Back-Reflected Light and the Reduction of Nonreciprocal Phase Noise in the Fiber Back-Link on LISA

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The Laser Interferometer Space Antenna (LISA) is a joint ESA NASA project with the aim of detecting gravitational waves. The mission will use three spacecraft in a triangular constellation in space acting as three separate interferometers. As a space based interferometer LISA will hold several advantages over its ground based counterparts. For example, LISA will not have to correct for any seismic noise which ground based interferometers must adjust for. Additionally, being in space, LISA will be able to take on a much greater scale than any interferometer based on earth with an arm length of five million kilometers. One of the primary reasons LISA can use such a large arm length is because of the fact that while the three spacecraft orbit the sun in a triangular constellation the position of the craft are not fixed relative to each other. For this reason it is necessary to have dual optical benches so that the lasers on each craft maintain their alignment as the position of the crafts change in respect to one another. For various reasons, such as laser frequency locking, light must be exchanged between the two benches. An optical fiber is used for this task as it eliminates the need for extra components for maintaining alignment as the angle between the benches changes. A major drawback to this setup is that the fiber may introduce unwanted phase noise which is above the LISA requirements. Reciprocal phase noise can be subtracted, but that is not the case for phase noise which is not common to both paths within the fiber. Because of this it is necessary to verify that the phase noise introduced by the fiber can be corrected for and or reduced such that it will be below the LISA requirements of 5 $\mu\text{rad}/\sqrt{\text{Hz}}$.

The setup used for detecting nonreciprocal phase noise is detailed in Fig. 1. Beams 1 and 2 have a 1.6 kHz offset so that when they are interfered they produce a 1.6 kHz beat note. Light from Beam 1 travels through the fiber after being reflected by beamsplitters 7, 1, and 2, and then transmitted through beamsplitter 5. After passing through the fiber, light from beam 1 interferes with light from beam 2 which has not passed through the fiber. This occurs at beam combiner 2. Light from beam 2 also interferes with light from beam 1 at beam combiner 1 after passing through the fiber. The light from beam 1 which interferes at beam combiner 1 does not pass through the fiber. Also, a beam dump is placed between beam splitters 5 and 6 when a measurement using the fiber is being done. When the fiber is not used in the experiment it is be removed and the beam dump is taken out so that a null measurement can be performed to detect the noise of the setup without the fiber in place.

The phase noise introduced by the fiber can be seen by monitoring the 1.6 kHz beat notes at beam combiners 1 and 2 because of the fact that in each of these signals only one of the two beams which is interfered has actually passed through the fiber. Therefore, photodiodes 1 and 2 monitor the phase noise introduced by the setup as well as the fiber in beam 2, whereas photodiodes 3 and 4 view the phase noise introduced by the set up and the fiber in the direction of beam 1. Phase noise which is common to both beam 1 and 2 as they pass through the fiber goes to zero as the signals from photodiodes 1 and 3, and 2 and 4 are subtracted. Some phase noise is produced by the set up rather than the fiber, but will be discussed in a bit. Photodiodes R1 and R2 make a reference measurement which helps correct for some of this noise in the setup. Photodiodes S1, S2, A1, and A2 measure the

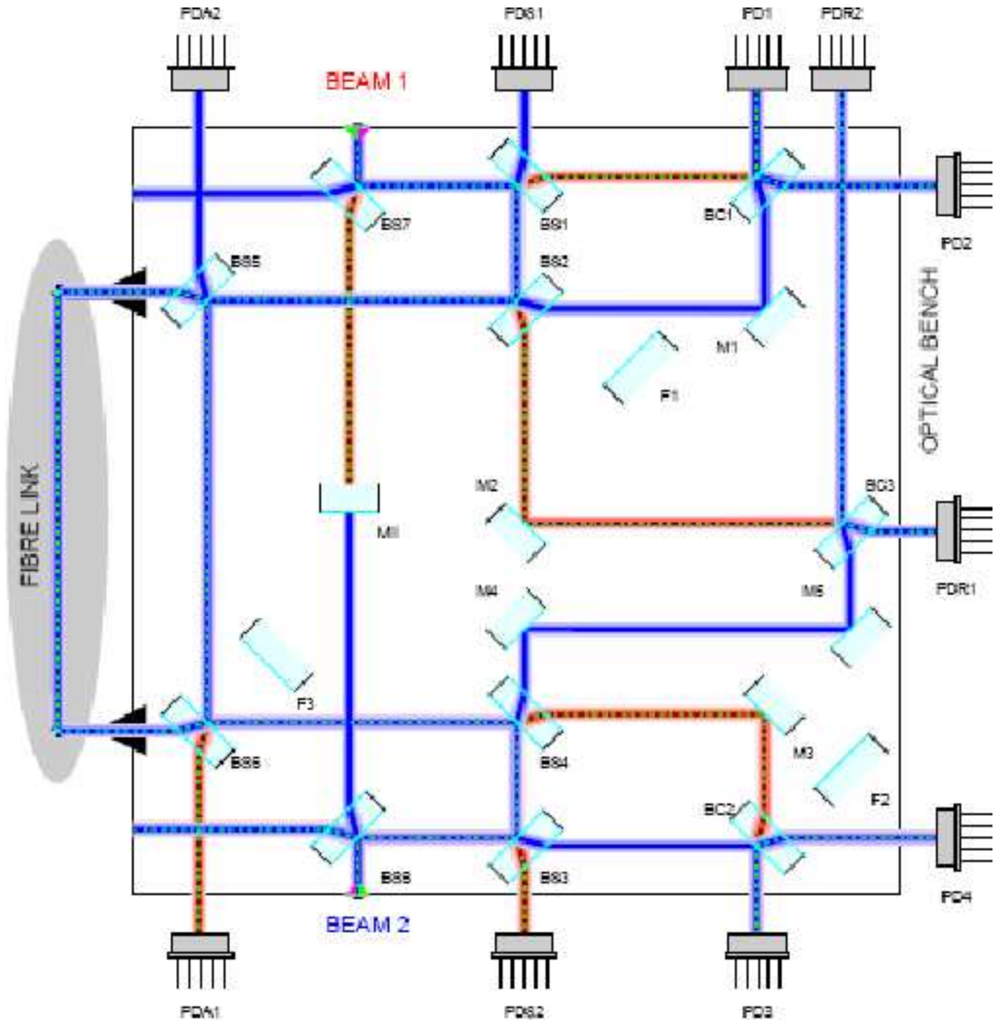

Figure 1: The nonreciprocal phase noise setup.

AC signal of the back-reflected light interfering with the light coming from the fiber. Fig. 2 shows the various noise levels with different schemes for correcting for the noise. These measurements were all done before I arrived at AEI.

The red line indicates the phase noise induced with no corrections in place. Clearly it is far above the LISA requirement in black. However, when the signal is corrected for back-reflection, as seen in the blue line the noise is reduced by roughly a factor of five. The methodology behind this correction can be clearly seen when looking at the phasor diagram of the signal as shown in Fig. 3. Light which is back-reflected off of the fiber brings in a pseudo signal which distorts the phase of the measured signal. While photodiode 1 should measure signal B, the blue phasor, because of the back-reflection it actual measures the green measurement B. Along the same lines, photodiode 2 should measure the red phasor signal A, but actually sees the orange phasor measurement A. To combat this measurement A is subtracted from measurement B leaving only twice the magnitude of signal B as the two

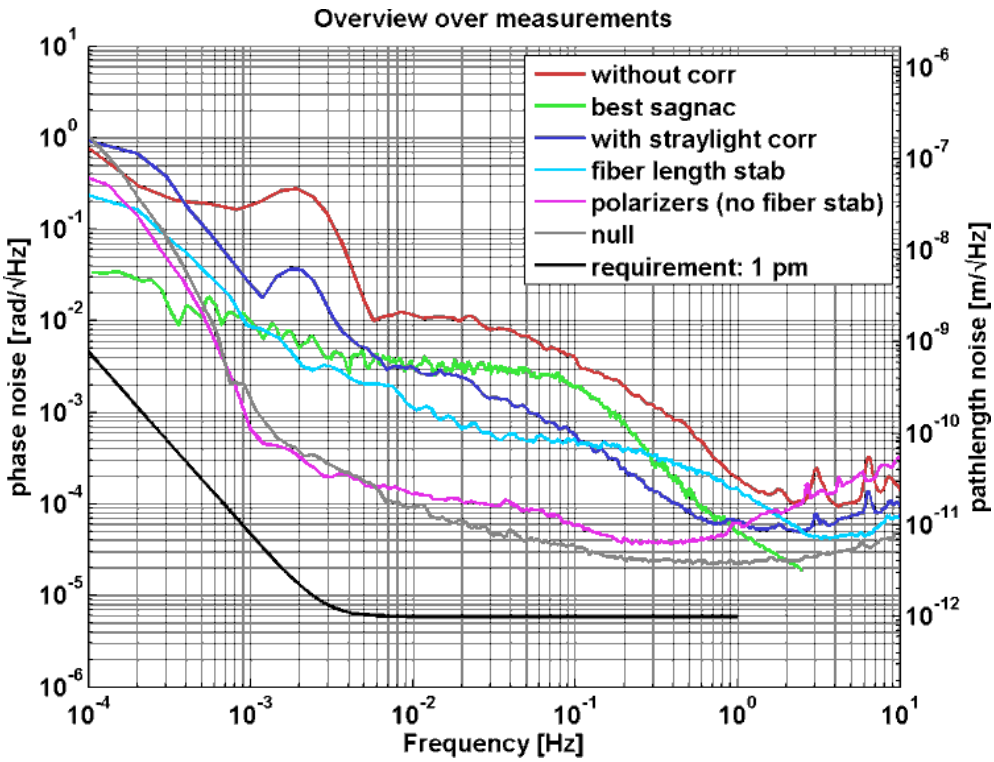

Figure 2: Noise levels for various nonreciprocal phase noise measurements.

pseudo signals cancel. As the beams interfere at beam combiner 1 signal B, on photodiode 1, and signal A, on photodiode 2 have the same amplitude, but are 180 degrees out of phase.

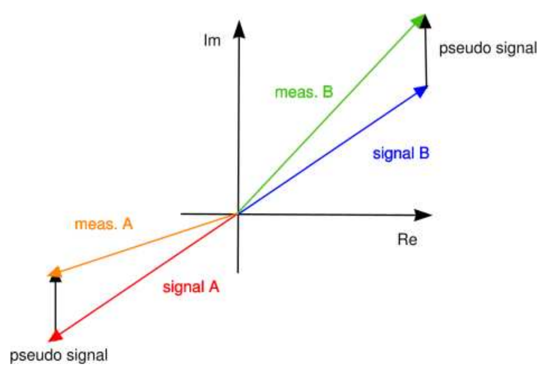

Figure 3: Phasor diagram for the correction for back-reflected light.

Another step taken to lower the noise level was the addition of polarizers between beam splitters 2 and 5, and 4 and 6. This stabilized the polarizations of the beams and helped lower the noise to the same level as the null measurement. The null measurement is done without the fiber or the beam dump in place. This shows the phase noise introduced by the setup itself. The fact that the noise level of the null measurement was nearly as high as the noise level of the measurement with polarizers and back-reflection correction was an indication that the phase noise was limited by something within the setup itself. While the fiber was not in place for the null measurement, beam 1 and 2 were brought into the setup through the use of optical fibers. Therefore it was possible that there was some back-reflection coming from the outputs of beams 1 and 2 and at this point we began to investigate this as a possible source of this noise as it was assumed that the back-reflection correction was not perfect.

The first step in evaluating the influence of back-reflection on phase noise was to produce a reliable setup which would could measure the amount of back-reflection from various fibers and help determine the location of where the light was actually reflecting. After discussing several ideas we finally arrived on the setup shown in Figs. 4 and 5. Output 1 was used as a local oscillator and light was always shining through it. The isolator in front of it prevented any back-reflection from being produced by this fiber. To maintain consistent results the same fiber was always used as local oscillator. Output 3 was used as the test fiber for measuring the amount of back-reflection off of it. First, however, a direct beat signal had to be obtained and the setup for measuring that is shown in Fig. 4. Light is put through Outputs 1 and 3 and they interfere at the beamsplitter. This produces a 1.6 kHz beat signal. The amplitude of this interference signal is used to scale the amount of back-reflected so that for each fiber we could obtain a reflectivity for the AC back-reflected light. Fig. 5 shows the setup we used to actually measure the back-reflected light of the fibers. Again Output 1 is used as the local oscillator, but in this setup Output 2 is used as the incident light. The light which comes from Output 2 and passes through the beamsplitter is reflected out of the setup by the isolator in front of Output 1. Also, light from Output 1 which passes through the beamspitter could be back-reflected off of Output 2, but for it to be seen on photodiode 1 that back-reflection would then have to be back-reflected off of Output 3 and that point that signal becomes negligible as each reflection only reflects roughly less than one percent of the signal. Light from Output 2 which is reflected by the beamsplitter is then aligned to pass through the fiber at Output 3 and the coupling efficiency is monitored. At this point a certain percentage of the light is reflected by the fiber at Output 3 and onto photodiode 1. The flip mirror and photodiode 2 are in place to measure the amount of light coming from output 2. It is important to ensure that the amount of light coming from output 2 in this setup is the same as the amount of light coming from output 3 in the other setup to ensure that the percentage of light reflected is an accurate measurement of how much light is actually reflected.

This setup has several advantages over some of the other setups we developed when we were first brainstorming ideas for the how to measure back-reflection. One of these advantages is the fact that the only back-reflected light which we see on photodiode 1 is that which is reflected off of output 3. Also this setup allows for the measurement of back-reflection with and without a fiber in place in output 3. Because of this we were able to determine whether or not the light was being reflected off of the fiber itself or the fiber coupler. Another nice thing about this setup is that it allows for the detection of both the AC and DC back-reflection. The DC reflection can be measured with the setup in fig. 5 by blocking the signal from output 1 and simply measuring the amount of light reflected by the fiber in output 3. We did experience some difficulties when attempting to measure the DC back-reflection because of the fact that the reflected signals have such a low power that the background light make it very difficult to discern how much of the DC signal is truly from the

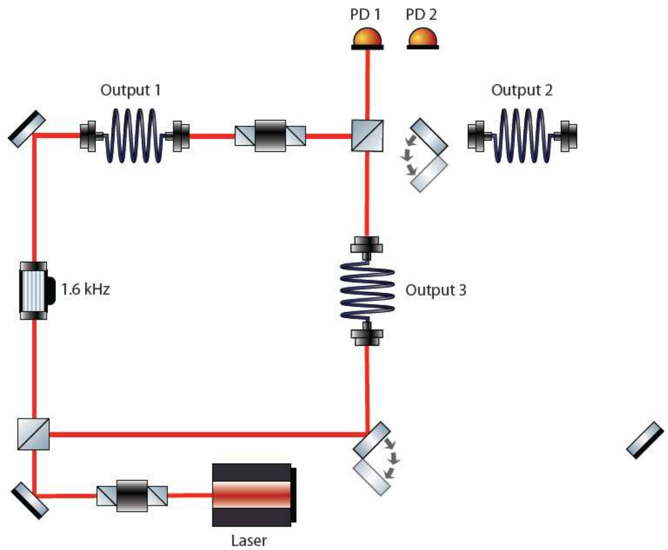

Figure 4: The setup used to measure the direct beat signal of the beams from outputs 1 and 3.

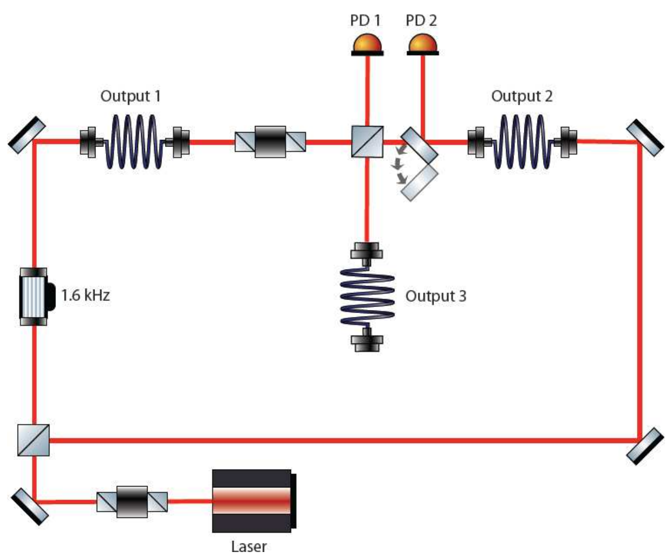

Figure 5: The setup for measuring the back-reflection of the fiber in output 3. Output 1 is used as the local oscillator while output 2 provides the incident light which is reflected off of output 3.

back-reflection. Because the inconsistencies in our measurements of the DC back-reflection and the fact that only the AC back-reflection plays a role in the fiber non-reciprocity test we decided to focus most of our attention to the measurement of AC back-reflection.

Table 1 shows results we obtained from the setup shown in Figs. 4 and 5. Fig. 6 is a bar graph of the percentages of the direct beat which was back-reflected off all of the fibers while Fig. 7 shows the just the last four. It is quite clear when looking at the data that fiber 4 from Glasgow had the highest back-reflection by a significant margin. The fiber and fiber coupler were actually designed for the LISA pathfinder mission and the difference between it and the other fibers is that it was not cut at an eight degree angle so that any light that is reflected off of the front face is reflected back in the original direction of the beam rather than reflected in the direction of the eight degree offset. Fiber 2 from SEDI also reflected quite a bit of light, however we believe that this due number of differences present in the fiber stemming from the fact that this fiber was manufactured by a different company. A chart of the four fibers with the lowest amount of back-reflection is shown in Fig. 7. Fibers 5 and 8 had the lowest reflectivities and it is important here to note that fiber 8 is the fiber used in the non-reciprocal phase noise test. Because of this it is unlikely that we will find a fiber with a very low reflectivity which will significantly improve our phase noise levels. After measuring the back-reflection of each of these fibers at maximum coupling efficiency, we began to take a closer look at what part of the fiber the reflection was actually coming from.

#	Color	Length	Company	N.A.	Max Coupling Eff.	Percent BRL
1	dark red	6m	Schäfer+Kirchoff	0.12	0.61	5.57×10^{-3}
2	Green	4m	SEDI	0.2	0.53	1.25×10^{-1}
3	black(p)	4m	Schäfer+Kirchoff	0.12	0.77	1.15×10^{-2}
4	Clear	UNK	Glasgow	UNK	0.57	1.87×10^{-1}
5	Black	4m	Schäfer+Kirchoff	0.12	0.91	5.57×10^{-3}
6	Yellow(v)	6m	Schäfer+Kirchoff	0.12	0.81	5.57×10^{-3}
7	green(v)	6m	Schäfer+Kirchoff	0.12	0.85	5.57×10^{-3}
8	green(vp)	4m	Schäfer+Kirchoff	0.12	0.77	5.57×10^{-3}

Table I: Results from the fiber back-reflection measurement.

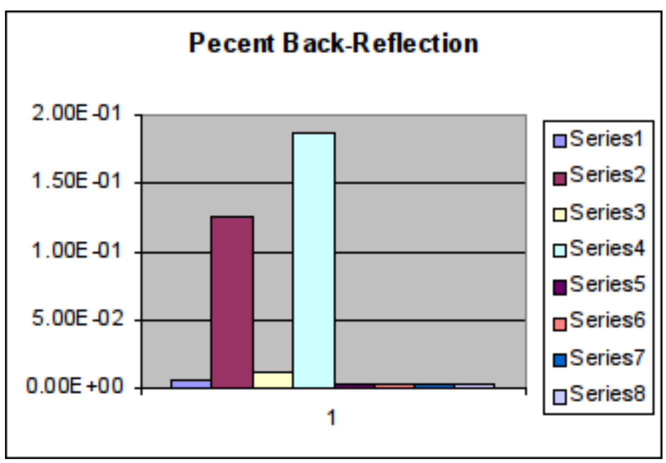

Figure 6: Percent back-reflection.

The next step we took was to explore the actual source of the back-reflection by modulating the laser frequency and examining the signal from fiber 5. At first we attempted to modulate fiber length using a fiber glued to a piezo and later by modulating the distance of the fiber coupler from the incident beam, however both of these methods proved to be

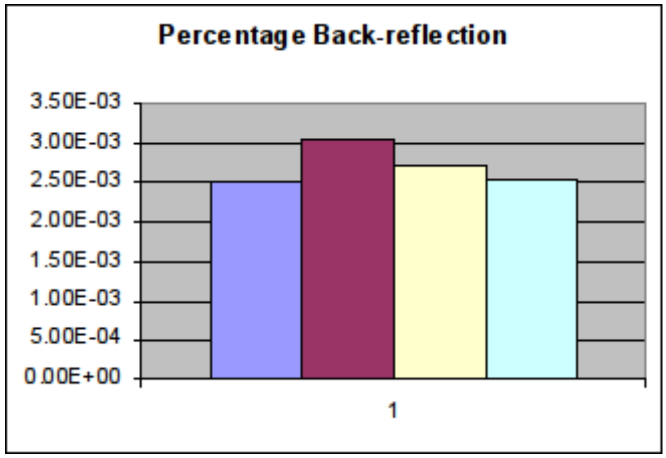

Figure 7: Bar graph of the percent back-reflection. Fiber 5 is in blue, fiber 6 maroon, fiber 7 peach, and fiber 8 teal.

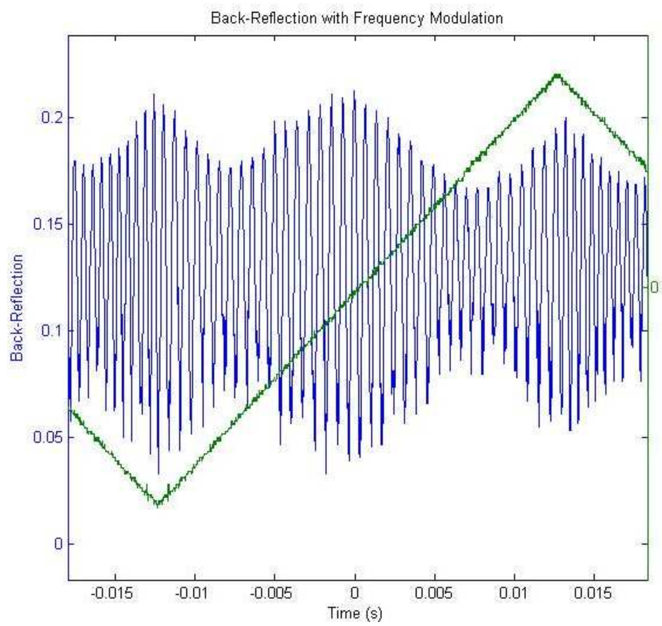

Figure 8: Back-reflected signal with frequency modulation (20 V, 20 Hz) and high coupling efficiency.

extremely inconsistent. Because of this we began to modulate the laser frequency which gave us results we were able to reproduce. By modulating the laser frequency we could see the optical cavity which was formed inside the fiber as light which was reflected off of the front face of the fiber and interfered with light which reflected off of the internal face of the fiber producing an amplitude modulation. By calculating the voltage difference in one free spectral range we could discern the length of the cavity. Fig. 8 shows the amplitude modulation present in the signal. The voltage difference between the two minimums in this fig. 8 was 12.8 V and using the laser specifications of 2 MHz per volt the free spectral range was calculated to be 25.6 MHz. Then by using the equation for free spectral range, FSR=cmedium/(2L), we solved for the length of the cavity and found it to be roughly 4 m, the length of our fiber. This confirmed that the cavity was being formed within the fiber itself as there was no other part of the setup which was longer than 30cm. To ensure that the cavity was being formed by equal amounts of light being reflected off of the internal and front faces of the fiber we then tried modulating the laser and looking at the back-reflected signal while using a very low coupling efficiency. In Fig. 9 it can been seen that no amplitude modulation was present when a very low coupling efficiency through the test fiber was used. This indicates that the back-reflection which is normally seen in the fibers we tested is a combination of the reflections off of the internal and the external face of the fiber. We then began to investigate whether or not we could reduce the percent back-reflection by lowering the coupling efficiency through the test fiber.

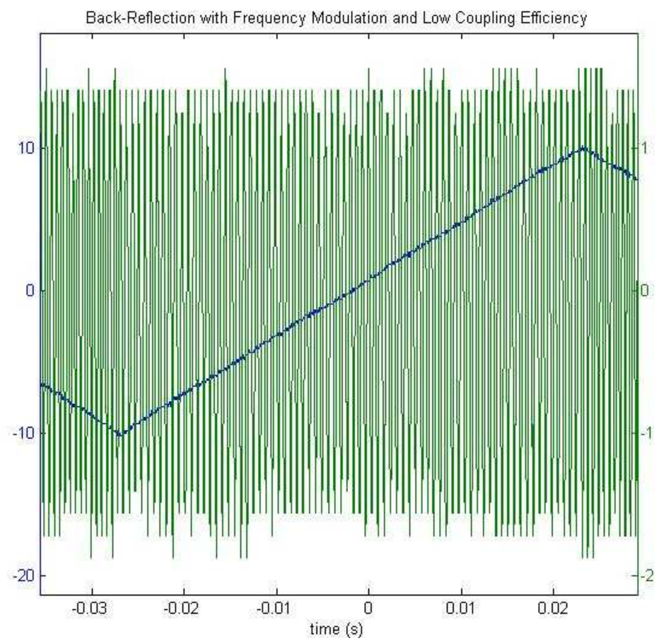

Figure 9: Back-reflected signal with frequency modulation (20 V, 10 Hz) and high coupling efficiency.

To test the effect coupling efficiency had on the percent back reflection we used the same setup shown in Figs. 4 and 5. The only difference was that when we aligned the incident light from output 2 through the fiber in output 3 we varied the coupling efficiency by misaligning the beam along the horizontal axis, the same axis as the eight degree cut in the fiber, instead of trying to maximize coupling. The results from testing fibers 5, 6, and 7 are shown in Fig. 10. These fibers were used because they were the best three fibers that were readily available. Fiber 8 could not be used in this particular test because it was in vacuum being used for the nonreciprocal phase noise tests. We found that there is roughly a linear trend between coupling efficiency and percent back-reflection, but this is not helpful if applied to the phase noise test as even though the percentage of the back-reflection is reduced by some factor with poor coupling, the direct beat signal would also be reduced by the same factor leading to no gain in the signal to noise ratio. A method of reducing the percentage of back-reflection in the direct beat signal by adding attenuators was experimented with next.

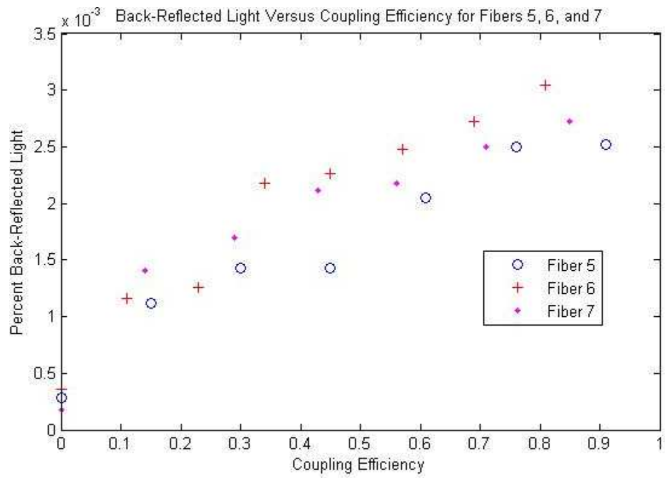

Figure 10: Plot of percent back-reflection versus coupling efficiency.

There were two possible locations to add attenuators in the fiber non-reciprocity test. The first location attenuators were added was between beamsplitters 1 and 2 and beamsplitters 3 and 4. The attenuators being used were neutral density filters which converted light to heat. The ND filters used in this arrangement attenuated the beam by a factor of 100. The equation for the interference signal used for measuring the phase noise is. P1 is the power of the beam which never travels through the fiber and additionally never gets attenuated. P2 is the beam which does travel through the fiber and gets attenuated by a factor of 100. This leads to attenuation in the amplitude of this direct beat signal by a factor of ten. For the back-reflected case light which is incident on the fiber and then back-reflected, P1 for this instance, is attenuated by a factor of 100. Again, light coming from the fiber, P2, has already been attenuated by a factor of 100. Thus the amplitude of the back-reflected signal is attenuated by a factor 100. Therefore, even though we reduced the amplitude of the direct beat signal by a factor of ten, we reduced the amplitude of the back-reflected by a factor of 100 reducing the percentage of the back-reflected light by a ten. Because of this we expected to see an improvement in the noise levels of the phase noise measurements, especially those which were not corrected for the back-reflection. We did not see this improvement in the noise levels so we tried to attenuate the signal again, but at another position. This time we chose to attenuate between beamsplitters 2 and 5 as well as 4 and 6. Here, however, we used ND filters which had attenuation factors of ten rather than 100 and we were still able reduce the percent back-reflection by a factor of ten. The reason for was the fact that the light from the fiber travels through both attenuators and still gets attenuated by a factor of 100 where the incident light gets attenuated by a factor of ten and then the light which is back-reflected also get attenuated by a factor of ten thus attenuating this beam by a factor of 100. Therefore the percent back-reflection is still reduced by a factor of ten even though the ND filters being used had one tenth the attenuation factor. Once more we thought that this reduction in back-reflection would lead to lower phase noise levels particularly in the uncorrected noise measurements and yet again we were wrong. As shown in Fig. 11 the noise level for the uncorrected measurement without attenuation, the red line, is actually lower than the measurement with attenuation, green. The same is true for the measurements in which back-reflection was corrected for. The attenuated signal, in orange, had higher noise levels than the measurement which was not attenuated, blue. The reason we expected to see the lower noise levels was because we thought that in reducing the percentage of back-reflected light we would significantly lower the magnitude of that pseudo signal. It is possible that this did indeed happen, but since we reduced the amplitude of the direct beat signal, our electronics, for the most part the photodiodes, were not sensitive enough to handle the attenuation and introduced new noise which was not present when signal was strong enough such that the photodiode sensitivity did not come into play.

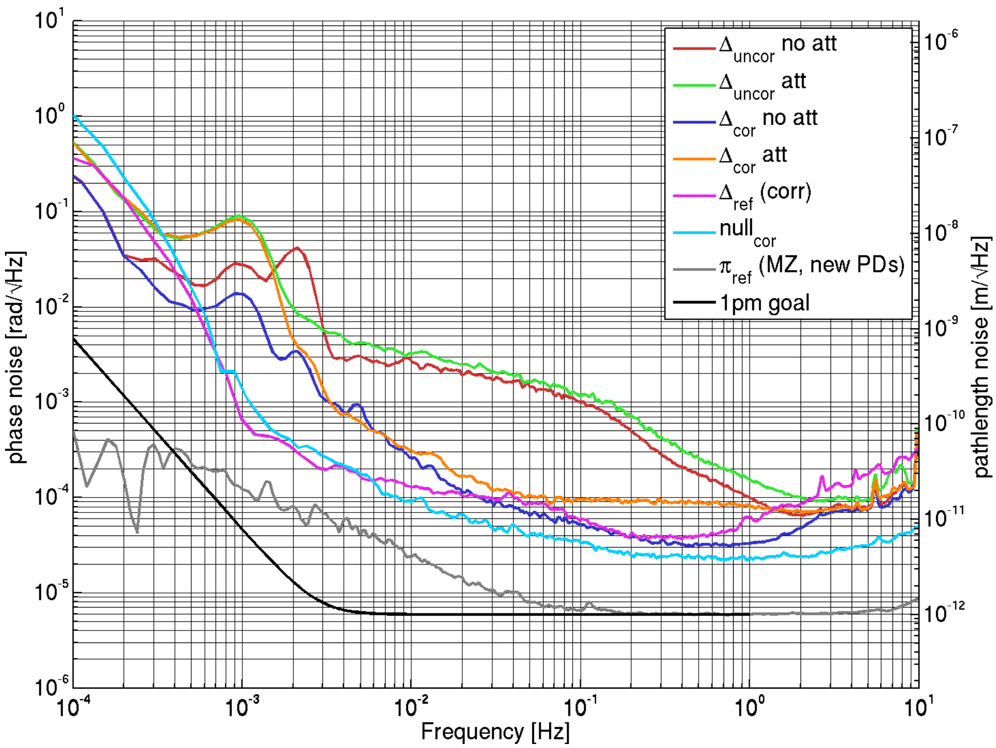

Figure 11: Noise levels with and without attenuation.

To verify that the attenuation actually lowers the percentage of back-reflected light we altered the back-reflection test so that it more closely resembled the phase noise test and then used fiber coupling to attenuate the beams rather than ND filters. The setup for this is shown in Figs. 12 and 13. The main difference between this setup and the one for simply testing the back-reflection is that output 3 is used as the test fiber as well as the local oscillator. To attenuate the back-reflection the coupling efficiency through output 2 and output 3 were reduced by the attenuation factor. Output 1 was used only for the direct beat signal and because of this the coupling efficiency was always kept at its maximum value. Using this scheme the amplitude of the back-reflected signal should have been attenuated by the same factor that the coupling efficiency was reduced. The direct beat signal was expected to be reduced by the square root of the reduction in coupling efficiency while the percent back-reflection was also supposed to be reduced by the square root of the attenuating factor, or the reduction in coupling efficiency. The results were very close to what was expected as seen in Fig. 13. There is a definite trend which resembles a square root function between the percentages of the back-reflection and the attenuation factor. This shows that attenuating the signal can reduce the back-reflection even though it does not necessarily reduce the amount of phase noise.

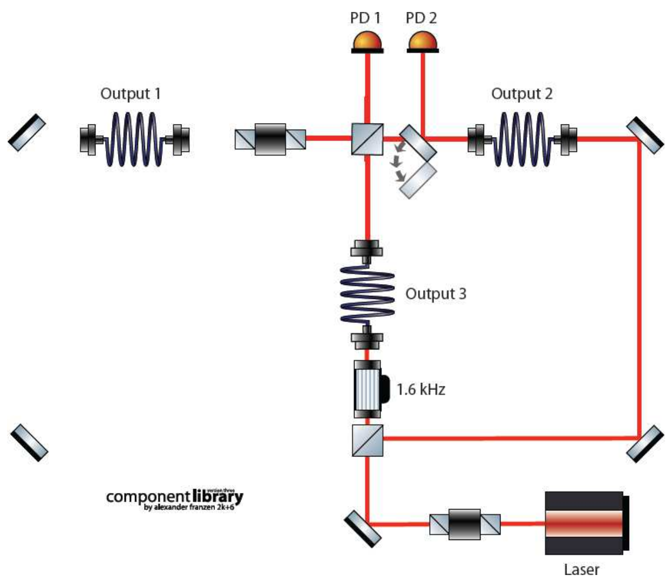

Figure 12: Set-up for measuring attenuated back-reflected light.

Far more research must be done on back-reflection to determine how much of a role it plays in the production of nonreciprocal phase noise. The most pressing issue at the moment is the electronic noise and photodiode sensitivity. Because the correction for the back-reflection works so well at reducing the phase noise levels, it is clear that the back-reflection does effect the phase noise measurement. However, until the electronics are improved it is unclear as to whether or not attenuation will help in reducing the nonreciprocal phase noise. Theoretically it should as our research shows the attenuation schemes we used do reduce the percentage of the back-reflected light in the direct beat signal, but more work must be done to investigate this. Also different attenuation schemes with different methods of attenuation other than the use of ND filters should be examined. It would be very interesting to see if a method of attenuating the back-reflection by altering the coupling efficiency through the back link fiber would be possible. Probably the most useful method of attenuation would be the use of a beamsplitter with an extremely high reflectivity. This would allow for the light to be used somewhere else rather than simply just converted to heat as is the case with ND filters. Finally, a large variety of fibers must be tested to see if there are any fibers with an extremely low back-reflection which could be immediately utilized in the nonreciprocal phase noise tests. If there were such a fiber this would probably be the easiest solution to the problem of back-reflection.

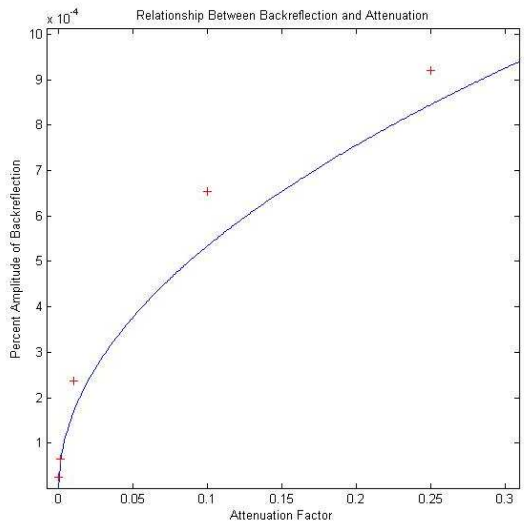

Figure 13: Percent back-reflection versus attenuation factor.

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