LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
-LIGO-
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Backscatter noise

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ABSTRACT

At the TNI (Thermal Noise Interferometer) we have noticed that light reflected back through the arm cavities from reflections off the output cameras contributes noticeable to the noise in the interferometer at high sensitivity levels. This document is a preliminary sketch of how this might work, in preparation for a detailed study.

KEYWORDS

Thermal Noise Interferometer; TNI; Scattered Light

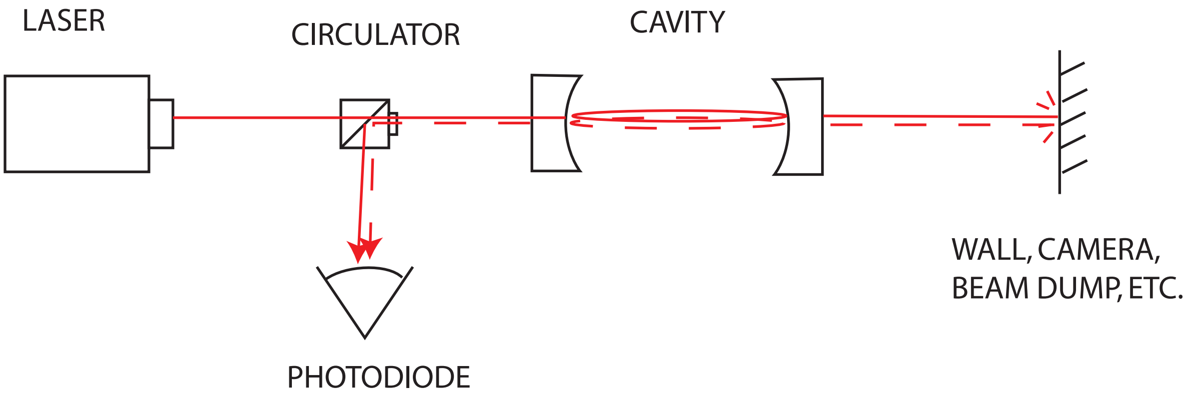

Figure 1: Sketch of the backscatter mechanism. Carrier light that gets transmitted through the resonant cavity reflects off of whatever it encounters on the other side, even if only a small amount, and comes back through the cavity to land on the photodiode, mimicking a length change in the cavity. If the path length of the reflected light changes, then the phase of the reflected light will change and mimic a time-dependent cavity-length change.

1 Introduction

It is a common practice, when using a Fabry-Perot cavity in an experiment, to place a camera in the path of the beam transmitted through the cavity to monitor the spatial mode the cavity is resonating in. (We usually just want the TEM-00 mode.) I have noticed that, at the TNI, reflections off our cameras back into the arm cavities produce noticeable noise at audio frequencies. I can wiggle the table with the cameras on it and, while listening to the error signals from each arm cavity through headphones, hear a noticeable response. This document is a first pass at quantifying the coupling between the cameras and the error signal.

2 Backscatter mechanism

On resonance, a Fabry-Perot cavity becomes transmissive to light of a certain frequency. This is true, to some extent, regardless of the coupling of the cavity, *i.e.* whether it is over-, under-, or critically-coupled. Critically-coupled cavities become perfectly transparent, while over- and under-coupled cavities only become partly transparent.

When we lock a cavity to light of a certain frequency, using the Pound-Drever-Hall technique, we rely on the small amount of reflected carrier light to tell us when the cavity is off resonance, and in which direction. This serves as both the error signal for the control system and as a measure of any length change in the cavity. In the language I am used to [1], the sidebands oscillate along the imaginary axis, and any carrier light with a component along that axis is interpreted as a deviation from resonance, or length change in the cavity.

Now, it is all well and good to say that a small deviation from resonance gives rise to a small amount of reflected carrier, while most of the carrier still gets transmitted through the cavity, but what happens to that light after it leaves the cavity? It has to land somewhere, and some of it must get reflected back to the cavity. Since the cavity is on (or near) resonance, it is (at least partially) transmissive to that reflected carrier light, and some of the reflected light will make its way back to the photodiode. The phase of this reflected light will depend on the optical path length between the cavity and the reflecting surface (and maybe on the surface itself), and any component along the imaginary axis (again using my phase convention) will appear to be a length change in the cavity.

The question I want to answer in this document is, very simply, ”How much light has to get reflected back into the photodiode to mimic a cavity-length change on the order of 10^{-16} or 10^-18 meters?” For an optimally-coupled cavity, the reflected carrier field as a function of cavity-length change is, approximately,

$$E_{carrier} \sim i\mathcal{F}\sqrt{P_c}\frac{\delta L}{\lambda},$$

where $\mathcal{F}$ is the finesse of the cavity, P_c is the incident power in the carrier, λ is the wavelength of the resonant light (the carrier), and δL is the cavity-length change.

Consider that a small field $E_{backscatter}e^{i\theta}$ makes it back from the other side of the cavity to the photodiode, with some phase θ that depends on the total path length travelled on the other side of the cavity. The contribution to the error signal will be maximum when the phase it $\theta = \pi/2$, and that backscattered field will make it look like the cavity length has changed by an amount

$$\delta L_{apparent} = \frac{\lambda}{\mathcal{F}}\frac{E_{backscatter}}{\sqrt{P_c}}.$$

For the TNI, $\mathcal{F} = 10^4$, and $\lambda \approx 1\mu m$. For these parameters, the apparent length change is

$$\delta L_{apparent} = 10^{-10}m\left(\frac{\lambda}{1\mu m}\right)\left(\frac{10^4}{\mathcal{F}}\right)\sqrt{\frac{P_{backscatter}}{P_c}},$$

where $P_{backscatter} = |E_{backscatter}|^2$ is the backscattered power.

Right away we should notice that it doesn’t take much backscattered power to mimic a small length change. To get $\delta L_{apparent} = 10^{-16}m$, a very large signal in the TNI, we would only need to backscatter 10^{-12} of the incident power. This is consistent with my observations at the TNI. I tried dumping the transmitted beams into beam dumps, instead of cameras with lenses and ND filters, and the coupling between the table motion and the error signal only got worse. I tried a Faraday Isolator, but that didn’t help either.

3 Over- and under-coupled cavities

You might think, at first, that this effect would only be a problem with optimally-coupled cavities, since over- and under-coupled cavities already have a significant amount of light reflected back onto the photodiode. However, I suspect that over- and under-coupled cavities will be just as sensitive to this effect as optimally coupled ones, since the on-resonance reflected light from these cavities is always 90° out of phase with the sidebands and therefore cannot contribute to the error signal, whereas backscattered light could be at any phase and will still mimic just as much of a length change as in an optimally-coupled cavity. The only thing you would gain by going to, for example, an over-coupled cavity would be to cut down on the total reflected power that makes it to the photodiode, by cutting down on the transmission of the cavity itself.

4 More work to do

It is obvious that backscattered light is going to contribute to the noise curve of the TNI at some level. This effect may also contribute to the noise curves of LIGO, TAMA, etc. It is also obvious that it will contribute at the same frequencies at which the phase θ varies, and it is not unreasonable to expect this phase (spurious interferometer fringes) to vary at audio frequencies.

What is not obvious is how much this backscattered light contributes to the total noise curve, *e.g.* whether or not it is dominant right now, and what its frequency spectrum looks like. These are issues that ought to be addressed, and it might also be useful to address them in LIGO as well.

References

[1] Eric D. Black, *An introduction to Pound-Drever-Hall laser frequency stabilization*, Am. J. Phys. 69, 79-87 (2001).