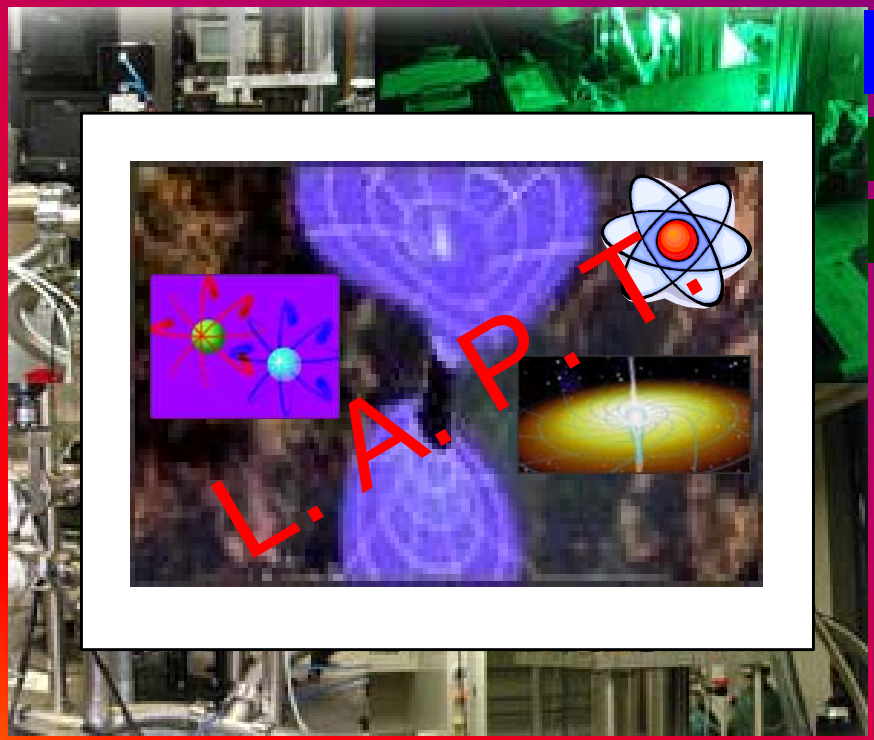
White Light Cavity to Aid Gravitational Wave Detection: A Proposal for Collaboration with the LSC



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Proposing to Join the Existing Group at NU

Existing Group at NU

Group Name: Northwestern University Gravitational Wave Astrophysics Group **(NUGWAG)**

Group Leader: Prof. Vicky Kalogera, Northwestern University

Proposed Expansion of This Group

If my application to join the LSC is approved, I will become a member of this group (NUGWAG). Prof. Kalogera will remain the Group Leader.

Personnel and Facilities

- Prof. Shahriar, the PI, received his SB (Physics), SB, SM and PhD (EECS) from MIT. His adviser was Prof. Shaoul Ezekiel. Dr. Shahriar has extensive experience in precision metrology, including atomic clocks, atomic interferometers, and optical gyroscopes. He has also worked in the fields of quantum information processing, cooling and trapping of atoms, squeezing, and slow and fast light. Two graduate students and a post-doc are part of this effort.

- The laboratory at NU is equipped with four Ti-Sapphire lasers, many diode lasers, floated optical tables, Nd-YAG laser, trapped atoms, atomic beams, optical components, microwave components, and sophisticated measurement tools.

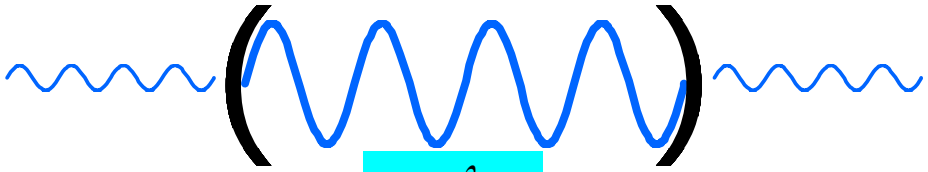
Outline of Proposed Activities

- Become a Member of the Advanced Interferomteric Configuration Workgroup (AICWG). Participate in the activities of the AICWG in particular and LSC in general, beyond the specific technical ideas I am planning to pursue.

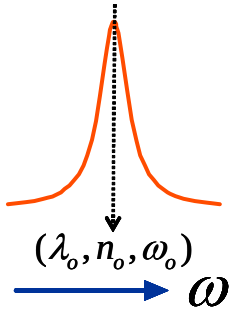
- Investigate the feasibility of using the White Light Cavity to enhance the bandwidth of the Next Generation LIGO without reducing sensitivity

- Participate in the operational activities of the LIGO lab with a student on site as needed

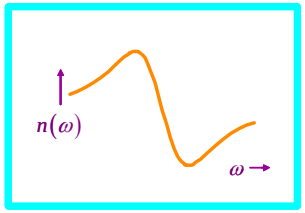
White Light Cavity: Basic Idea



$$\lambda = \frac{\lambda_{vac}}{n}$$



- Condition for WLC: $[\lambda = \lambda_{vac} / n = 2\pi C_o / (n\omega)]$ remains constant as the frequency is varied around
- This simply implies an *anomalous* dispersion:



$$\left.\frac{\partial(n\omega)}{\partial\omega}\right|_{\omega_o} = 0 \quad \Rightarrow \quad \left.\frac{\partial n}{\partial\omega}\right|_{\omega_o} = -\frac{n_o}{\omega_o}$$

- This happens to correspond to *fast-light* with infinite group velocity:

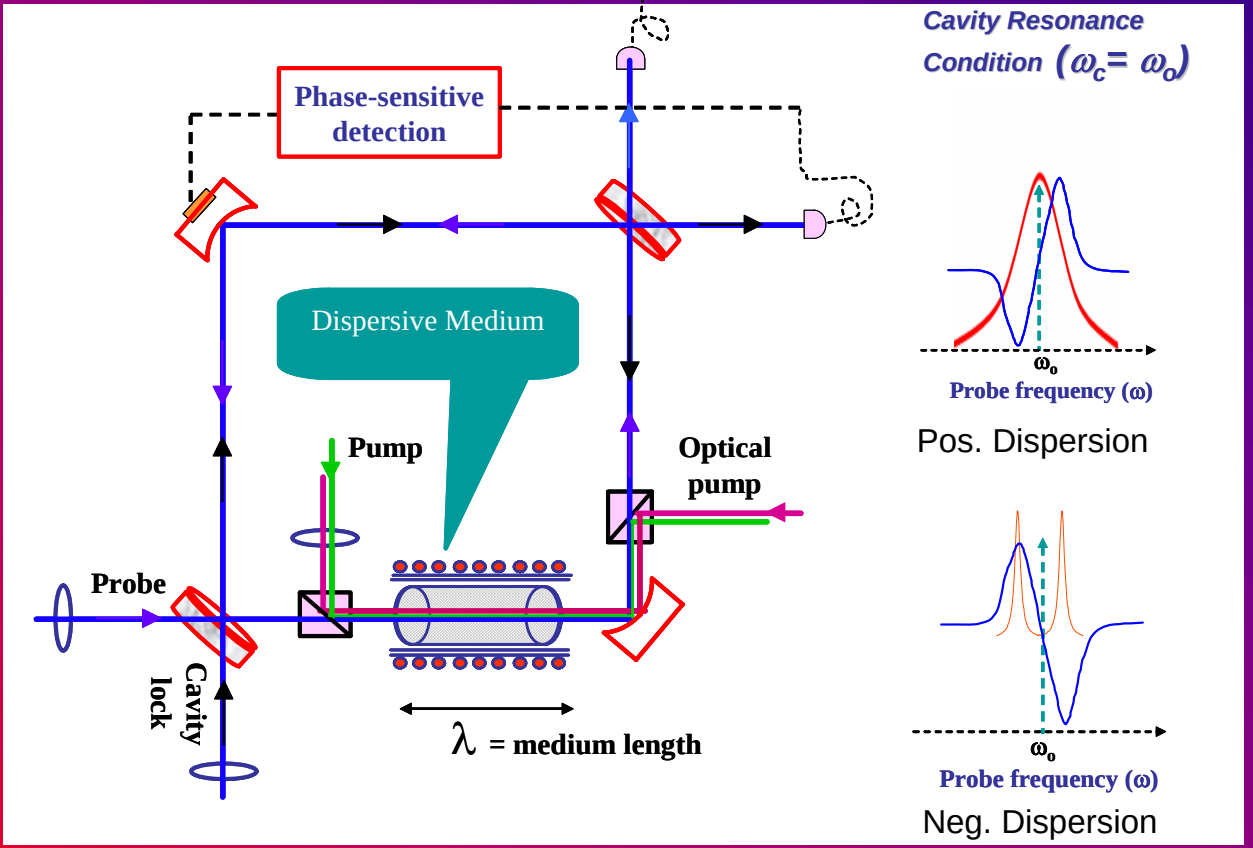
$$v_g = C_o / n_g; \quad n_g \equiv [\partial(n\omega)/\partial\omega]\big|_{\omega_o} = 0$$

A. Wicht, K. Danzmann, M. Fleischhauer, M. Scully, G. Miiller, R.H. Rinkleff, "White-light cavities, atomic phase coherence, and gravitational wave detectors", Opt. Commun. 134, 431 (1997).

R.H. Rinkleff, A. Wicht, "The concept of white light cavities using atomic phase coherence," Physica Scripta T118, 85 (2005)

S. Wise, G. Mueller, D. Reitze, D.B. Tanner, B.F. Whiting," Linewidth-broadened Fabry–Perot cavities within future gravitational wave detectors", Class. Quant. Grav. 21, S1031 (2004).

White Light Cavity: Experimental Demonstration



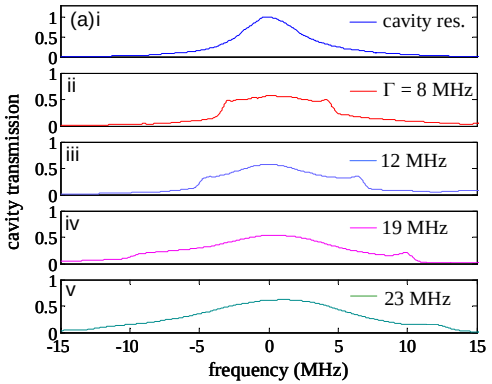
G.S. Pati, M. Messal, K. Salit, M.S. Shahriar, Phys. Rev. Lett. 99, 133601 (2007)

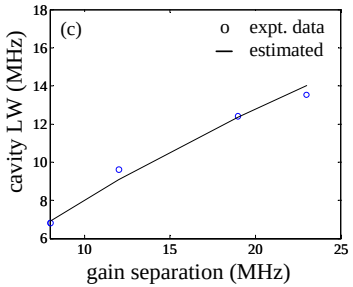
M.S. Shahriar, G.S. Pati, R. Tripathi, V. Gopal, M. Messal, Phys. Rev. A 75, 053807 (2007)

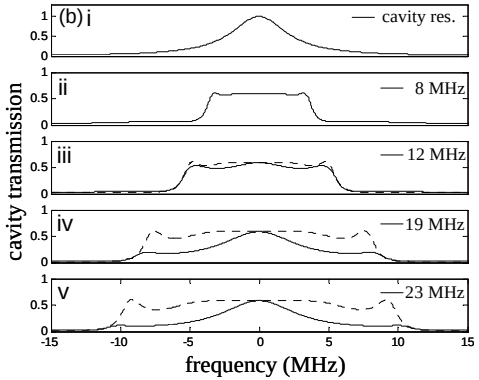
R. Tripathi, G.S. Pati, M. Messall, K. Salit, M.S. Shahriar, Opt. Commun. 266, 604 (2006)

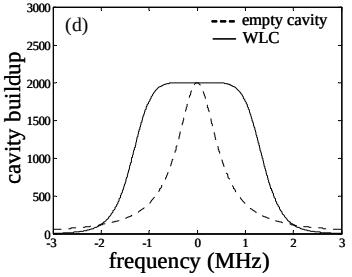
Salit, M., Pati, G. S., Salit, K. and Shahriar, M. S., Journal of Modern Optics, 54:16, 2425 (2007)

White Light Cavity: Experimental Demonstration









G.S. Pati, M. Messal, K. Salit, M.S. Shahriar, "Demonstration of a tunable-bandwidth white light interferometer using anomalous dispersion in atomic vapor," Phys. Rev. Lett. 99, 133601 (2007)

Relevance of White Light Cavity to Ad-LIGO

- The WLC would enhance the Sensitivity-Bandwidth Product of the Advanced LIGO

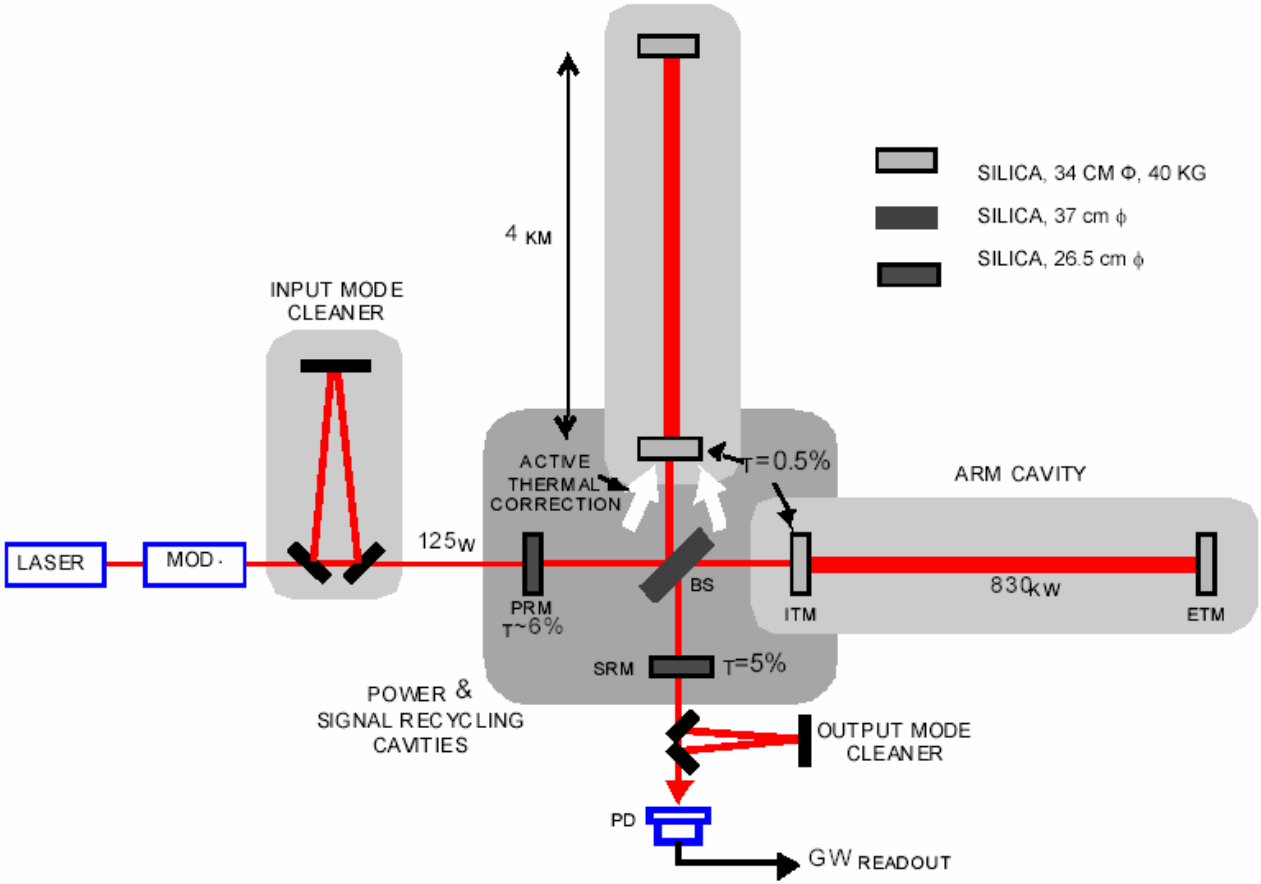
- We believe the WLC can, at some point, be added to the existing arhitecture of the Advanced LIGO

- Alternatively, the WLC can be considered for the Next-Generation LIGO

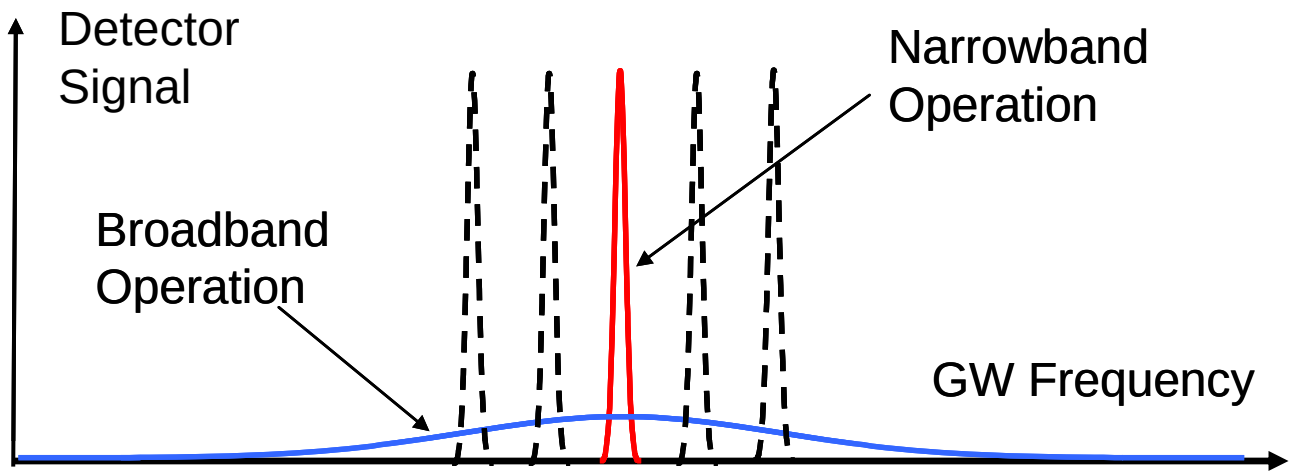
- WLC is compatible with other ideas such as use of Squeezed Light

Salit, M., Pati, G. S., Salit, K. and Shahriar, M. S. , Journal of Modern Optics, 54:16, 2425 (2007)

BASIC FEATURES OF ADVANCED LIGO

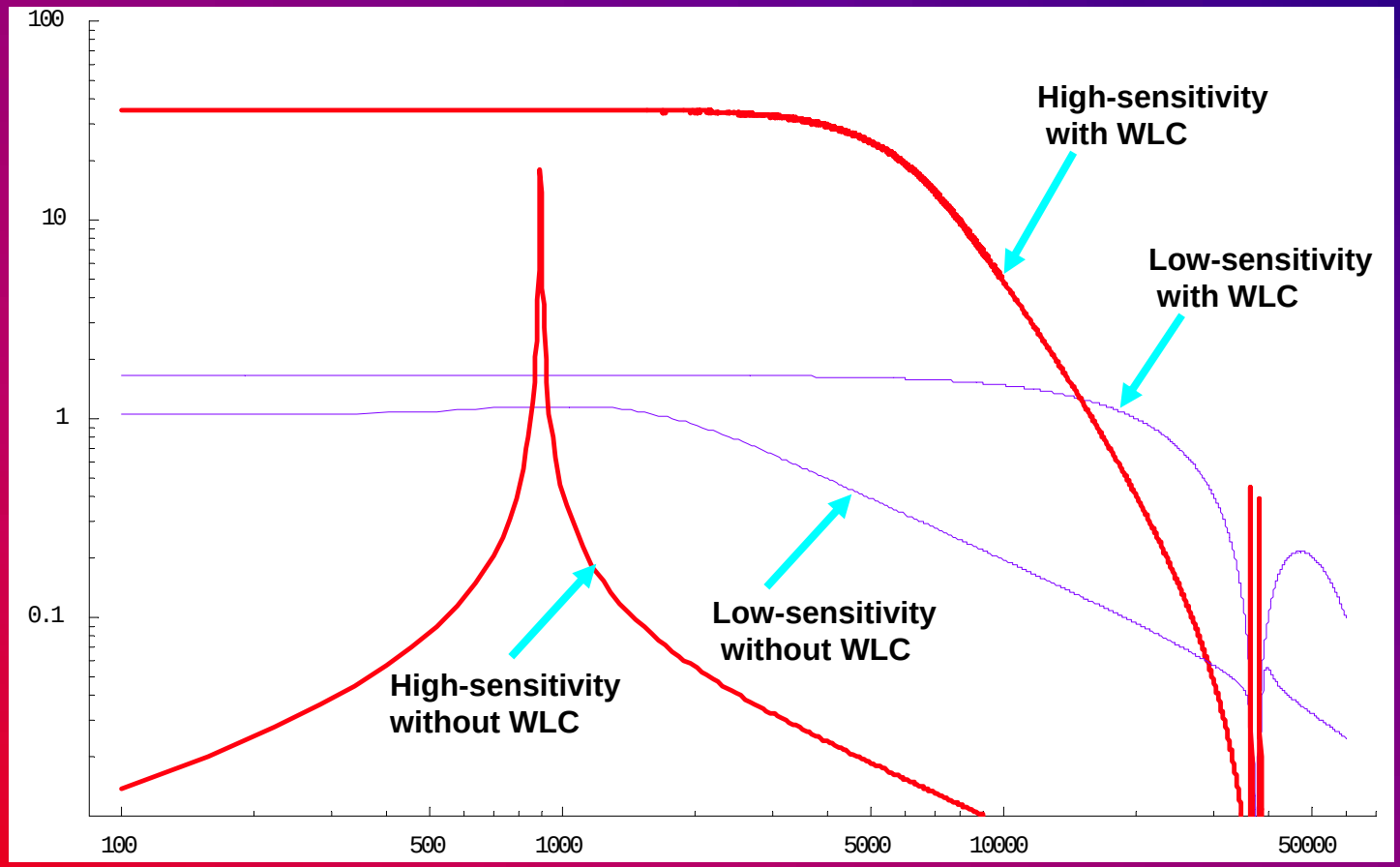


Limitation of Advanced LIGO: Sensitivity-Bandwidth Product



- Sensitivity-Bandwidth Product is fixed by system parameters
- Sensitivity is of paramount importance for Advanced LIGO design
- Problem for inherently broadband and chirped sources
- Several ideas have been proposed to solve this problem. These include (i) Simply broadband dual recycling (ii) Frequency agile interferometers that can follow a chirp, and (iii) input/output cavity techniques that can make optimal filters for specific source spectra. Our approach seems the simplest, and is to be compared/contrasted with these as part of this collaboration

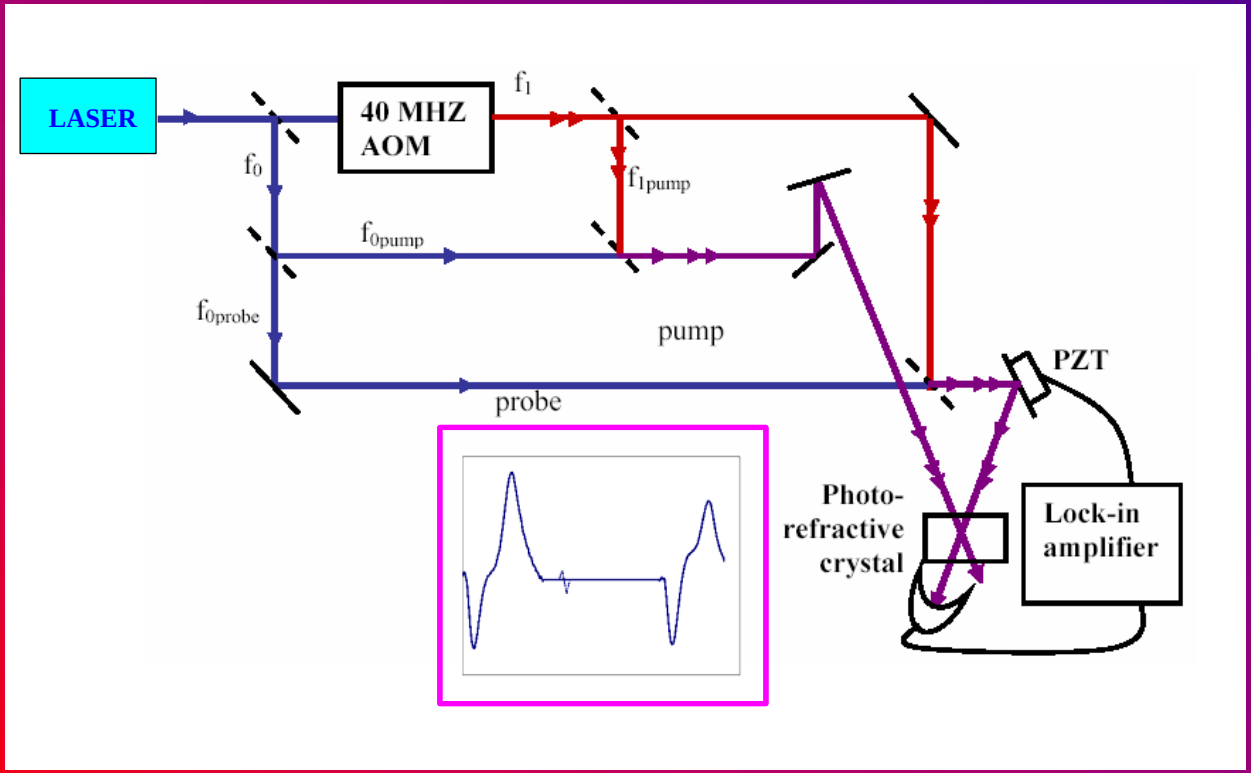
Ad-LIGO with and without the WLC

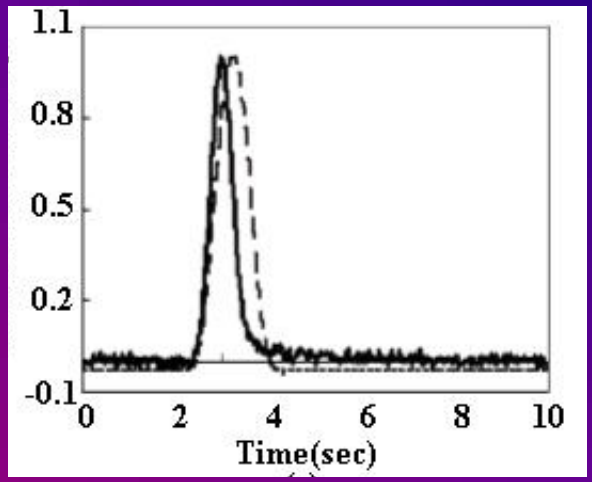


Note: The factor of 2 enhancment in sensitivity is due to the fact that both sidebands are resonant under WLC

Salit, M., and Shahriar, M. S. "Enhancement of Sensitivity-Bandwidth Product for a White Light Cavity LIGO Interferometer with Power and Signal Recycling," (Preprint)

Fast-Light for WLC demonstrated for LIGO wavelength





H.N. Yum, M. Salit, G.S. Pati, S.Tseng, P.R. Hemmer and M.S. Shahriar, "Tunable Fast Light for a White Light Cavity using a Photorferactive Crystal" (preprint) (http://lapt.eecs.northwestern.edu/preprints/demo-bto-for-wlc.pdf)

Q. Sun, M. S. Shahriar, M. S. Zubairy, "Slow light and fast light in a photorefractive crystal" (preprint) (http://lapt.eecs.northwestern.edu/preprints/slow-fast-prc.pdf)

Plan for Next Year in Collaboration with the AIC Workgroup

1. Construct And Test A Table-Top Version Of the Ad-LIGO Interferometer, Including SR and PR Mirrors, at the LIGO Wavelength:

This will be done with optics for the 1064 nm wavelength. The strain due to a + polarized gravitational wave will be simulated by modulating the position of the extremal mirros of the FPC's inside the MI. The system parameters will be adjusted in order to go from narrow-band to wide-band operations, and the concommitant drop in measurement sensitivity will be catalogued.

During this experiment, we will consult extensively with the AICWG in order to ensure that the features of AdLIGO are reproduced with as much fidelity as possible.

2. Add A WLC Dispersive Element To This System, And Demonstrate The Bandwidth Enhancement Effect:

Once the model AdLIGO is operational, we will insert an SPS Crystal based WLC in the system. We will demonstrate how the complete system achieves the same bandwidth as the broad-band case when the WLC is activated, without losing the sensitivity.

During this experiment, we will work closely with the AICWG, both at the design phase as well at the operational phase.

We will work with AICWG as well other members of the LSC in order to ensure compatibility of this system with the planned insertion of squeezed light.

We will also work with AICWG and others to characterize, theoretically and experimentally, all sources of potential noise contributed by the WLC. Our preliminary analysis indicate that it should be possible to suppress the residual noise to a level below the expected Ad-LIGO sensitivity.

How would my effort benefit from joining the LSC?

- My students and I would be able to consult with cognizant members of LSC and the AICWG as we proceed with our theoretical and experimental work towards testing the feasibility of using the WLC for LIGO.

- We would be able to attend meetings of AICWG and other workgroups in order to keep abreast of emerging issuse and ideas, and determine how they may affect our workplan.

- By participating in the operational activities of the LIGO lab, my students and I will develop a comprehensive understanding of some of the experimental details that are important as we develop the design for adding WLC to LIGO.

- Feedback and guidance from LSC members would be important as we seek financial support for our work, which is difficult to pursue without such support

- While, in principle, such collaboration can happen even without my membership in LSC, it is likely to be very limited in scope. For example, some of the meetings of the workgroups are open to LSC members only.

Why should LSC add me as a member?

- The concept of using the WLC to enhance the sensitivity-bandwidth product of LIGO has been around for more than a decade, and is widely accepted by the AICWG community as a valid and important idea.

- Several groups in Europe and the USA have pursued various experimental approaches to demonstrate a WLC that yields the desired functionality. In a recent experiment published in PRL, we have finally showed that a WLC can indeed be realized, and has the desired properties suited for LIGO. As such, it is a viable and important technical breakthrough for the next generation LIGO, and should be looked at seriously by the AICWG.

- In the unlikely event that for some unforeseen reason the WLC will not work for Advanced LIGO or beyond, we will redirect our resources to help with other issues being addressed by the AICWG. Given the expertise of my group in interferometry (optical and atomic), quantum noise studies, and precision metrology, we can contribute significantly to many aspects of the activities of the AICG. The experimental facilities in our laboratory would serve as a valuable resource as well.

Relevant Publications and Preprints

Experimental

G.S. Pati, M. Messal, K. Salit, M.S. Shahriar, Phys. Rev. Lett. 99, 133601 (2007)

R. Tripathi, G.S. Pati, M. Messall, K. Salit, M.S. Shahriar, Opt. Commun. 266, 604 (2006)

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G.S. Pati, M. Messal, K. Salit, M.S. Shahriar, "Demonstration of tunable displacement- measurement-sensitivity using variable group index in a ring resonator," (preprint) (http://lapt.ece.northwestern.edu/preprints/demo-of-tunable-sensitivity.pdf)

Salit, M., and Shahriar, M. S. "Enhancement of Sensitivity-Bandwidth Product for a White Light Cavity LIGO Interferometer with Power and Signal Recycling," (Preprint)

Theoretical

M.S. Shahriar, G.S. Pati, R. Tripathi, V. Gopal, M. Messal, Phys. Rev. A 75, 053807 (2007)

H.N. Yum, M. Salit, G.S. Pati, S.Tseng, P.R. Hemmer and M.S. Shahriar, "Tunable Fast Light for a White Light Cavity using a Photorferactive Crystal" (preprint) (http://lapt.eecs.northwestern.edu/preprints/demo-bto-for-wlc.pdf)

Q. Sun, M. S. Shahriar, M. S. Zubairy, "Slow light and fast light in a photorefractive crystal" (preprint) (http://lapt.eecs.northwestern.edu/preprints/slow-fast-prc.pdf)

M.S. Shahriar and M. Salit, "Fast-Light Enhanced Strain Sensitivity for Gravitational Wave Detection," (preprint) (http://lapt.eecs.northwestern.edu/preprints/FE-ZASRL-GWD.pdf)

M.S. Shahriar and M. Salit, "A Fast-Light Enhanced Zero-Area Sagnac Ring Laser Gravitational Wave Detector," in Proceedings of the SPIE Photonics West, San Jose, CA (2008)

Q. Sun, M. S. Shahriar, M. S. Zubairy, "Effects of parameter variations and noises on a double-Raman white light cavity", (http://lapt.eecs.northwestern.edu/preprints/noise-in-double-raman-wlc.pdf)