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Proposed Plan for Developing LIGO-Scale Optical Components

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Abstract

Recent tests on cavities ranging from 30 cm to 9 m in length have evoked severe thermally-related distortion of cavity modes. These observations—consistent with preliminary models—indicate that mirrors of the type used in the prototype are incapable of handling the power levels planned for even the earliest ligo interferometers. A research program aimed at developing mirrors and other optical components with power-handling capability, aperture, and beam quality required for the ligo is outlined.

1 Introduction

Several years ago we were informed of (unpublished) measurements at JILA showing thermal deformations of mirrors similar to the ones used in the 40-meter interferometer. They indicated that the power absorbed in the coatings and transferred to the substrates caused significant thermal expansion of the mirror substrates. The effect showed as an asymmetry in a rapidly scanned resonance peak, and was not observable in the Caltech prototype cavities in their ordinary mode of operation. A preliminary theoretical investigation suggested that substrate deformation would not be a significant noise source in ligo detectors, and that the power density of spots on ligo mirrors would not be much higher than had already been successfully used in prototype mode cleaners.

In September of 1987 the mode cleaner then in use showed its output power saturating when the input power was around two watts. The power fell off a few hundred milliseconds after exceeding threshold for the onset of distortion, indicating thermal effects in the mirrors. Though significant, this was not alarming; it was believed that

- The effect was due to thermal expansion of the substrate.
- It would be reduced by increasing the spot size, and the spots on ligo mirrors would naturally be large enough to make the expansion effect safely small.

Literature searches, measurements, and calculations conducted in recent months refute both of these assumptions. We now believe that

- The effect is attributable to thermal lensing of the input mirror substrate, which can be much larger than the expansion effect.
- It is independent of spot size.

In short, mirrors of the type used so far in the prototype cannot handle the power levels planned for even early ligo interferometers. They are at best marginal for prototype operations planned for the next several months.

Other requirements for ligo mirrors that have not yet been fully demonstrated in prototype research are

1. Small wavefront distortion over large apertures
2. Good figure for the surfaces over large aperture
3. Low loss in the substrate

Components other than mirrors—isolators, modulators, and lenses in critical beam paths—share these requirements. Because of their specialized nature, components meeting these criteria will not likely be developed independently by industry or by other research groups; we propose setting up an in-house R&D program to test and develop the needed components. Related issues in optical science important for operation of ligo detectors, such as sensitivity to spatial fluctuations in beam geometry and addition of lasers, can be explored in conjunction with component development.

2 Present State of Knowledge

2.1 Mirror Heating Data

Table 1 shows the power threshold for the onset of thermal effects in cavities of three different geometries, and includes parameters for the 40-meter interferometer cavities, which have not yet been operated above a few tens of milliwatts.

Thermal Effects in Cavities—Measurements and Requirements

Cavity	Length	Spot Dia.	g	$\overline{L}$	T_1	Threshold (W)	
	l (m)	$2w_0$ (mm)	$1 - l/R$	(ppm)		P_{out}	$P_{\text{out}}\frac{L_1}{T_2}$
MC 1	0.35	0.49	0.30	390	1000	.32	0.12
MC 2	0.94	1.1	-0.88	210	1200	1.2	0.20
Test	9.0	3.8	0.71	120	270	—	0.11
Prototype	40	4.4	-0.29	60	450	—	> 0.01
Ligo MC	12			50(?)	1000(?)	100(?)	5(?)
Ligo Arm	4000					—	20(?)

Table 1: Measurements of the power threshold for distortion of cavity modes (*above line*), and required power-handling capability of ligo mirrors (*below line*). MC = Mode Cleaner, "Test" is a cavity set up specially to measure mirror heating. The g-parameter depends on the cavity length and mirror radius of curvature; in general $-1 < g < 1$, and g near ± 1 corresponds to a nearly unstable geometry. The measurements are for mirrors made on substrates of fused silica. The rightmost column is the power loss at the input mirror for the onset of uncorrectable distortion; the uncertainty in this measurement is approximately ± 20%. In addition to absorption, the threshold power includes an unknown amount of scattering loss, which will not contribute to the heating. The rows for ligo mode cleaner and ligo arms assume 100 watts input per interferometer.

Several sets of mirrors were used in the 35-cm and 94-cm cavities; tests on the 9-meter cavity are still in progress. In each measurement, the onset of thermal effects occurs near the maximum usable power. Contrast is suddenly degraded by about a factor of two, and in severe cases the TEM_{00}

mode is replaced by a swimming pattern of dozens of spots. For some geometries, the threshold could be increased by a factor as large as 1.5 by adjusting the mode matching to compensate for the distortion at high power. The observed threshold is approximately 0.2 W loss per mirror for the highest-quality mirrors tested, and is roughly independent of the cavity length and spot size. If similar mirrors were used in a ligo interferometer optimized for minimum shot noise, they would limit the usable input power to approximately one watt, 100 times smaller than the design goal.

2.2 Models for Mirror Heating

The observed effects are consistent with calculations by Andrej, which model how a hot spot on the mirror coating transfers heat to the substrate. The resulting temperature gradient sets up a gradient in the index of refraction, which, for fused silica, is the dominant thermal distortion. For power P dissipated in the mirror, the coupling efficiency is $M \approx \frac{1}{1+(P/P_0)^2}$. P_0 depends on the thermal properties of the substrate, and is independent of the spot size. For fused silica $P_0 = 0.22$ W: in good agreement with the measurements, *assuming that absorption dominates over scattering in the coating.*

Table 2 shows thermal parameters for some candidate substrate materials. High thermal conductivity λ, low $\Delta n/\Delta T$, and low thermal expansion α are desirable. Other important substrate parameters are transparency, homogeneity, and birefringence. Compared to fused silica, BK7—a commonly used substrate—has smaller $\Delta n/\Delta T$ but larger α. Its dominant

Thermal Properties of Some Prospect Substrate Materials

Material	Thermal Cond. λ (W/m-K)	Index Change $\Delta n/\Delta T$ (10^{-6}/K)	Linear Expansion α (10^{-6}/K)
Fused Silica	1.3	12	0.59
BK7	1.1	0.6	7.1
Sapphire	35	13	8.4

Table 2: The thermal properties of fused silica, BK7, and sapphire, relevant to mirror heating effects. Each material is good in one parameter and poor in the other two.

thermal distortion is expansion of the substrates for both mirrors of a cavity; this would occur at roughly the same power as thermal lensing at an input mirror of fused silica.

Sapphire is not commonly used for high-quality mirrors, because it requires unconventional polishing techniques. Its large λ gives it promise to reduce both the lensing and expansion effects by as much as a factor of 30. This would raise the usable input power for ligo interferometers to approximately 30 watts; the remaining factor of 3 required to reach 100 watts might be obtained by improved coatings to reduce absorption, or by adaptive optics to counteract thermal effects. Sapphire has the additional desirable property of very high mechanical Q.

2.3 Other Components

We have experience with Pockels cells, Faraday isolators, acousto-optic modulators, polarizers, and photodetectors used in the prototype, with beam sizes ranging from 0.2 mm to 1 cm, and power levels up to 5 watts. Each of these components has at one time or another exhibited power limitations, though so far not at a level that limits prototype performance.

Pockels cells capable of withstanding 5 watts (20 watts within a laser) at 514 nm are used for modulation and phase correction, and ligo-scale diameter Pockels cells have been manufactured, though not yet tested. Acousto-optic modulators are typically made with glass that has a higher power threshold than the crystals used in Pockels cells, though this will require experimental verification if acoustos are to be used in the ligo; similar assurances and concerns apply to the glass used in Faraday isolators. High-quality polarizers of large aperture are commercially available, though they too need testing at ligo power levels. Some development in photodetectors will be required to improve quantum efficiency and perhaps uniformity, though current designs do not require exposing photodetectors to high power.

3 Proposed Program

Alex and Mike Burka have outlined a series of measurements to be carried out in coming months, concentrating on measuring losses and optical homogeneity in mirrors of the type in use (fused silica substrates, superpolish, ion-beam low-loss coating). These tests (*see attachments?*) are a start, but they need to be supplemented by a long-range program, including materials research, general qualification procedures, and a refinement of our understanding of the requirements imposed by ligo sensitivity goals on optical components and systems.

3.1 Substrate Materials

Discovering and testing alternative substrate materials is a possible solution to the mirror heating problem. This work should start with an extensive search to identify candidate substrates (I imagine an extension of Table 2, augmented by many more parameters for many more materials, with an overall figure of merit for each candidate). The most promising materials should be acquired, sent out for polishing, and tested for absorption, homogeneity, scattering, and other losses before being coated. The tests can be conducted in-house, by, for example, inserting the blanks between the mirrors of a stabilized cavity and measuring the resulting loss and change in mode structure. It may be possible to directly determine substrate absorption by measuring joule heating, or by other techniques described in the literature.

3.2 Coatings

Heating of optical components depends on transparency of the material that beams pass through, and on absorption loss at surfaces. For cavity mirrors made of standard optics stock the latter effect dominates, though transparency is important for components within recycled cavities. Loss in mirror coatings is a key parameter driving the sensitivity of interferometers, but improving coating techniques is beyond the scope of the Caltech and MIT research groups. To obtain the best coatings, we should expand our contacts with industrial firms making super mirrors.

3.3 In-House Test Facilities

To prevent interference with development of the prototypes proper at MIT and Caltech, optics components tests should be conducted with a dedicated facility. There is a 9-meter cavity in the Caltech prototype lab suitable for some tests, but it requires borrowing apparatus from the prototype. Ideally the test facilities, complete with a high-power laser to study heating effects, would be housed separately from the prototypes. This would require purchasing another laser, and (at Caltech at least) some additional building wiring. A Cadillac version would include

1. One Coherent I-100-20 laser, or similar, including cooling and power.
2. A good-sized optics bench
3. Enough pipes, pumps, and space to make a cavity on the order of 10-meters in length, with small chambers at either end.
4. The usual allotment of general-purpose optics components, specialized electronics, and instrumentation.

This facility would be ideal for investigating heating effects in mirrors and other components. Large-aperture optics could be tested with apparatus similar to the scanning optical phase detector used for aligning cavities in the Caltech prototype.

Such a facility would be expensive, and one must ask whether it is worth the cost if its primary use is to test optics. The answer depends on how critical the tests are to the project, on whether manpower is available, and on how much additional science might result directly or indirectly from the measurements. The involvement of at least one senior scientist is required. The measurements should be complemented by modeling, both analytical and numerical. Examples of additional uses for the facility are the testing of new cavity geometries and optics suspension techniques, and quantifying suspected noise sources such as fluctuations in beam geometry.