

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) January 2013		2. REPORT TYPE Journal Article		3. DATES COVERED (From - To) January 2013- March 2013	
4. TITLE AND SUBTITLE External Multipass Optical Ring Cavity for Counterpropagating Pulsed Laser Applications				5a. CONTRACT NUMBER In-House	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Jacob S. Graul, Taylor C. Lilly, Geoff P. Andersen, Andrew Ketsdever				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER Q12G	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/RQRS 1 Ara Drive. Edwards AFB CA 93524-7013				8. PERFORMING ORGANIZATION REPORT NO.	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/RQR 5 Pollux Drive Edwards AFB CA 93524-7048				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-RQ-ED-JA-2013-058	
12. DISTRIBUTION / AVAILABILITY STATEMENT Distribution A: Approved for Public Release; Distribution Unlimited. PA#13212					
13. SUPPLEMENTARY NOTES Journal Article for Applied Physics B.					
14. ABSTRACT With the intent of increasing the efficiency of laser-gas interactions, an external bidirectional multipass optical cavity has been developed for use with counterpropagating high energy pulsed lasers. By exploiting the closed-path recirculation of two counterpropagating laser pulses, obtained through polarization-dependent trapping of the pulses inside the cavity via a Pockels cell, such an optical cavity allows the counterpropagating pulses to repeatedly and concurrently interact within a specific region in space. This cavity allows the setup to exhibit an effective pulse repetition frequency much higher than the loading laser. This increased repetition frequency permits greater sensitivity in probing a medium or increased energy deposition, depending on application, over the single pass case. Pulses from a 12 mJ, frequency doubled, 5 ns FWHM, pulsed Nd:YAG laser were split and injected into opposing sides of a symmetric multipass 2.44 m (96 in) optical ring cavity. Using a Pockels cell, the counterpropagating pulses were 'locked' into the cavity for ≥ 50 cavity round trips. This represents an 8 fold increase in the interacting laser energy over the single pass case. This cavity concept suggests a variety of potential applications ranging from established cavity processes, e.g. laser-based absorption spectroscopy studies and x-ray production, to new processes which can benefit from the counterpropagating feature of this design, such as non-resonant optical lattice gas heating and time-resolved coherent Rayleigh-Brillouin scattering diagnostic studies of a rapidly evolving flow.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Marcus Young
Unclassified	Unclassified	Unclassified	SAR	11	19b. TELEPHONE NO (include area code) 661-525-6264

Standard Form
298 (Rev. 8-98)
Prescribed by ANSI
Std. Z39.18

External Multipass Optical Ring Cavity for Counterpropagating Pulsed Laser Applications

Jacob S. Graul¹

ERC Inc., Edwards AFB, CA 93524, USA

Taylor C. Lilly²

University of Colorado, Colorado Springs, CO80918, USA

Geoff P. Andersen³

United States Air Force Academy, Colorado Springs, CO 80840, USA

Andrew D. Ketsdever⁴

Air Force Research Laboratory, Edwards AFB, CA 93524, USA

With the intent of increasing the efficiency of laser-gas interactions, an external bidirectional multipass optical cavity has been developed for use with counterpropagating high energy pulsed lasers. By exploiting the closed-path recirculation of two counterpropagating laser pulses, obtained through polarization-dependent trapping of the pulses inside the cavity via a Pockels cell, such an optical cavity allows the counterpropagating pulses to repeatedly and concurrently interact within a specific region in space. This cavity allows the setup to exhibit an effective pulse repetition frequency much higher than the loading laser. This increased repetition frequency permits greater sensitivity in probing a medium or increased energy deposition, depending on application, over the single pass case. Pulses from a 12 mJ, frequency doubled, 5 ns FWHM, pulsed Nd:YAG

¹ Co-op Researcher

² Assistant Professor, Dept. of Mechanical and Aerospace Engineering

³ Senior Scientist, Laser and Optics Research Center

⁴ Senior Research Engineer, AFRL/RQRS

laser were split and injected into opposing sides of a symmetric multipass 2.44 m (96 in) optical ring cavity. Using a Pockels cell, the counterpropagating pulses were ‘locked’ into the cavity for ≥ 50 cavity round trips. This represents an 8 fold increase in the interacting laser energy over the single pass case. This cavity concept suggests a variety of potential applications ranging from established cavity processes, e.g. laser-based absorption spectroscopy studies and x-ray production, to new processes which can benefit from the counterpropagating feature of this design, such as non-resonant optical lattice gas heating and time-resolved coherent Rayleigh-Brillouin scattering diagnostic studies of a rapidly evolving flow.

1. Introduction

One solution for increasing laser gas interaction frequency and efficiency is a multipass cavity. An external, bidirectional multipass optical ring cavity has been developed for use in counterpropagating high energy pulsed laser-gas interactions. By exploiting the closed-path recirculation of two counterpropagating laser pulses, obtained through polarization-dependent trapping of the pulses using a Pockels cell, this cavity setup allows counterpropagating pulses to repeatedly and concurrently interact within a specific region in space with a frequency much higher than the loading laser. This permits the setup greater sensitivity in probing a gas medium, or alternatively, increased energy deposition over the single pass case. Apart from potential applications in various atomic and molecular spectroscopy studies, scattering experiments, and energy storage and amplification schemes, the counterpropagating nature of this cavity lends itself to implementation in applications requiring the interaction between counterpropagating high energy laser pulses.

Two specific applications that stand to benefit from the multipass cavity characterized by this study are coherent Rayleigh-Brillouin scattering (CRBS) [1-4] and optical lattice gas heating [5-7], both requiring counterpropagating pulses and therefore unable to utilize previous, single pulse, single direction designs. CRBS is a non-resonant four-wave mixing technique that has proven to be a useful gas-phase diagnostic tool, able to yield valuable thermodynamic information about the scattering medium, e.g. temperature, density, and thermal conductivity, as well as bulk and shear viscosity. In CRBS an optical lattice, formed from the interference pattern created by two counterpropagating and colinearly polarized laser fields, is used to create a periodic density grating in a polarizable

gas medium. By scattering a third probe laser off of the resulting density perturbation, the line shape of the coherently backscattered signal can be analyzed using approximations to the 1-D Boltzmann equation. This analysis connects scatter signal intensity as a function of the signal frequency to thermodynamic and kinetic properties of the gas medium. Experimentally obtaining these line shapes has proven to be labor intensive. For example, the CRBS studies of Cornella et al. [1] required scanning over a pump frequency difference of ~5 GHz. To achieve the necessary resolution, this scanning could only be performed in increments of 15 MHz, with 100 shots taken per increment. For a given CRBS line shape presented, approximately 30,000 shots were required at 10 Hz. Using broadband pumps, a narrowband probe, and an etalon to resolve the spectrum of the CRBS signal, a similar study by Pan [3] also required thousands of laser shots to scan one line shape. Current experimental approaches required to obtain a CRBS line shapes limit the potential of CRBS as a laser gas diagnostic tool for dynamic processes. Given an ability to obtain the full spectral profile in one shot, the multipass cavity proposed and characterized in this study suggests that time-resolved CRBS diagnostics of a medium may be possible. The use of the described multipass cavity could allow for time-resolved gas medium diagnostics by yielding discrete CRBS line shapes over a predictable and constant cavity-dependent time interval.

The second application that could potentially benefit from implementation of this study's optical cavity is that of non-resonant optical lattice gas heating; a technique that has recently been experimentally validated by Cornella [8]. Detailed more fully in references that follow, the axially periodic optical potential comprising an optical lattice exerts a force on polarizable molecules. Lilly et al. [5-7] have presented the results of several Direct Simulation Monte Carlo (DSMC) simulations investigating various parameters involved in the formation of optical lattices in an idealized optical cavity. Since the "ratio of deposited energy to total laser energy is small for gases at atmospheric pressures, typically below 10^{-6} ," [7] the implementation of multipass optical cavities in these simulations leverages the fact that optical cavities are able to provide specific interaction regions where anti-parallel counterpropagating laser pulses may be passed rapidly many times. This rapid pulse recycling thereby provides these pulsed beams with the repeated opportunity to deposit energy into a test gas, increasing the efficiency of energy deposition.

As a basis for the studied cavity, single direction, single pulse multipass optical cavities are referenced for increasing the efficiency of several particle and optical absorption-based experiments [9-11]. For example, in an effort to develop more compact X-ray sources over conventional synchrotron radiation methods, Meng et al. [9]

designed and tested a multipass optical cavity to increase the intensity of X-rays obtained through inverse Compton scattering. Using a polarization sensitive cavity, Meng obtained greater than 15 round trips using a pulsed (1.4 mJ, 10 ns) frequency-doubled Nd:YAG. This corresponded to a 3.5-fold increase in the total laser interaction per pulse.

2. Design Considerations and Experimental Setup

To support the counterpropagating pulse requirement, it was determined that a potential cavity must 1.) be able to efficiently trap and contain light at the desired wavelength, 532 nm, 2.) exhibit a high damage threshold, 3.) allow for the simultaneous injection of pulses, and 4.) support the spatial and temporal superposition of the counterpropagating pulses, while 5.) reducing beam diameters in the pulse interaction region down to approximately 50 μm to achieve the necessary laser intensity for future counterpropagating laser-gas interaction studies. Inspired by the unidirectional energy storage Pockels cell cavity design of Mohamed et al. [10, 11] and the Compton scattering cavity of Meng et al. [9], a notional illustration of the tested cavity design is shown in Figure 1.

After passing through a series of conditioning $\lambda/2$ and $\lambda/4$ wave plates and an Electro-Optics Technology Inc. Faraday isolator to prevent damaging back reflections, pulsed broadband light (532 nm, 4 mJ, 5 ns FWHM pulse) from a Nd:YAG Continuum Minilite was split using a 50:50 non-polarizing beam splitter. Each pulse was then routed through either a divergent or convergent Galilean telescope, which was pre-determined to offset the direction-dependent convergence or divergence induced an intracavity Keplerian telescope. Each pulse was simultaneously injected into the 2.44 m (96 in) cavity by traversing two polarizing beam splitting cubes (PBC), which serve as injection gates and then mirrors. Upon passing through these PBCs for the first time, s-polarized light in the pulse was ejected from the cavity.

Each pulse then transited the intracavity, 6 mm aperture, longitudinal-type, Leysop KD*P Pockels cell. KD*P was chosen for its high relative damage threshold and availability, as well as its transparency from the UV to infrared. The Pockels cell was held at the 532 nm half-wave voltage (~ 3 kV) on the first pass only, driven by a 250 ps rise time, ~ 6 ns FWHM pulse width, 10 Hz PRF high-voltage driver. Upon transiting the Pockels cell, a 180° phase shift in polarization was induced in both pulses. This phase shift effectively trapped both pulses inside the cavity. Each pulse, now trapped, was directed through a Keplerian lens set, whereupon the pulses continued propagating around the ring cavity until completely extinguished due to the accumulation of losses on successive roundtrips. Due to the relatively low Pockels cell driver pulse repetition frequency, ‘opening’ the cavity by re-

pulsing the Pockels cell was not possible. Precise timing control of the laser, as well as the Pockels cell voltage driver was achieved using Stanford Research DG535 delay generators. To characterize the performance of the cavity, a biased Si PIN photodiode was used in conjunction with an Agilent 54855A oscilloscope to monitor a purposely-induced cavity loss. To diagnose the cavity, a slight $\lambda/2$ wave plate-induced loss was used on successive round trips at one of the polarizing beam splitting cubes. With this purposely-induced loss, it was possible to quantitatively monitor the number of total round trips obtained for a given cavity geometry in both counterpropagating directions, as well as qualitatively evaluate the stability of the cavity.

The optical focusing system, comprised of the two upstream Galilean telescopes and one intracavity Keplerian telescope, was implemented and optimized to maintain the pulses within the cavity and control the downstream spot size, particularly for the application requirement of micron-sized spot sizes between the Keplerian lenses. The upstream extracavity Galilean telescopes were used to induce beam divergence or convergence in order to offset the direction-dependent convergence or divergence caused by the asymmetric intracavity Keplerian telescope. The intracavity Keplerian was used to magnify or demagnify the beam, depending on which direction the light was passed, as well as for its ability to focus the trapped laser pulses down to a very small focal point between the Keplerian lenses. The Keplerian telescope was asymmetric in order to provide a stable spot size condition within the cavity on successive round-trips. The small focal region, producing beam diameters on the order of 50 μm , was necessary for CRBS studies.

A MATLAB-based numerical analysis was conducted to optimize the lens and length combinations. Requiring lens focal lengths, cavity length, and input beam diameter, the analysis accounted for the geometry of this study's cavity, and solved a system of equations that relate the various telescope optics' focal lengths, separation, image and object distances, and relative positions outside of and within the symmetric cavity. The analysis allowed for the numerical propagation of a single pulse, in each direction, around the cavity; thereby revealing valuable pulse diameter information as a function of cavity location on the n^{th} cavity round trip. A plot of beam diameters as a function of location within the cavity, generated by this analysis, is shown in Figure 2.

3. Results and Discussion

The cavity was experimentally characterized using pulses (4 mJ each, 532 nm, ~5 ns FWHM) from a broadband Q-switched Continuum Minilite Nd:YAG. These results, shown in Figure 3B, were obtained by injecting

pulses into the cavity in both directions and monitoring the wave plate-induced loss at each PBC. The data were taken as an average over 1000 laser shots. The results suggest that, for 4 mJ pulses at 532 nm, the cavity is able to trap and contain pulses in the cavity for approximately 400 ns or 50 round trips. As expected, the pulse periodicity illustrated agrees well with the time required (8.1 ns) for the pulses to make one full round trip around the 2.44 m (96 in) cavity. Aside from the number of round trips supported by the cavity, these results confirm temporal superposition at all times within the Keplerian confocal region. Spatial superposition of the pulses was confirmed on the first round trip using a knife-edging system. However, due to the intrusive nature of this technique, spatial superposition could not be verified on subsequent round trips. To gain a sense of the cavity's pulse retention efficiency, a curve fit, shown in red, was manually applied to the data. This fit approximates round trip pulse amplitudes subject to an 8% loss on successive round trips. Although the round trip pulse amplitudes in the convergent direction are generally larger than those in the divergent direction—a consequence of the direction-dependent spot size difference in optical intensity seen by the photodiode, both propagation directions exhibit comparable round trip energy losses of approximately 10%, which agree with estimated half-wave induced and PBC losses. The variability in pulse amplitude observed between consecutive pulse round trips, in contrast to the predicted results of Figure 3A, suggests that the spatial location of the pulse varies slightly, but consistently, from one round trip to the next. This is an effect that is further compounded by the small photodiode active area (.006 mm²).

These results give an indication of the amount of energy that the cavity provides over the single-pulse case. For the laser parameters used in this study (4 mJ) and the approximate round trip loss observed, 50, the total energy to interact with the interaction region corresponds to 37.1 mJ.

4. Conclusion

Building upon the increased pulse repetition frequency and consequent increases in available light for laser-gas energy deposition conferred by multipass optical cavities, a bidirectional optical ring cavity was developed for the trapping and repeated superposition of counterpropagating high energy laser pulses. To this author's knowledge, this is the first cavity designed to circulate counterpropagating high energy laser pulses. Employing a one-time polarization change provided by a Pockels cell, in conjunction with polarization-sensitive optics, this symmetric 2.44m (96 in) cavity was able to trap pulses (4 mJ, 5 ns FWHM) provided by a broadband 532 nm Nd:YAG laser.

The cavity was able to trap these pulses for approximately 400 ns, corresponding to approximately 50 round trips. Temporal pulse superposition was confirmed on all cavity round trips, with spatial superposition confirmed using knife edges on the first round trip. Based on an observed 8% intentionally induced loss, the 50 pulse round trips sustained by this cavity equates to approximately 37.1 mJ interacting with the gas; an 8-fold increase over a single-pass case. This cavity concepts suggests future application in non-resonant laser gas heating, as well as time-resolved CRBS diagnostic studies.

Acknowledgments

The authors would like to thank the ERC, Inc., the Air Force Office of Scientific Research (AFOSR), and the Air Force Research Laboratory (AFRL/RQRS). In particular the authors wish to thank Dr. Tatjana Curcic (AFOSR/RSE), Dr. David Campbell (ERC, Inc.), and Dr. Barry Cornella (ERC, Inc.) for their generous support throughout this project.

References

- [1] B. M. Cornella, S. F. Gimelshein, M. N. Shneider, T. C. Lilly, and A. D. Ketsdever, "Experimental and numerical analysis of narrowband coherent Rayleigh-Brillouin scattering in atomic and molecular species," *Optics Express*, vol. 20, pp. 12975-12986, 2012.
- [2] X. Pan, "Coherent Rayleigh-Brillouin Scattering," Doctor of Philosophy, Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ, 2003.
- [3] X. Pan, M. N. Shneider, and R. B. Miles, "Coherent Rayleigh-Brillouin scattering in molecular gases," *Physical Review A*, vol. 69, p. 033814, March 22 2004.
- [4] X. Pan, M. N. Shneider, and R. B. Miles, "Coherent Rayleigh-Brillouin Scattering," *Physical Review Letters*, vol. 89, p. 183001, October 28 2002.
- [5] T. C. Lilly, "Laser Manipulation of Atomic and Molecular Flows," Doctor of Philosophy, Aerospace and Mechanical Engineering, University of Southern California, Los Angeles, CA, USA, 2010.
- [6] T. Lilly, S. Gimelshein, and M. Shneider, "Energy Deposition and Chemical Reactions in Gases Stimulated by Interaction with Pulsed Optical Lattices," presented at the AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, USA, 2008.
- [7] T. C. Lilly, S. F. Gimelshein, A. D. Ketsdever, and M. N. Shneider, "Energy Deposition into a Collisional Gas from Optical Lattices Formed in an Optical Cavity," in *26th International Symposium on Rarefied Gas Dynamics*, Kyoto, Japan, 2008, pp. 533-538.
- [8] B. M. Cornella, "Neutral Gas Heating via Non-Resonant Optical Lattices," Doctor of Philosophy, Mechanical and Aerospace Engineering, University of Colorado Colorado Springs, Colorado Springs, CO, USA, 2012.
- [9] D. Meng, F. Sakamoto, T. Yamamoto, K. Dobashi, M. Uesaka, H. Nose, *et al.*, "High power laser pulse circulation experiment for compact quasi-monochromatic tunable X-ray source," *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 261, pp. 52-55, 8// 2007.
- [10] T. Mohamed, G. Andler, and R. Schuch, "Development of an electro-optical device for storage of high power laser pulses," *Optics Communications*, vol. 214, pp. 291-295, 2002.
- [11] T. Mohamed, G. Andler, and R. Schuch, "Active optical storage ring for high-power laser pulses," *Applied Physics B: Lasers and Optics*, vol. 79, pp. 817-821, 2004.

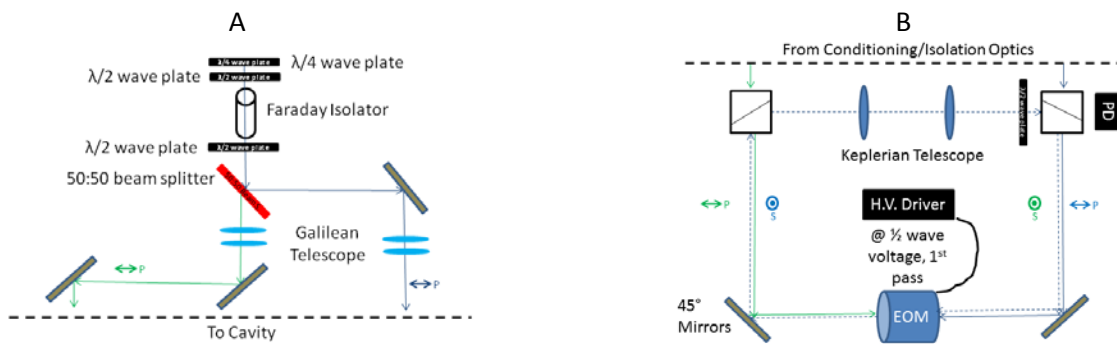


Figure 1. Notional diagrams of A.) upstream optical conditioning and isolation cascade and B.) counterpropagating multipass optical cavity

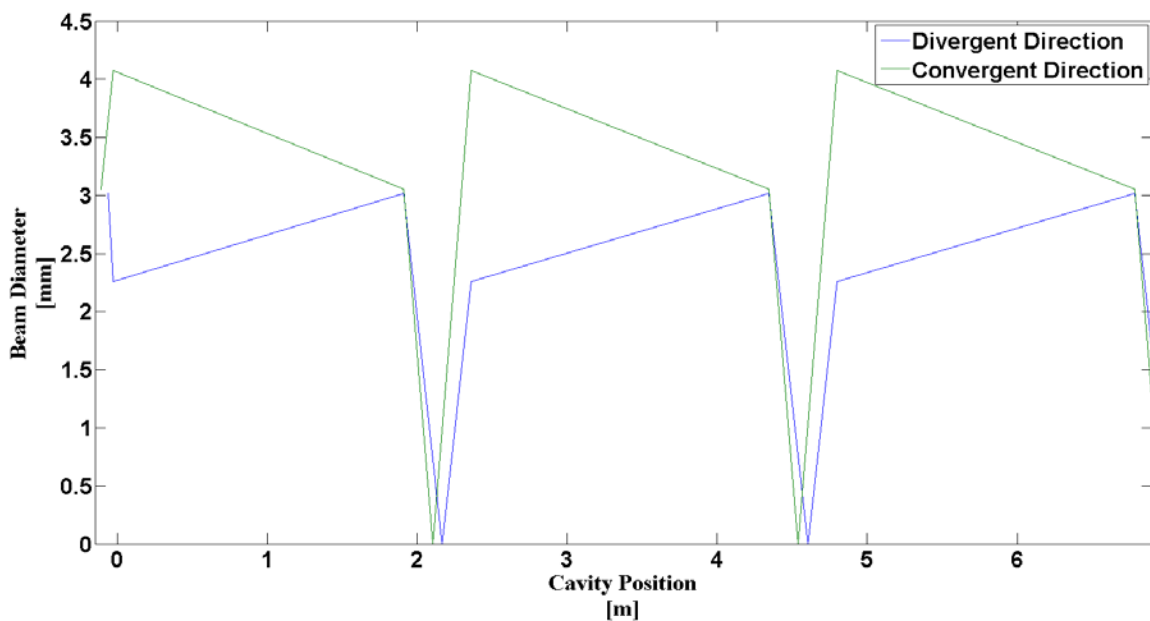


Figure 2. Plot of counterpropagating pulse beam diameter as a function of position within the 2.44 m cavity. Due to the asymmetric nature of the intracavity Keplerian telescope, the Keplerian focal points of the counterpropagating pulses, though not coincident in this plot, are indeed collocated spatially within the Keplerian lens set.

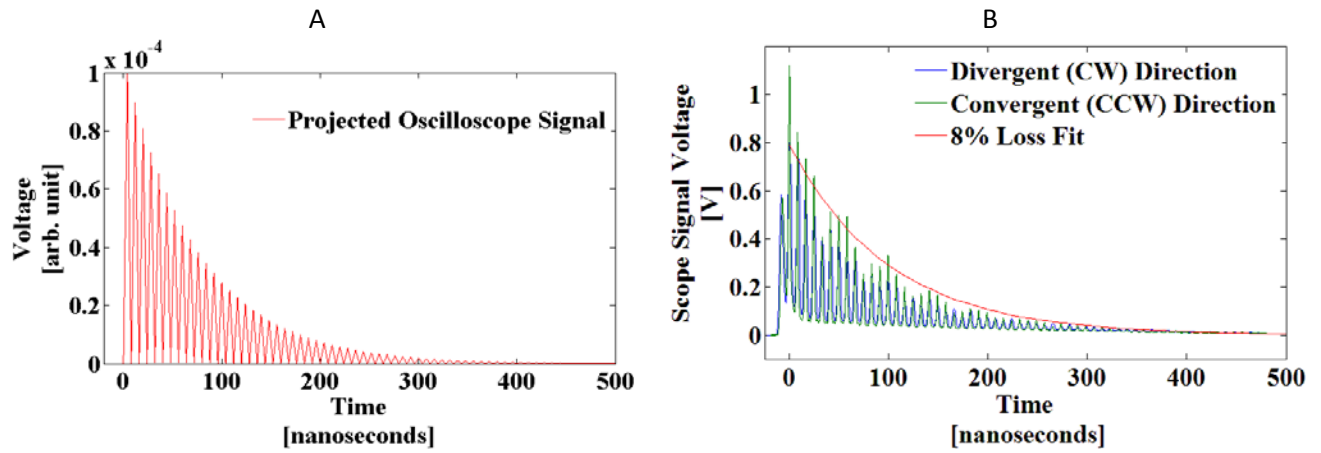


Figure 3.A.) Projected oscillogram based on an induced 10% round trip loss with a cavity length-dependent 8.1 ns round trip period. B.) Broadband 4 mJ Nd:YAG laser oscillogram of purposely induced cavity loss indicating cavity round trips and laser pulse temporal superposition in both the convergent and divergent cavity directions. Please note that the pulse at time $t=0$ is the initial s-polarized kick upon cavity pulse injection.