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13. SUPPLEMENTARY NOTES

14. ABSTRACT
This report describes the technical progress towards the development of wide-band chaotic lidar technologies designed to provide performance improvements in turbid water

15. SUBJECT TERMS
Chaotic Lidar

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WALLACE H. COULTER SCHOOL OF ENGINEERING
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MEMORANDUM

Subject: Annual Report
ULI: FY2012

This document provides a annual report on the project "Advanced Digital Signal Processing" covering FY2012.

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Award Information

Award Number	N000141010906
Title of Research	Chaotic LIDAR for Naval Applications
Principal Investigator	William D. Jemison
Organization	Clarkson University

Technical Section

Technical Objectives

The original proposal identified the following three tasks:

- Task 1 involves the generation and characterization of a wideband chaotic lidar (CLIDAR) signal suitable for system-level experiments.
- Task 2 involves a system-level investigation into the underwater propagation/scattering characteristics of the CLIDAR signals. The investigation will be performed as a function of both optical wavelength and water turbidity (absorption and scattering) in order to determine the range resolution/accuracy and signal to noise performance that can be expected using CLIDAR.
- Task 3 involves the development of an advanced chaotic laser, or CLASER, for use as a compact and cost-effective optical source for CLIDAR. This approach integrates a laser gain medium into an OOR to produce an integrated chaotic optical source.

Progress Statement Summary

Early in the program Task 1 efforts focused on the feasibility of using the open optical resonator (OOR) approach to produce wideband chaotic laser signals. This task was identified as a precursor to Task 3. Last year we reported that we abandoned the OOR approach in favor of a fiber ring laser approach for several reasons. This effectively allowed us to focus more effort on the more important Task 3. We also reported the development of two infrared (IR) low-power fiber ring lasers that exhibited wide instantaneous bandwidth.

Significant progress has been made this past year towards the development of a fiber laser that will satisfy three critical requirements which are 1) an output wavelength in the blue-green; 2) sufficient output power to support underwater experiments; and 3) a chaotic output with an instantaneous bandwidth of at least one gigahertz. To achieve this we adopted a laser design that consisted of low-power chaotic laser source (to achieve the bandwidth), a two-stage fiber amplifier (to achieve high power), and a frequency doubler (to convert from the IR wavelength of 1064nm to a blue-green wavelength of 532nm).

Specifically, we adopted a fiber Fabry-Perot architecture in favor of the fiber ring architecture to reduce cavity losses, which resulted in improved performance with a 20x increase in optical power output from the chaotic laser. This greatly improved our ability to amplify the chaotic laser output. Numerical modeling software was developed based on fundamental laser physics to predict fiber amplifier performance. The pre-amplifier was developed and produced output powers that approached those predicted by simulation. The gain amplifier has also been developed and is producing an output power at 1064 nm of over 5W. The frequency doubler uses a non-linear PPKTP crystal with associated input and output lenses to preserve optical beam quality. The doubler was tested using a commercially available 700mW 1064 nm source and efficiencies were achieved that exceeded the manufacturer's data sheet be insufficient for subsequent amplification, as the preamplifier became ASE-limited at 25mW. A redesigned chaotic fiber laser using a Fabry-Perot cavity configuration emitted over 60mW, a x20 increase over the fiber ring configuration, allowing for full amplification. The Fabry-Perot laser configuration and experimental output power is shown in the following figure.

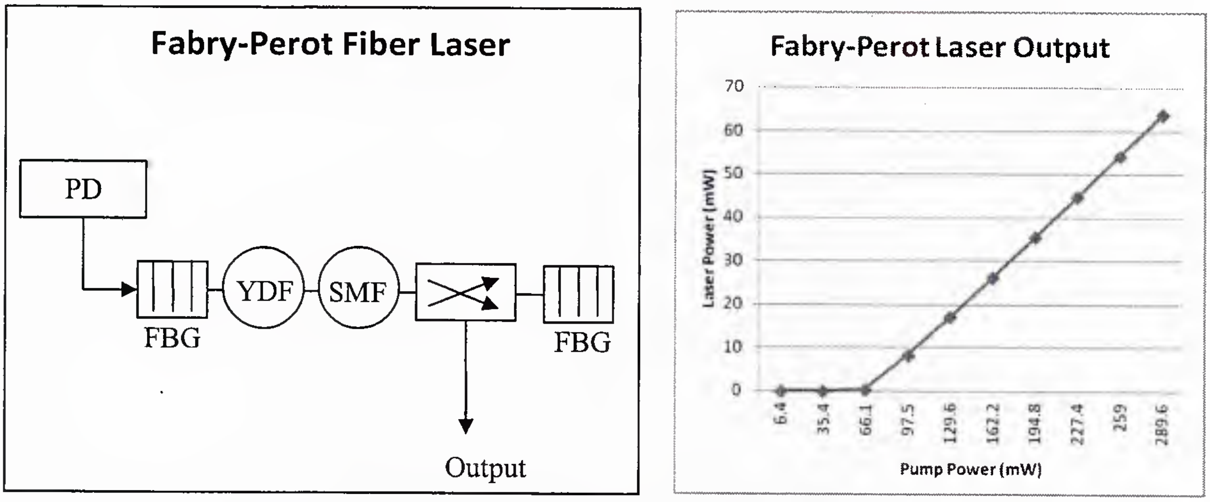


Fig 2. Fabry-Perot chaotic fiber laser. Left: Block diagram of the laser. Right: Output power versus pump power. (PD: Pump Diode; FBG: Fiber Braggs Grating; YDF: Ytterbium Doped Fiber; SMF: Single Mode Fiber.)

Preamplifier Simulation and Experimental Results

The preamplifier was designed to take a nominal 20mW signal and amplify it to 200mW, a gain of 10dB. Numerical simulations of the fundamental laser rate equations predicted that this amplification could occur in 30cm of ytterbium doped fiber, in a single-pass forward-pumped configuration. Figure 3 shows the predicted inversion ratio, gain, and output power of the fiber preamplifer.

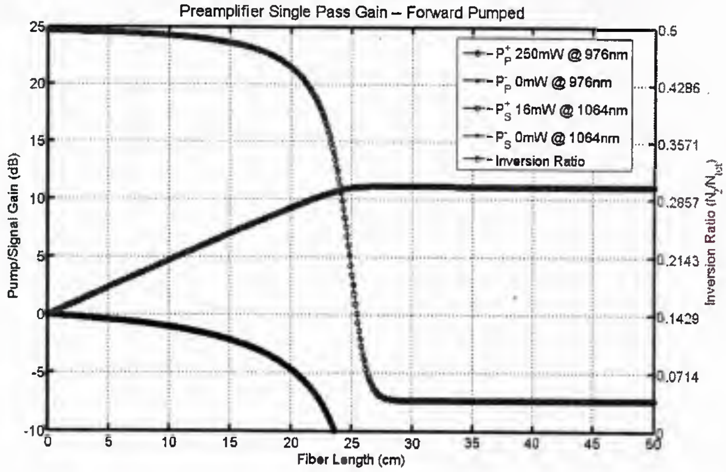


Figure 3. Simulated preamplifier performance. Using a 280mW diode laser to core-pump Yb-doped fiber in a forward pumped, single-pass configuration results in an output signal of 200mW.

The experimental preamplifier performance lagged the simulation predictions. The initial attempt at amplifying using the fiber ring laser failed at an output level of just 25mW, when the preamplifier started

Gain Amplifier Simulation and Experimental Results

The gain amplifier was designed to take a 200mW signal and amplify it to 10W, a gain of 17dB. Numerical simulations of the fundamental laser rate equations predicted that this amplification could occur in 3-4m of ytterbium doped fiber, in a single-pass forward pumped configuration. Multiple fiber-coupled high power pumps are necessary to deliver the required 20W of pump power. The following figure shows the predicted output power of the fiber amplifier.

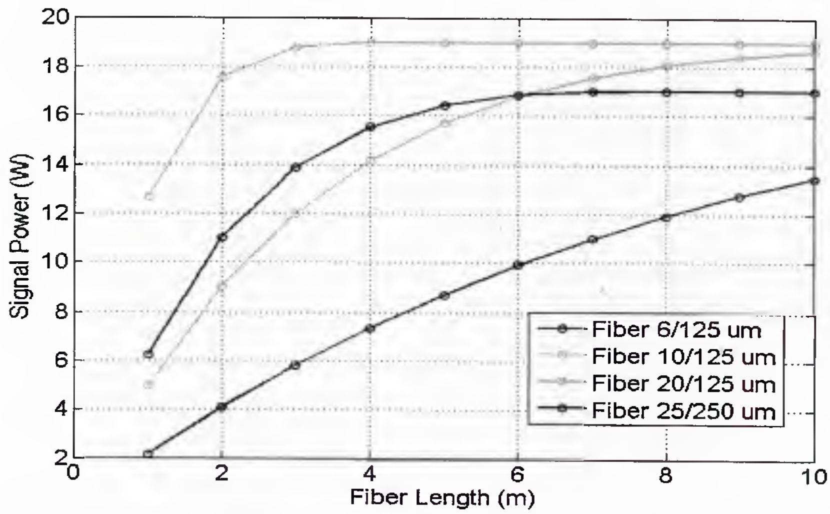


Figure 5. Simulated gain amplifier performance. Several fiber types are shown; for performance and compatibility the 10/125DC was chosen. Following the 10/125DC green line, by using 20W of pump power to cladding-pump double-clad Yb-doped fiber in a forward pumped, single-pass configuration, an output signal of 12W after 3m of fiber, and 14W after 4m, is predicted.

While the experimental gain amplifier performance was satisfactory, it did vary from the simulated predictions. The maximum pump power that has been delivered to the fiber is estimated to be 10W, which resulted in a signal output of 5.1W. This represents a conversion efficiency of 50%, vs. the expected 75%. Investigation is ongoing into the cause of this discrepancy, and fiber length changes may have to be made in the future. Even projecting this efficiency to the full pump strength of 20W, however, the amplifier should be able to deliver the desired 10W in the IR for doubling to green. This will be confirmed in upcoming tests.

The polarization and signal behavior were tested at the output of the amplifier stages. Both were found to be largely unchanged from the original chaotic source laser, so this IR signal is appropriate for use in producing a CLIDAR signal in green light. A block diagram and photograph of the gain amplifier is shown below.

Frequency Doubling Experimental Results

Wavelength conversion has been performed using a temperature controlled, periodically poled crystal for frequency doubling. A test assembly was constructed using a commercial 700mW 1064nm laser, whose beam was expanded to 15mm and then focused through the long, narrow (0.5 x 0.5 x 20 mm) PPKTP crystal. Conversion efficiencies of 1.5% per W were reached while maintaining beam quality and collimation. This efficiency exceeded the manufacturer's specification and we expect to exceed 1 W of green light when a 10 W IR signal is used.

Having demonstrated that this optical assembly can be used for successful frequency, the assembly is now being integrated with the laser and amplifier stages to produce the chaotic signal in green light.

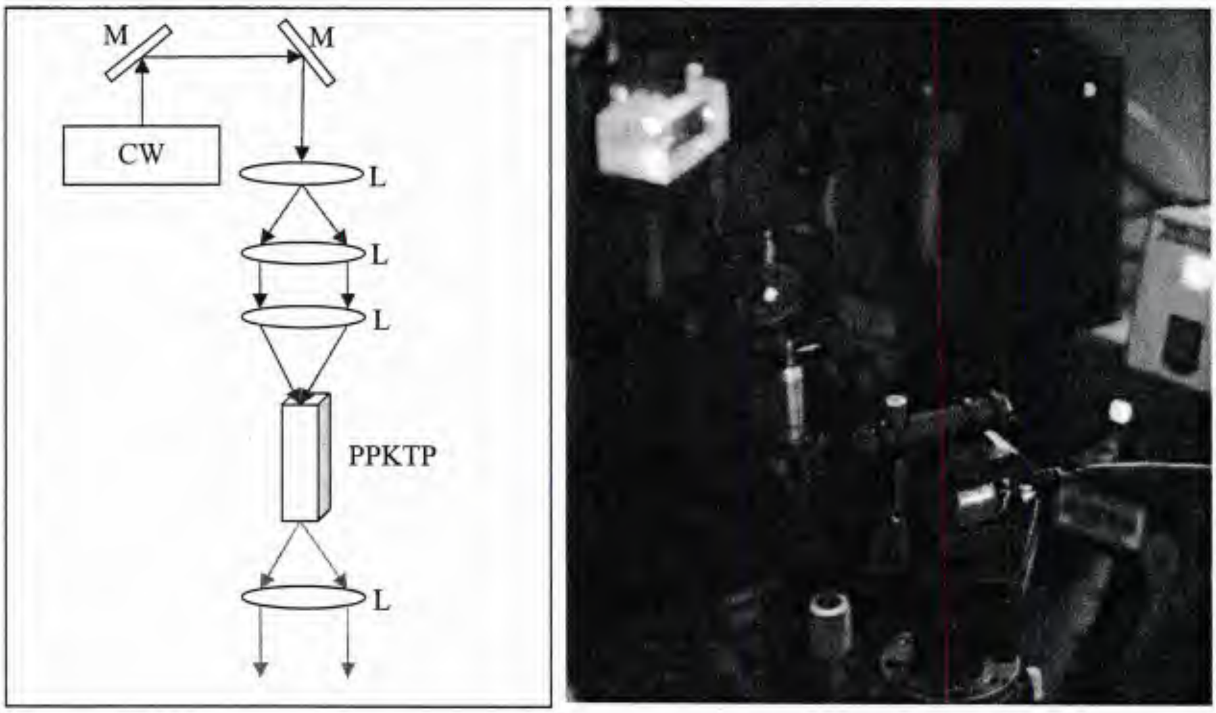


Fig 3. Frequency doubling from IR to green. Left: Block diagram of frequency doubling scheme, showing beam expanding and then focusing on the crystal, which changes the IR (red) to green light. Right: Photo of doubling setup; infrared light enters and visible green light exits the crystal. (L: Lens; M: Mirror; CW: Continuous wave source; PPKTP: periodically poled KTP crystal.)

Chaotic LIDAR for Naval Applications
N000141010906

Objective:

Investigate chaotic LIDAR for high resolution imaging and ranging.
•Develop a chaotic laser for use as a compact and cost-effective wideband optical source
•Perform system-level investigations into the underwater propagation/scattering characteristics chaotic laser signal in order to determine the range resolution/accuracy and signal to noise performance that can be expected from this approach

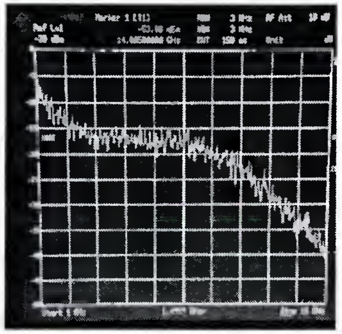
Approach:

• Use long-cavity fiber lasers to support simultaneous lasing modes

•Use a two-stage fiber amplifier to achieve sufficient optical power for doubling.

•Use a PPKTP crystal for frequency doubling to the blue-green

Figure:



The frequency content of the chaotic fiber laser developed for underwater LIDAR is comprised of many simultaneous lasing modes which generate a wide instantaneous bandwidth.

Scientific or Naval Impact/ Results:

•Introduced a long-cavity fiber laser as novel means of generating wideband signals.

•Demonstrated potential for underwater application of the laser signal through amplification and wavelength conversion to the blue-green.

•Investigating a custom signal processing solution to leverage wide bandwidth for LIDAR.

•Will characterize the underwater optical channel over a wide bandwidth to determine optimum frequency modulation for backscatter reduction.

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MEMORANDUM

Subject: Annual Report
Chaotic LIDAR for Naval Applications: FY13

This document provides an annual report on the project "Chaotic LIDAR for Naval Applications" covering FY13.

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Award Information

Award Number	N000141010906
Title of Research	Chaotic LIDAR for Naval Applications
Principal Investigator	William D. Jemison
Organization	Clarkson University

Technical Section

Technical Objectives

The original proposal identified the following three tasks:

- Task 1 involves the generation and characterization of a wideband CLIDAR signal suitable for system-level experiments.
- Task 2 involves a system-level investigation into the underwater propagation/scattering characteristics of the CLIDAR signals. The investigation will be performed as a function of both optical wavelength and water turbidity (absorption and scattering) in order to determine the range resolution/accuracy and signal to noise performance that can be expected using CLIDAR.
- Task 3 involves the development of an advanced chaotic laser, or CLASER, for use as a compact and cost-effective optical source for CLIDAR. This approach integrates a laser gain medium into an OOR to produce an integrated chaotic optical source.

Progress Statement Summary

We have previously reported the development of wideband chaotic lidar (CLIDAR) signals using low-power fiber ring lasers operating at infrared wavelengths (Task 1). Multiple infrared laser configurations were designed, built, and characterized in order to determine the best configuration for frequency doubling to blue-green wavelengths. We also initiated the design and testing a frequency doubler last year. In FY2013, we fully designed and built all necessary components for the blue-green chaotic CLIDAR source (infrared chaotic laser, fiber preamplifier, fiber gain amplifier, and frequency doubler) and have integrated them into a working CLIDAR transmitter (Task 3). We also have begun using the transmitter to conduct system experiments to demonstrate and explore the CLIDAR's performance in underwater environments (Task 2).

The completed CLIDAR transmitter operates at 150 mW continuous output power at 532 nm. The intensity modulation signal of the output is chaotic, with instantaneous wide bandwidth of at least 3 GHz. This transmitter consists of a low-power chaotic infrared fiber laser source, two fiber amplifier stages, and a frequency doubler to convert the wavelength from 1064 nm to 532 nm. Custom computer code has been developed to solve the rate equations governing rare-earth doped fiber lasers and amplifiers, and this code has been used to design the laser and amplifiers for the CLIDAR transmitter. This code has also been packaged and published as a design toolbox for use by the research community, and has downloaded several hundred times to date. Using the CLIDAR transmitter, ranging has been performed in a water tank, where 8 mm accuracy and +/-4 cm resolution has been demonstrated, as limited by the receiver's sampling speed and analog bandwidth. Since the signal is non-repeating, the range measurements are also unambiguous. These results were obtained in clean water, and investigation of the system performance in turbid water is now underway.

Detailed Progress Report

The following progress will be described below:

1. CLIDAR Transmitter
    a. Design
    b. Performance
    c. Simulation of Fiber Laser and Amplifiers
2. Ranging using CLIDAR Transmitter

CLIDAR Transmitter: Performance Overview

The CLIDAR transmitter's wideband, high frequency chaotic signal is generated by the intensity modulation of a 1064 nm ytterbium-doped fiber laser (YDFL). This modulation is completely internal and is determined by the cavity physics, so that no signal generator or electro-optic modulator are needed. The modulation obtained extends at least to 3 GHz (measurement limited by the bandwidth of the spectrum analyzer used). The power spectral density is made to be flat by adjusting the active fiber length, and incoherent mode competition is encouraged by adding a 100 m passive fiber to the cavity, greatly increasing the number of simultaneously resonating modes. By these modifications, a noise-like chaotic signal is obtained, which has an easily resolved, non-repeating, thumbtack

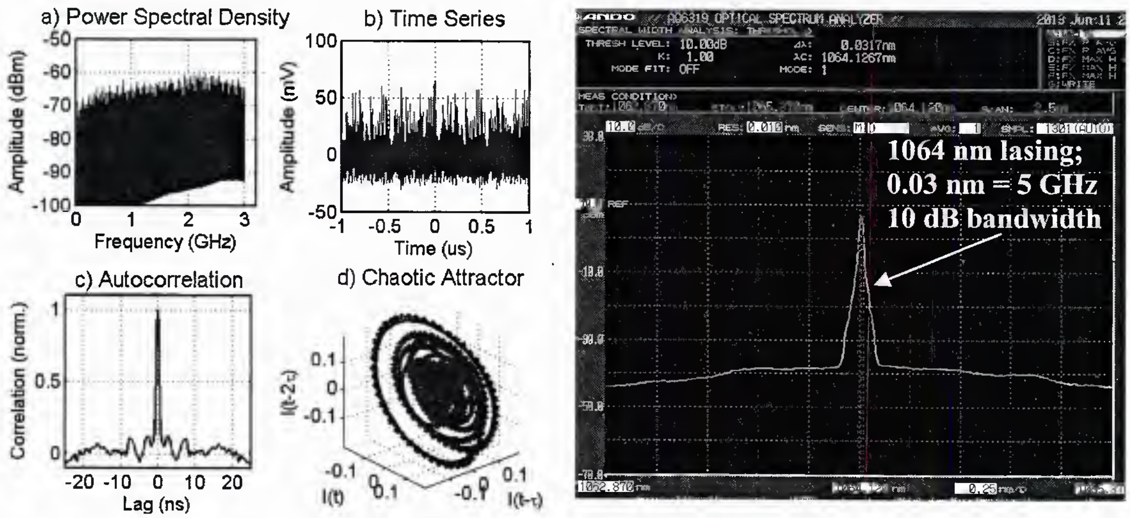


Fig 3. Output of the fiber laser. [*Left panel*] *Top left*: The frequency spectrum extends to 3 GHz, with a flat envelope. *Top right*: the modulation output is noise-like and non-periodic. *Bottom left*: the autocorrelation is a sharp non-repeating thumbtack function. *Bottom right*: a distinctive attractor pattern is indicative of deterministic chaos. [*Right panel*] Optical spectrum showing 0.03 nm (5 GHz) 10 dB bandwidth.

autocorrelation function that is well-suited for ranging. The YDFL signal's wide, flat spectrum, noiselike trace, sharp autocorrelation peak, and chaos are shown in Figure 3.

The YDFL outputs 15 mW power at 1064 nm. Since watt-level infrared powers are necessary for efficient frequency doubling, two fiber amplifiers are used to boost the signal to 40 mW, and then to 6 W. The signal then leaves the fiber and is passed through the frequency doubling crystal, which outputs 150 mW light at 532 nm. The single-pass crystal conversion efficiency of 3% is consistent with the expected efficiency of 4% at these power levels, and output power level is sufficient to perform system experiments in turbid waters. In the next section, the design of the amplifiers and laser will be presented.

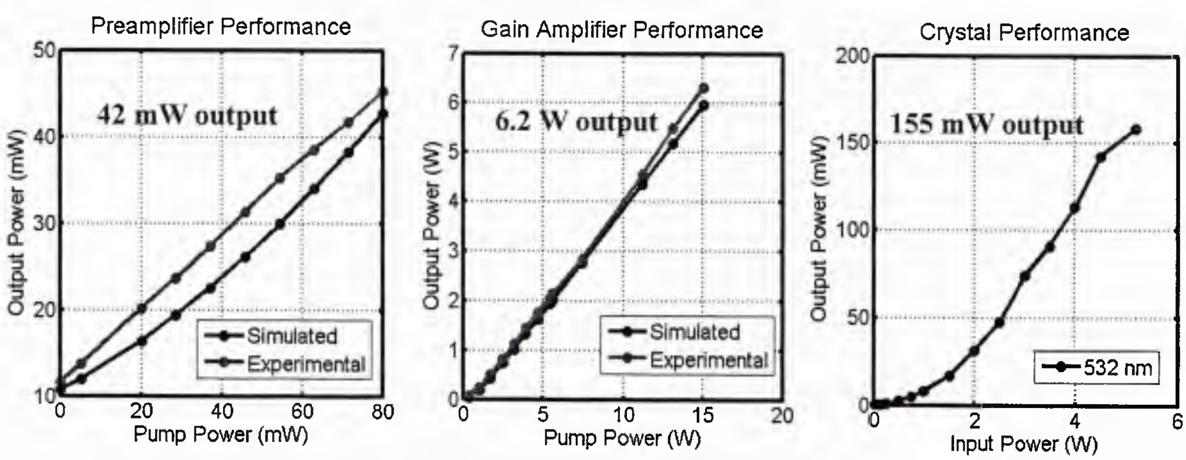


Fig 4. Output of the fiber amplifiers (preamplifier and gain amplifier) and frequency doubler (crystal).

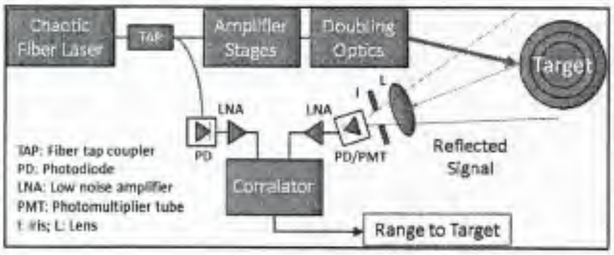
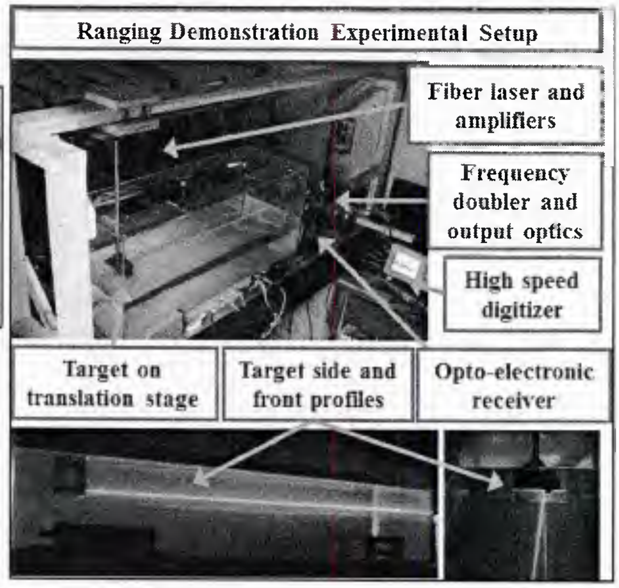


Fig 7. Ranging demonstration setup. *Top*: Block diagram of CLIDAR ranging. *Right:* The CLIDAR system (behind the tank) uses the 532 nm chaotic signal to determine the range to the target.



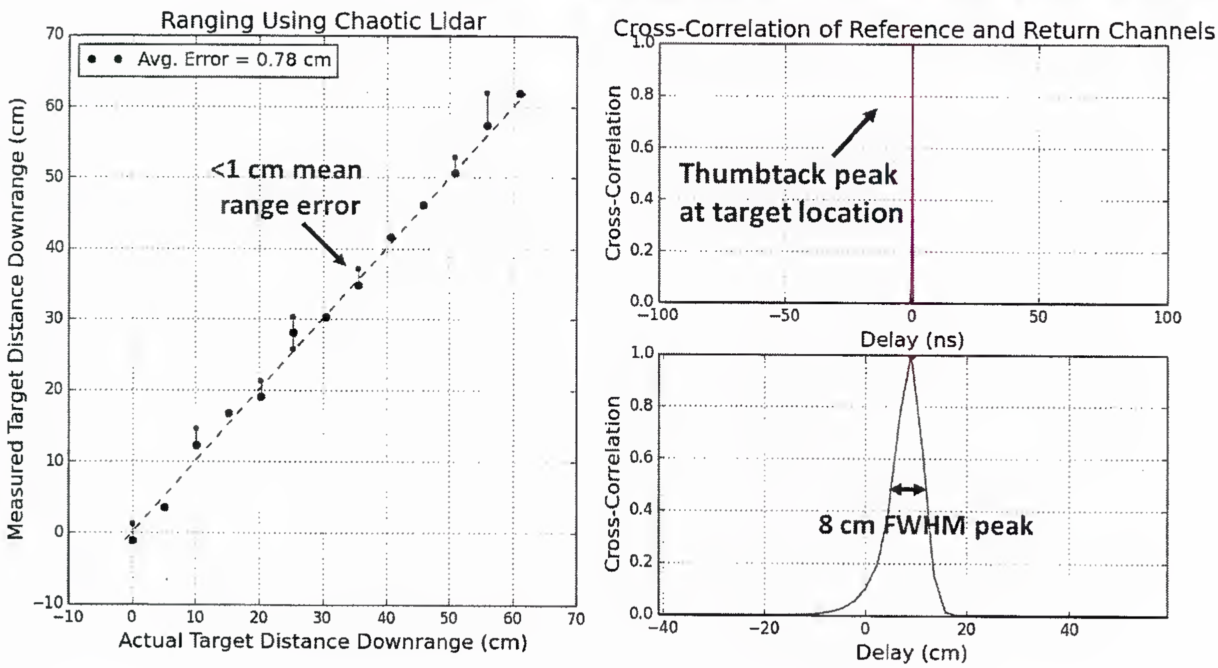


Fig 8. Ranging demonstration results. *Left*: Actual versus target range showing an average error of <1 cm. *Top right:* The target peak is a sharp and unambiguous thumbtack. *Bottom right:* Zooming in on the target peak, the resolution is seen to be +/- 4 cm full width half maximum (FWHM).

and so would be both complex and computationally intensive; however, the efficient simulation algorithms developed to date may make these calculations feasible.

Chaotic LIDAR for Naval Applications
N000141010906

Objective:

Investigate chaotic LIDAR for high resolution underwater imaging and ranging.

•Develop a blue-green wideband chaotic laser to support scientific experiments

•Perform system-level investigations into the underwater propagation/scattering characteristics chaotic laser signal in order to determine the range resolution/accuracy and backscatter suppression that can be expected from this approach

Approach:

- Create optical chaos by using long-cavity infrared fiber lasers to support many simultaneous lasing modes
- Amplify the infrared chaotic signal using a two-stage fiber amplifier to achieve sufficient optical power for doubling.
- Use a PPKTP crystal for frequency doubling to the blue-green wavelengths desired for underwater operation
- Integrate all components into a chaotic lidar transmitter and use it to conduct system experiments to explore the potential of chaotic lidar for underwater applications.

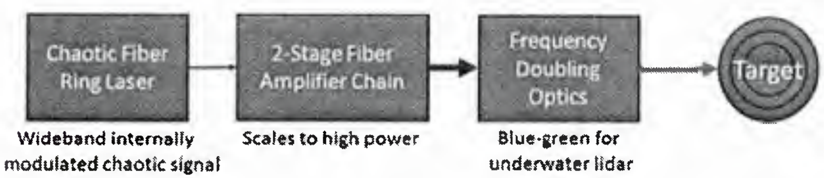
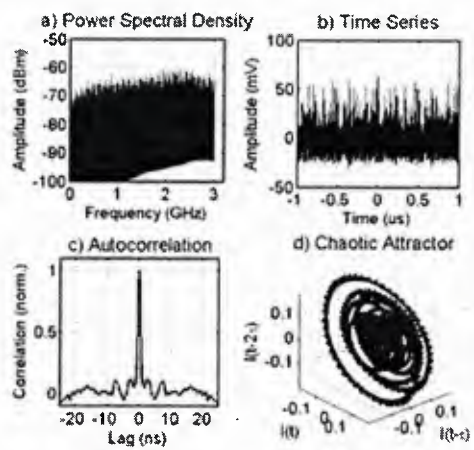
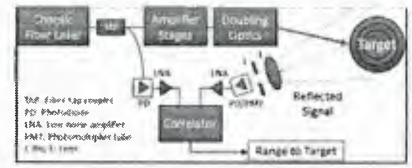
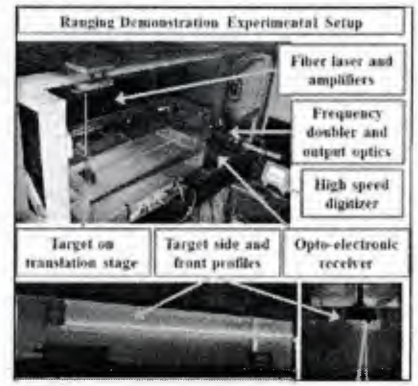


Figure:

A blue-green chaotic laser transmitter has been built and system experiments have been initiated







Scientific or Naval Impact/ Results:

- Successfully designed, built, and integrated a wideband (~ 3GHz) 150 mW chaotic blue-green laser transmitter.
- Developed a custom "Fiber Lasers and Amplifiers" MATLAB toolbox that performs efficient numerical simulations of fiber lasers and fiber amplifiers.
- Achieved receiver-limited 8 mm accuracy and +/-4 cm unambiguous range resolution in a proof-of-concept underwater ranging experiment.
- Currently designing experiments to characterize chaotic lidar ranging performance and backscatter suppression in turbid water.

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MEMORANDUM

Subject: Annual Report
Chaotic LIDAR for Naval Applications: FY14

This document provides an annual report on the project "Chaotic LIDAR for Naval Applications" covering FY14.

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Award Information

Award Number	N000141010906
Title of Research	Chaotic LIDAR for Naval Applications
Principal Investigator	William D. Jemison
Organization	Clarkson University

Technical Section

Technical Objectives

The technical objectives of the project were identified in the original proposal as three tasks:

- Task 1 involves the generation and characterization of a wideband CLIDAR signal suitable for system-level experiments.
- Task 2 involves a system-level investigation into the underwater propagation/scattering characteristics of the CLIDAR signals. The investigation will be performed as a function of both optical wavelength and water turbidity (absorption and scattering) in order to determine the range resolution/accuracy and signal to noise performance that can be expected using CLIDAR.
- Task 3 involves the development of an advanced chaotic laser, or CLASER, for use as a compact and cost-effective optical source for CLIDAR. This approach integrates a laser gain medium into an OOR to produce an integrated chaotic optical source.

Technical Approach

The technical approach taken to develop the chaotic laser is shown in Figure 1. The chaotic laser (CLASER) signal source (block 1) is a 1064 nm infrared ytterbium-doped fiber laser (YDFL), which outputs a >1 GHz noise-like chaotic intensity modulation. This signal is amplified by a 2-stage fiber amplifier chain to boost the signal power to 6W. A free space frequency doubling crystal is then used to generate a blue-green wavelength. This 200mW signal is used with a digital receiver to form a chaotic LIDAR (CLIDAR) ranging system. The design of the chaotic fiber ring laser and the fiber amplifiers are guided by laser simulation tools developed under the project. Ranging experiments are performed in a small water tank to investigate CLIDAR system performance.

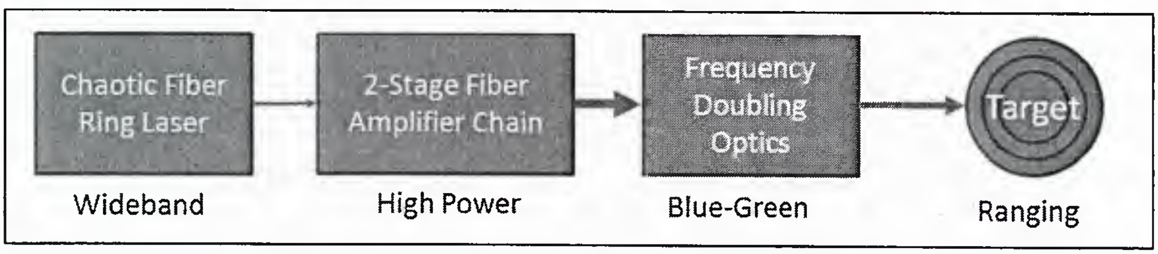

Fig 1. The chaotic LIDAR (CLIDAR) transmitter approach. Several stages are used to generate high power blue-green light suitable for underwater ranging. Experiments are performed in a small water tank.

Progress Statement Summary

A 532 nm chaotic laser (CLASER) transmitter was developed to investigate the performance of wideband chaotic lidar (CLIDAR) for naval underwater applications. The transmitter was built using a frequency doubled infrared fiber laser. Multiple fiber laser architectures were studied, built, and tested. A novel ultralong cavity (~100m) ring resonator was implemented for its noise-like chaotic intensity modulation. This laser generated wideband intensity modulation in the laser itself and did not require a separate optical modulator or RF signal source. The final configuration produced two hundred milliwatts of power at 532 nm with > 1GHz of noise-like chaotic intensity

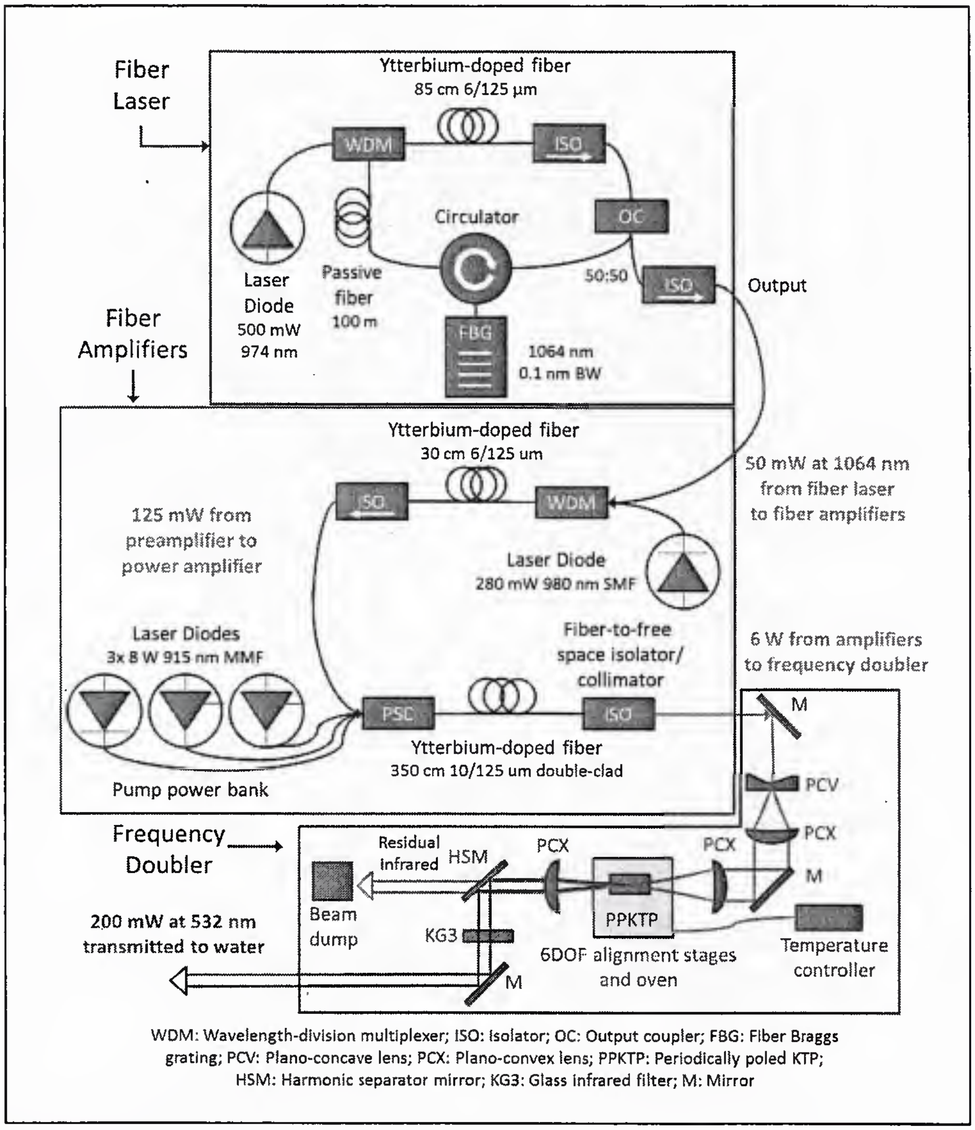

Fig 2. The chaotic LIDAR (CLIDAR) transmitter detailed design, showing each component of the fiber laser, the fiber amplifiers, and the frequency doubler.

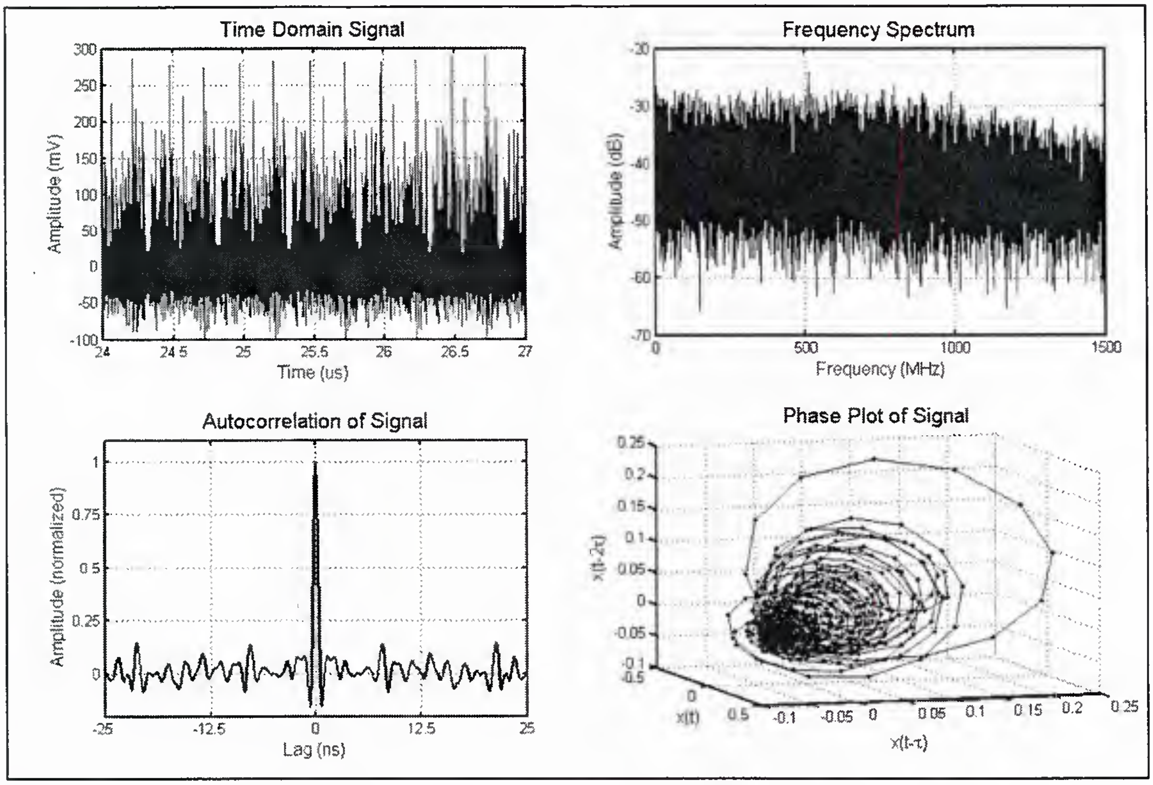

Fig 4. The CLIDAR transmitter intensity modulation signal. Top left: Time-domain view of the noise-like signal. Top right: The frequency-domain shows a wideband spectrum. Bottom left: The autocorrelation function is a sharp narrow peak. Bottom right: The phase plot shows an attractor shape typical of chaotic systems.

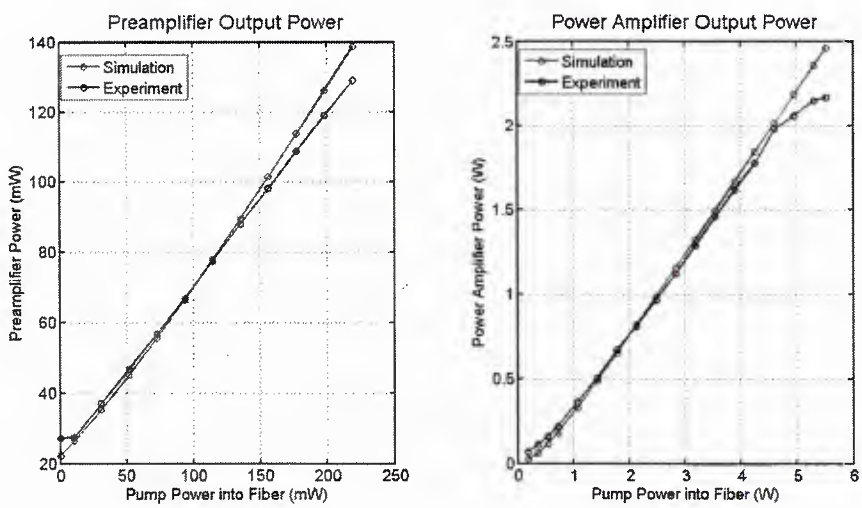

Fig 5. Power output of the CLIDAR transmitter. Left: Preamplifier simulation and experimental results. Right: Power amplifier simulation and experimental results up to 5 W output.

System Experiments - A block diagram of the system experimental set-up is shown in Figure 6. Targets in a small water tank can be precisely moved on a translation stage. The water turbidity can be varied via the use of liquid

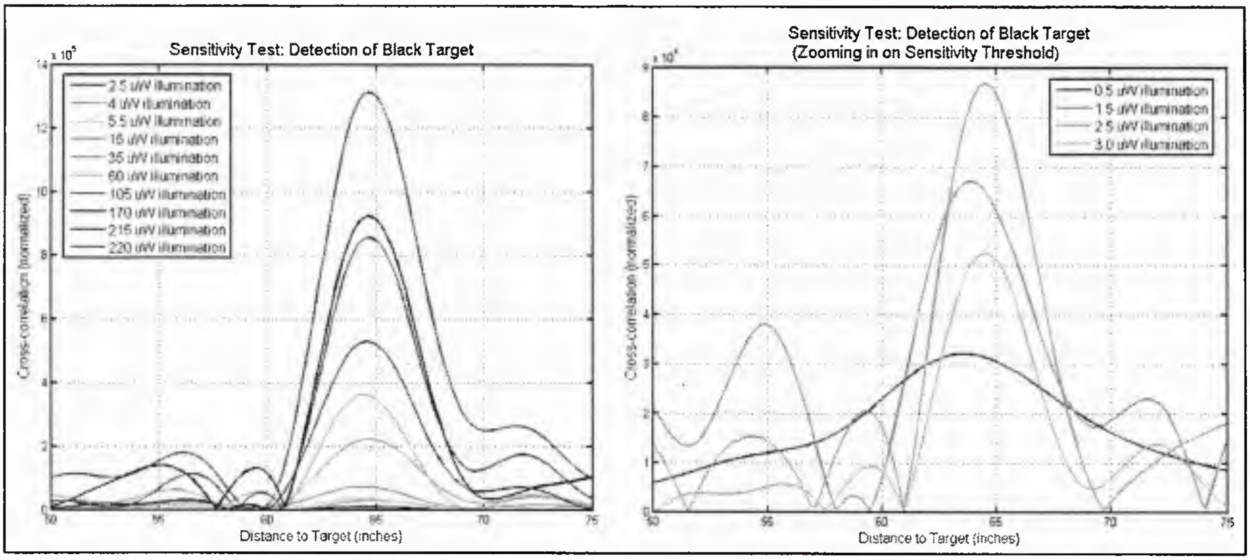

Fig 8. CLIDAR system experimental results: detection sensitivity, showing the potential of the system for detecting dark targets with low light levels.

<u>Target Detection in Turbid Water</u> – Figure 9 shows target detection at a variety of turbidities. The target, the volumetric backscatter response, and the response of a submerged mirror can all be seen in the range plots. While the backscatter response increases with increased turbidity, the target is detectable up to high turbidity with little change in measurement accuracy or peak width. In this test, gray and white targets were submerged, and the beam traveled through about 56" or 1.42m of turbid water on its way to the target. Thus the high turbidity case where the attenuation coefficient c is 3.5/m demonstrates the potential for sub-inch accuracy in about 5 attenuation lengths standoff distance.

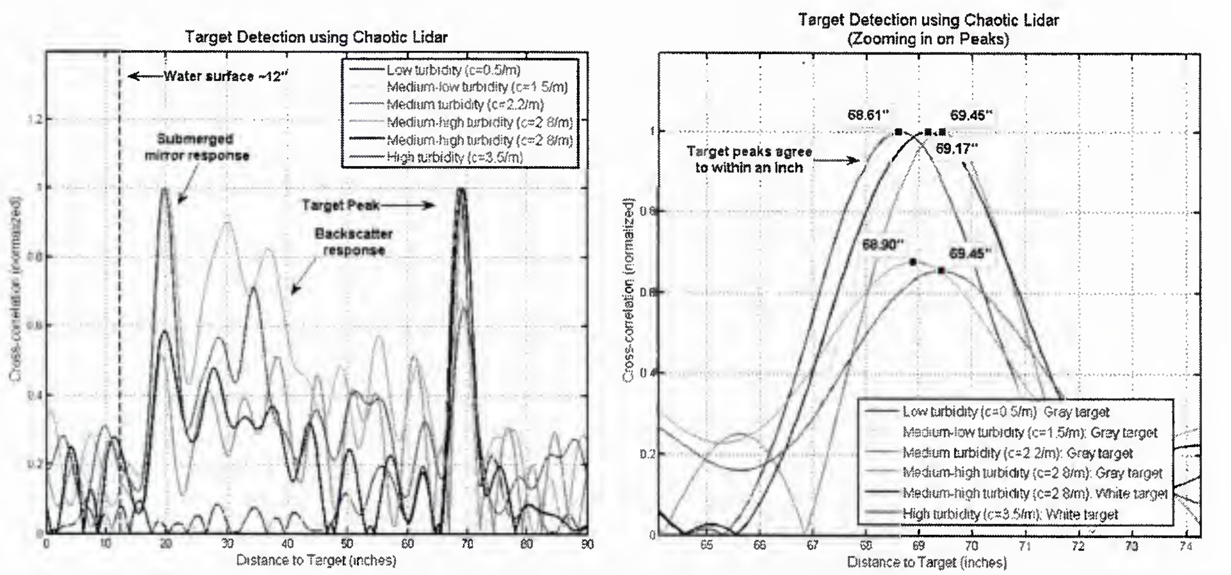

Fig 9. CLIDAR system experimental results: target ranging, demonstrating sub-inch detection accuracy at five attenuation lengths of turbid water.

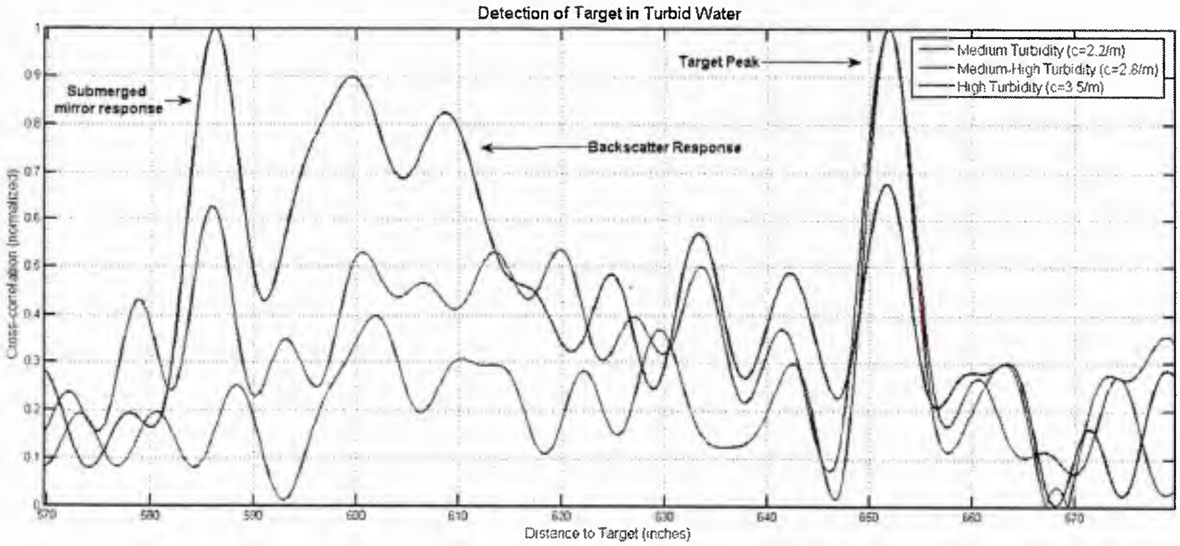

Fig 11. CLIDAR system experimental results: simultaneous backscatter and target detection. The broad response of the volumetric backscatter is seen on the left side of the graph, while the target peak is visible on the right.

Figure 12 shows the results for the same experiment when the low frequency content of the received signal is removed via filtering. A reduction on the backscatter response is clearly. The c=3.5 results also show the CLIDAR's ability to detect a target whose signal level is lower than the backscatter level. These results are very promising; however, additional work is required to calibrate the CLIDAR return in order to quantify the backscatter suppression.

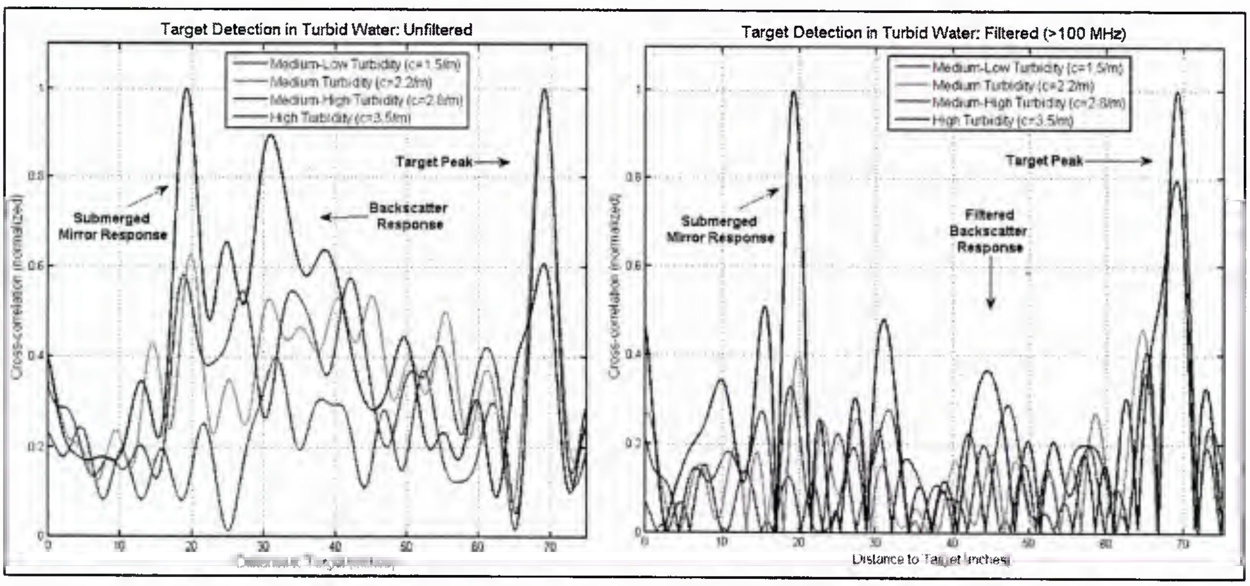

Fig 12. CLIDAR system experimental results: backscatter suppression and target detection. The volumetric backscatter response is attenuated by digital signal filtering, while the target peak remains strong and is slightly enhanced at c=3.5/m.

Chaotic LIDAR for Naval Applications
N000141010906

Objective:

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- Develop a blue-green wideband chaotic lidar transmitter to support scientific experiments
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Approach:

- Create optical chaos by using long-cavity infrared fiber lasers to support many simultaneous lasing modes
- Amplify the infrared chaotic signal using a two-stage fiber amplifier to achieve sufficient optical power for frequency doubling.
- Use a PPKTP crystal for frequency doubling to the blue-green wavelengths desired for underwater operation
- Integrate all components into a chaotic lidar transmitter and use it to conduct system experiments to explore the potential of chaotic lidar for underwater applications.

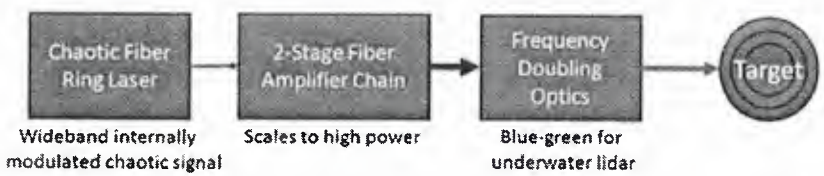
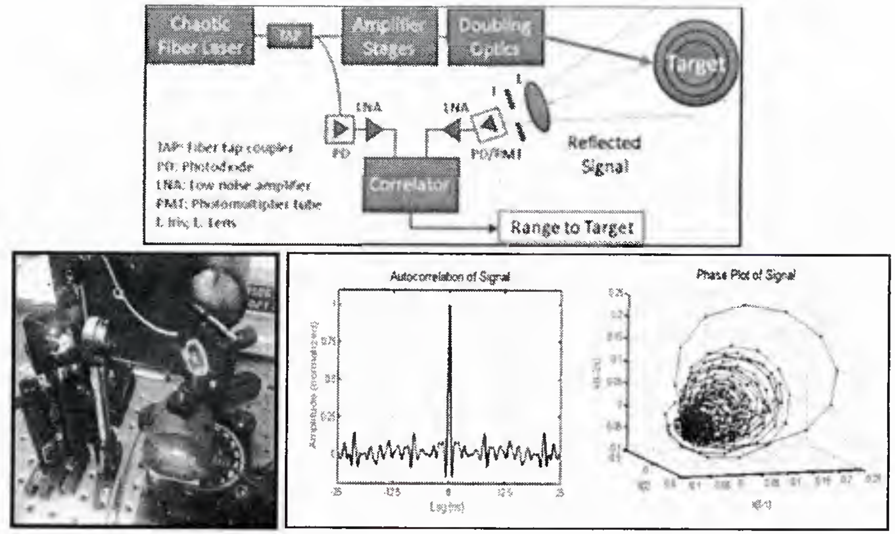


Figure:

A blue-green chaotic lidar transmitter has been built and system experiments have been performed



Scientific or Naval Impact/ Results:

- Successfully designed, built, and integrated a wideband (>1 GHz) 200 mW chaotic blue-green laser transmitter.
- Developed a custom Fiber Laser and Amplifier Toolbox in MATLAB that performs efficient numerical simulations of fiber lasers and fiber amplifiers.
- Achieved receiver-limited sub-inch detection accuracy in five attenuation lengths of turbid water.
- Demonstrated backscatter suppression using frequency-domain filtering.