LIGO - T890045-00-R

73

List of 5/01/89

Notes on the Mirror Heating Problem
FJR—3/29/89

I. Experimental Observations:

1. We have observed a threshold in the power handling capabilities of fused silica supermirrors used to construct Fabry-Perot cavities. This arises from heating of the mirrors due to absorption of the laser light.
2. Measurements of several mirror sets in different cavity geometries indicate that the power handling threshold corresponds to losses of 0.1-0.2 W per mirror, and appears to be independent of spot size and mirror curvature.
3. We have found that once threshold is reached, readjustment of the input mode matching allows the cavity to operate at 2-2.5 times the threshold power level, but that further readjustments at higher power are impossible due to mode instabilities.

II. Analytical Results:

1. A preliminary model of mirror heating has been developed (by A. Cadez), which identifies the heating problem as a consequence of thermal gradients in the mirror substrate.
2. Thermal gradients arise from the process of heat deposition in the mirror coatings due to absorption of the light, subsequent conduction throughout the substrate and radiative cooling from the surface.
3. The dominant optical effects of this thermal gradient are thermal expansion (due to α, the coefficient of thermal expansion) and thermal lensing (due to the temperature dependence of the index of refraction, dn/dT). Thus the heating effects can be modelled using α, dn/dT, and κ (thermal conductivity) of the substrate material, and P_A, the power absorbed in the coating.
4. For fused silica substrates the thermal lensing effect dominates thermal expansion (by a factor of 20).
5. A numerical estimate of the thermal lensing effect has been obtained by solving the heat diffusion equation and calculating the degradation of the coupling efficiency of power into the TEM_{00} mode of a Fabry Perot cavity versus power absorbed by the mirror coatings. This power related coupling efficiency drops from 1 to 0.25 as the power absorbed rises from 0 to 0.22 W, independent of spot size and mirror curvature (assuming the mirror is much larger then the spot size).

III. Conclusions from Experimental and Analytical Results:

1. Preliminary analysis agrees with experimental data we have obtained. The "predicted" threshold is within a factor of two of experimental observations. Having done the analysis we now have an algorithm which should allow more systematic observations to be performed.
2. The common mirror technology employed by all groups worldwide in gravity wave interferometer prototypes (i.e. fused silica supermirrors) is *inadequate* for the high power levels anticipated for LIGO interferometers. Contrary to popular belief, these heating effects will not "go away" in long baseline interferometers.

3. Current mirror technology can handle between 1-2 W detected power (bright fringe equivalent) in a single interferometer (two cavities forming an "L").
4. Order of magnitude improvements in power handling may arise from the development of better substrate materials. For instance equivalent coatings on sapphire substrates should handle about 30 W detected power if other optical effects (e.g. birefringence) can be accomodated.
5. To assess the likelihood and potential for improvements in mirror coatings would require disentangling the contributions of absorption and scattering to total mirror losses. Additional improvements of 2-5 in coatings may be obtainable.
6. We have not yet analyzed the implications of the mirror heating effects to delay line cavities. However, it appears that since the beam can be injected into a delay line cavity through a hole in the input mirror, the thermal lensing effect can be made to vanish. For a delay line with N mirror spots, the thermal expansion at any spot should be smaller than the corresponding expansion in a Fabry Perot by N/2. However one expects that the cumulative effect of many distorted mirror surfaces should make the overall effect on the cavity modes as bad or worse than the case for the Fabry Perot cavity. Obviously this case warrants further study by those groups emphasizing delay line technology.

IV. Strategies for Dealing with the Mirror Heating Effect:

1. The best strategy is to fix the basic problem by developing better mirror substrates and less absorptive coatings. The rest of the proposed strategies are based on methods which could in principle work with current fused silica mirrors.
2. Couple light into Fabry Perot cavity through an internal coupling plate. Here an internal plate (presumably near Brewster's angle) is used to couple light into and out of a Fabry Perot cavity with nontransmitting mirrors. Since light does not traverse the mirror substrates, the thermal lensing effect of the mirrors does not occur, and high power low expansion substrates such as zerodur can be used to eliminate the thermal expansion effect. While such cavity geometries have been used in the past, high finesse cavities using this technique have not been attempted.
3. Build a hybrid cavity which is a blend of Fabry Perot and delay line technologies. Here two mirrors are placed as in a delay line geometry to obtain N spots. The input and output beams are coupled through a hole in the first mirror. However a third mirror now folds the return beam back through the two mirror delay line to form a Fabry Perot/delay line hybrid cavity. Such a system has most of the optical advantages of a Fabry Perot (such as longer storage times) but can be made to give the same performance as a delay line in terms of mirror heating effects.
4. Mirror heat profile adjustments. Our preliminary analysis indicates that the thermal gradient which drives the optical defects involved in the mirror heating problem cannot be modified much by passive strategies, such as changing the mirror shape. However it is possible in principle to alter the thermal gradient by actively applying heat to portions of the substrate not exposed to light from the main beam. By rastering an IR light source across the mirror surface and modulating the IR intensity, one can selectively apply heat to the cooler areas of the substrate and thus smooth out the

thermal gradient. To win much by this strategy would require a servo system which could sense distortion at the input mirror and apply heat to the appropriate places. Thus this would be a complicated solution to the heating problem which could only be considered as a last resort.