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14. ABSTRACT

We demonstrated that an optical laser can operate with <1 photons on average inside the cavity while also obtaining significant spectral narrowing of the emitted light relative to the single atom transition linewidth. We further explored the power output properties and threshold conditions of this laser. We made direct measurements that showed that the lasing frequency can be made >10000 times less sensitive to the resonance frequency of the optical cavity than is the case for normal lasers or for passive optical reference cavities. Such a large reduction in sensitivity would essentially remove both thermal and technical mirror vibrations as a limitation on laser linewidth

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Report Title

Final Report: A Superradiant Laser: Toward mHZ Linewidth Lasers

ABSTRACT

We demonstrated that an optical laser can operate with <1 photons on average inside the cavity while also obtaining significant spectral narrowing of the emitted light relative to the single atom transition linewidth. We further explored the power output properties and threshold conditions of this laser. We made direct measurements that showed that the lasing frequency can be made >10000 times less sensitive to the resonance frequency of the optical cavity than is the case for normal lasers or for passive optical reference cavities. Such a large reduction in sensitivity would essentially remove both thermal and technical mirror vibrations as a limitation on laser linewidth. Other studies included how phase information can be stored and manipulated inside of our laser, such that it may be possible to have both an active laser and a passive Ramsey-like sensor in the same setup. We considered the fundamental limits on the atomic quantum information that can be extracted from the laser light and found that it corresponded closely to the fundamental atomic standard quantum limit on phase estimation.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
12/03/2014	3.00	Justin G Bohnet , Zilong Chen , Joshua M Weiner, Kevin C Cox, James K Thompson. Active and passive sensing of collective atomic coherence in a superradiant laser “, , PHYSICAL REVIEW A , (07 2013): 13826. doi:
12/03/2014	4.00	Justin G. Bohnet, Zilong Chen, James K. Thompson, Kevin C. Cox, Joshua M. Weiner . Superradiant Raman laser magnetometer, Applied Physics Letters, (12 2012): 261107. doi:

TOTAL: **2**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received		Paper
12/03/2014	1.00	Justin G. Bohnet, Zilong Chen, Joshua M. Weiner, Dominic Meiser, Murray J. Holland, , James K. Thompson. A steady-state superradiant laser with less than one intracavity photon, Nature, (04 2012): 78. doi:

TOTAL: **1**

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
12/03/2014	2.00	Justin G Bohnet, Zilong Chen, Joshua M Weiner, Kevin C Cox , Dominic Meiser, Murray J Holland , James K Thompson. A Quasi-Continuous Superradiant Raman Laser with <1 Intra-cavity Photon, ICAP 2012 – 23rd International Conference on Atomic Physics. 23-JUL-12, . : ,
TOTAL:		1

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper
TOTAL:	

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper
TOTAL:	

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Department of Commerce - Bronze Medal

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Kevin Christopher Cox	0.13	
Joshua M Weiner	0.13	
FTE Equivalent:	**0.26**	
Total Number:	**2**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Names of Under Graduate students supported

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

Final Progress Report: Contract # W911NF-11-1-0355

PI James K. Thompson

Problem Studied

The goal of this work was to study a regime of optical lasing in which most of the phase information of the laser is stored inside of the gain medium rather than the intracavity light field. Theoretical studies indicated that such a laser might one day lead to millihertz linewidth optical lasers. Such a laser would be 100 times better than the current world's best lasers, and extend optical coherence times to more than 1,000 seconds. The resulting ultrastable lasers would represent a dramatic breakthrough in fundamental precision measurement technologies impacting a broad range of metrology and research applications, including new optical atomic clocks, quantum information systems, gravity wave detection, optical interferometry, cavity-optomechanics, and the probing and control of quantum many-body systems that beat the standard quantum limits for measurement.

The goal of this work was to study many of the core theoretical predictions in a laser-cooled Rb system using synthetically engineered narrow optical transitions. This provides great flexibility for studying the core physical predictions, and should be understood as primarily a physics testbed for future attempts to develop ultranarrow lasers.

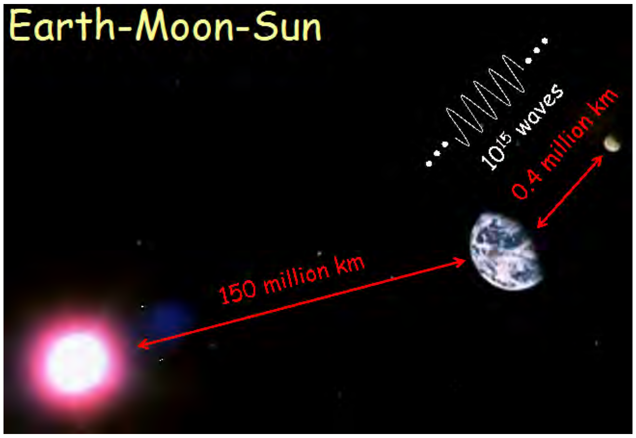

Figure 1. Lasers can be thought of as rulers with tick marks spaced by the wavelength of the light. The best current rulers span the distance from the earth to the moon, whereas this proposal may some day lead to rulers spanning the distance from the earth to the sun. The resulting impact on both time and length metrology will be profound.

Summary of the most important results

We demonstrated that an optical laser can operate with <1 intracavity photon while also obtaining significant spectral narrowing of the emitted light relative to the single atom transition linewidth. We further explored the power output properties and threshold conditions of our laser.

We made direct measurements that showed that the lasing frequency can be made >10000 times less sensitive to the resonance frequency of the optical cavity than is the case for normal lasers or for passive optical reference cavities. Such a large reduction in sensitivity would essentially remove both thermal and technical mirror vibrations as a limitation on laser linewidth.

The *Nature* [1] paper describing this work (with accompanying context article in *Nature*) generated a large amount of interest, including three invitations to give Hot Topic talks at well-established international conferences [2], as well as popular international interviews and articles (Science Daily, Physics World, Phys.org, CNET, Photonics.com, Ars Technica R&D Magazine, German Public Radio, German wire service, *Nature Photonics*, etc.), and a NIST produced video describing the work.

We also considered how phase information can be stored and manipulated inside of our laser [2], such that it may be possible to have both an active laser and a passive Ramsey-like sensor in the same setup. The hybrid active/passive sensor might switch between modes of operation in response to changing environmental conditions such as vibration levels. To determine the quality of the sensor, we considered the fundamental limits on the atomic quantum information that can be extracted from the laser light and found that it corresponded closely to the fundamental atomic standard quantum limit on phase estimation. This indicates that such a sensor would be of high quality. The core concepts of hybrid active/passive sensors were later demonstrated outside of the grant period in the context of a hybrid magnetometer [4].

Bibliography

[1] "A steady-state superradiant laser with less than one intracavity photon", *Nature* **484** , 78-81, April 4, (2012).

[2] "A Quasi-Continuous Superradiant Raman Laser with <1 Intra-cavity Photon," J. G. Bohnet, Z. Chen, J. M. Weiner, K. C. Cox, D. Meiser, M. J. Holland, J. K. Thompson, Proceedings of the 23rd International Conference on Atomic Physics, *EPJ Web of Conferences* **57**, 03003 (2013).

[3] "Active and passive sensing of collective atomic coherence in a superradiant laser ", Bohnet, Justin G. and Chen, Zilong and Weiner, Joshua M. and Cox, Kevin C. and Thompson, James K. *Physical Review A* **88** , 013826-013829 (2013).

[4] "Superradiant Raman laser magnetometer," J. M. Weiner, K. C. Cox, J. G. Bohnet, Z. Chen, J.K. Thompson, *Appl. Phys. Lett.* **101**, 261107 (2012)