local contaminant (e.g. epoxy used in assembly of the cavity) caused the problem. The cavity mirrors will be cleaned and the mode cleaner will be exposed to high light power to establish the rate of degradation[7] with time. A decreasing degradation rate would support the external contaminant model. This experiment will also study the behavior of the mirror losses when the mode cleaner is exposed to current-carrying resistors similar to those installed in the 40-m vacuum system just prior to the degradation episode.

Once the T = 110 ppm mirrors are shown to be able to handle high intensity light in the power tests and the low power contamination testing apparatus is shown to work, an additional two contamination test modules can be manufactured for testing light-exposure-induced degradation of mirrors. One test module will contain a control cavity in the cleanest vacuum environment possible[8]. The second test module will contain a potential contaminant to be studied. The first potential contaminants to study will be viton and silicone rubber.

Near-Term Schedule

Construction of the Exposure Test Station and Component Test Station should take approximately one week (after the laser installation) for a full-time graduate student and a half-time senior scientist. Exposure testing of the degraded mode cleaner cavity will consume 3–4 weeks as a background task. During this time initial testing of Faraday Isolators and other components will be done and optics will be set up for the Cavity Throughput/Calorimetry Station (one part time grad student and a 30% FTE senior scientist). Data from throughput measurements of mirrors with high circulating power should be available four weeks after installation of the laser.

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[7] The measure of degradation will be the decrease of storage time as measured by the ringdown method.

[8] If the short term power tests of mirrors reveal an intensity-dependent limitation, these additional test modules will be exposed at the maximum intensity possible.

Table 1

Comparison of Light Levels in Cavities

	Power (kW)	Intensity (kW/cm^2)
Initial LIGO		
4-km Cavities	$\lesssim 4.5$	$\lesssim 0.2$
12-m Mode Cleaner	$\lesssim 4.5$	$\lesssim 75$
40-m Prototype		
1-m Mode Cleaner	$\lesssim 0.8$	$\lesssim 70$

Table 2

Power Test Cavity Parameters*

Radius of Curvature (m)	Mirror Separation (m)	Circulating Power (kW)	Spot Intensity at Mirror 1 (kW/cm^2)
$R_1 = \infty$ $R_2 = 1.0$	0.30	0–5.5	0–2000
$R_1 = \infty$ $R_2 = 15$	0.50	0–5.5	0–360
$R_1 = \infty$ $R_2 = 15$	3.0	0–5.5	0–175

*Assuming $T_1 = T_2 = 110$ ppm, $L_1 = L_2 = 30$ ppm, 1 W incident light.

Figure 1

Power Test Station (Initial Configuration)

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