

REPORT DOCUMENTATION PAGE			Form Approved OMB NO. 0704-0188		
The 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 the 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 Washington Headquarters Services, Directorate for Information Operations and Reports, 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) 06-06-2017		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 23-May-2011 - 22-Feb-2018	
4. TITLE AND SUBTITLE Final Report: Optical-transition Clocks with Micro-Fabricated Frequency Combs for Performance Beyond the Standard Quantum Limit			5a. CONTRACT NUMBER W911NF-11-1-0202		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER 1D10BM		
6. AUTHORS Alexander Gaeta, Murray Holland, Tobias Kippenberg, Michal Lipson, Andrew Ludlow, Chris Oates, Helmut Ritsch, James Thompson, Vladan Vuletic, Jun Ye			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES Massachusetts Institute of Technology (MIT) 77 Massachusetts Ave. NE18-901 Cambridge, MA 02139 -4307			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSOR/MONITOR'S ACRONYM(S) ARO		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) 60300-PH-DRP.131		
12. DISTRIBUTION AVAILABILITY STATEMENT Approved for Public Release; Distribution Unlimited					
13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
14. ABSTRACT We have achieved world-record advances in atomic clocks, including the demonstration of the world's most stable/precise atomic clock with a stability below 1 part in 10^{17} , a precision in the one part in 10^{16} range in 1 second, elimination of the Dick effect by operating two clocks simultaneously, development of the first quantum degenerate gas based optical lattice clock in a three dimensional lattice, development of a clock system that can operate below the standard quantum limit via entanglement, and development of the world's most stable clock lasers, with laser linewidth approaching 10 mHz.					
15. SUBJECT TERMS atomic clock, frequency comb, optical transition clock, entanglement, spin squeezing					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Vladan Vuletic
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 617-324-1174

Report Title

Final Report: Optical-transition Clocks with Micro-Fabricated Frequency Combs for Performance Beyond the Standard Quantum Limit

ABSTRACT

We have achieved world-record advances in atomic clocks, including the demonstration of the world's most stable/precise atomic clock with a stability below 1 part in 10^{17} , a precision in the one part in 10^{16} range in 1 second, elimination of the Dick effect by operating two clocks simultaneously, development of the first quantum degenerate gas based optical lattice clock in a three dimensional lattice, development of a clock system that can operate below the standard quantum limit via entanglement, and development of the world's most stable clock lasers, with laser linewidth approaching 10 mHz.

Investigating microfabricated frequency combs, we have discovered temporal solitons in microresonators and elucidated their impact on frequency comb performance, and demonstrated the first self-referenced chip-based optical frequency comb without external broadening,

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)

<u>Received</u>	<u>Paper</u>
01/04/2014	1 Qian Lin, Mackenzie A. Van Camp, Hao Zhang, Branislav Jelenkovi?, Vladan Vuleti?. Long-external-cavity distributed Bragg reflector laser with subkilohertz intrinsic linewidth, Optics Letters, (05 2012): 0. doi: 10.1364/OL.37.001989 314,655.00
01/05/2014	2 Hao Zhang, Robert McConnell, Senka ?uk, Qian Lin, Monika H. Schleier-Smith, Ian D. Leroux, Vladan Vuleti?. Collective State Measurement of Mesoscopic Ensembles with Single-Atom Resolution, Physical Review Letters, (9 2012): 0. doi: 10.1103/PhysRevLett.109.133603 314,656.00
01/05/2014	3 Senka ?uk, Robert McConnell, Hao Zhang, Jiazhong Hu, Monika Schleier-Smith, Vladan Vuleti?. Generating entangled spin states for quantum metrology by single-photon detection, Physical Review A, (12 2013): 0. doi: 10.1103/PhysRevA.88.063802 314,657.00
01/06/2014	15 N. D. Lemke, J. A. Sherman, C. W. Oates, G. Quémener, J. von Stecher, A. M. Rey, A. D. Ludlow. Cold-collision-shift cancellation and inelastic scattering in a Yb optical lattice clock, Physical Review A, (11 2011): 0. doi: 10.1103/PhysRevA.84.052724 314,683.00
01/06/2014	30 Justin G. Bohnet, Zilong Chen, Joshua M. Weiner, Kevin C. Cox, Dominic Meiser, Murray J. Holland, James K. Thompson, O. Dulieu, P. Grangier, M. Leduc, H. Perrin. A quasi-continuous superradiant Raman laser with < 1 intracavity photon, EPJ Web of Conferences, (08 2013): 0. doi: 10.1051/epjconf/20135703003 314,698.00
01/06/2014	29 Minghui Xu, D. A. Tieri, M. J. Holland. Simulating open quantum systems by applying SU(4) to quantum master equations, Physical Review A, (06 2013): 0. doi: 10.1103/PhysRevA.87.062101 314,697.00
01/06/2014	28 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): 0. doi: 10.1038/nature10920 314,696.00
01/06/2014	25 N. Hinkley, J. A. Sherman, N. B. Phillips, M. Schioppo, N. D. Lemke, K. Beloy, M. Pizzocaro, C. W. Oates, A. D. Ludlow. An Atomic Clock with 10-18 Instability, Science, (08 2013): 0. doi: 10.1126/science.1240420 314,693.00
01/06/2014	23 K. Beloy, J. A. Sherman, N. D. Lemke, N. Hinkley, C. W. Oates, A. D. Ludlow. Determination of the 5d6s ^{3}D_{1} state lifetime and blackbody-radiation clock shift in Yb, Physical Review A, (11 2012): 0. doi: 10.1103/PhysRevA.86.051404 314,691.00
01/06/2014	7 M. J. Martin, D. Meiser, J. W. Thomsen, Jun Ye, M. J. Holland. Extreme nonlinear response of ultranarrow optical transitions in cavity QED for laser stabilization, Physical Review A, (12 2011): 0. doi: 10.1103/PhysRevA.84.063813 314,672.00
01/06/2014	16 J. A. Sherman, N. D. Lemke, N. Hinkley, M. Pizzocaro, R. W. Fox, A. D. Ludlow, C. W. Oates. High-Accuracy Measurement of Atomic Polarizability in an Optical Lattice Clock, Physical Review Letters, (04 2012): 0. doi: 10.1103/PhysRevLett.108.153002 314,684.00
01/07/2014	4 J. Ye, A. M. Rey, M. Bishof, Y. Lin, M. D. Swallows, A. V. Gorshkov. Resolved Atomic Interaction Sidebands in an Optical Clock Transition, Physical Review Letters, (06 2011): 0. doi: 10.1103/PhysRevLett.106.250801 314,669.00

- 01/07/2014 46 J. G. Bohnet, Z. Chen, J. M. Weiner, D. Meiser, M. J. Holland, J.K. Thompson. A Steady State Superradiant Laser with <1 Intracavity Photon, Nature, (04 2012): 78. doi: 314,724.00
- 01/07/2014 45 James K. Thompson, Joshua M. Weiner, Kevin C. Cox, Justin G. Bohnet, Zilong Chen. Superradiant Raman laser magnetometer, Applied Physics Letters, (10 2012): 0. doi: 10.1063/1.4773241 314,723.00
- 01/07/2014 44 Justin G. Bohnet, Zilong Chen, Joshua M. Weiner, Kevin C. Cox, James K. Thompson. Relaxation Oscillations, Stability, and Cavity Feedback in a Superradiant Raman Laser, Physical Review Letters, (12 2012): 0. doi: 10.1103/PhysRevLett.109.253602 314,722.00
- 01/07/2014 43 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): 0. doi: 10.1103/PhysRevA.88.013826 314,721.00
- 01/07/2014 41 T. Herr, V. Brasch, J. D. Jost, C. Y. Wang, N. M. Kondratiev, M. L. Gorodetsky, T. J. Kippenberg. Temporal solitons in optical microresonators, Nature Photonics, (12 2013): 0. doi: 10.1038/nphoton.2013.343 314,719.00
- 01/07/2014 40 C. Y. Wang, T. Herr, P. Del'Haye, A. Schliesser, J. Hofer, R. Holzwarth, T. W. Hänsch, N. Picqué, T. J. Kippenberg. Mid-infrared optical frequency combs at $2.5\text{ }\mu\text{m}$ based on crystalline microresonators, Nature Communications, (01 2013): 0. doi: 10.1038/ncomms2335 314,718.00
- 01/07/2014 38 Johann Riemensberger, Klaus Hartinger, Tobias Herr, Victor Brasch, Ronald Holzwarth, Tobias J. Kippenberg. Dispersion engineering of thick high-Q silicon nitride ring-resonators via atomic layer deposition, Optics Express, (11 2012): 0. doi: 10.1364/OE.20.027661 314,716.00
- 01/07/2014 37 T. Herr, K. Hartinger, J. Riemensberger, C. Y. Wang, E. Gavartin, R. Holzwarth, M. L. Gorodetsky, T. J. Kippenberg. Universal formation dynamics and noise of Kerr-frequency combs in microresonators, Nature Photonics, (06 2012): 0. doi: 10.1038/nphoton.2012.127 314,715.00
- 01/07/2014 35 H. Ritsch, H. Zoubi. Optical properties of collective excitations for an atomic chain with vacancies, The European Physical Journal D, (11 2012): 0. doi: 10.1140/epjd/e2012-30465-9 314,713.00
- 01/07/2014 34 Hashem Zoubi, Helmut Ritsch, Laurin Ostermann. Cascaded collective decay in regular arrays of cold trapped atoms, Optics Express, (12 2012): 0. doi: 10.1364/OE.20.029634 314,712.00
- 01/07/2014 33 Hashem Zoubi, Helmut Ritsch. Excitons and Cavity Polaritons for Optical Lattice Ultracold Atoms, Advances in Atomic, Molecular, and Optical Physics, (01 2013): 171. doi: 314,711.00
- 01/07/2014 32 Laurin Ostermann, Helmut Ritsch, Claudiu Genes. Protected State Enhanced Quantum Metrology with Interacting Two-Level Ensembles, Physical Review Letters, (09 2013): 0. doi: 10.1103/PhysRevLett.111.123601 314,710.00
- 01/07/2014 14 M. Bishof, X. Zhang, M. J. Martin, Jun Ye. Optical Spectrum Analyzer with Quantum-Limited Noise Floor, Physical Review Letters, (08 2013): 0. doi: 10.1103/PhysRevLett.111.093604 314,680.00
- 01/07/2014 13 M. J. Martin, M. Bishof, M. D. Swallows, X. Zhang, C. Benko, J. von-Stecher, A. V. Gorshkov, A. M. Rey, J. Ye. A Quantum Many-Body Spin System in an Optical Lattice Clock, Science, (08 2013): 0. doi: 10.1126/science.1236929 314,679.00
- 01/07/2014 12 Wei Zhang, Michael J. Martin, Jun Ye, Markus Aspelmeyer, Garrett D. Cole. Tenfold reduction of Brownian noise in high-reflectivity optical coatings, Nature Photonics, (07 2013): 0. doi: 10.1038/nphoton.2013.174 314,678.00
- 01/07/2014 11 T. L. Nicholson, M. J. Martin, J. R. Williams, B. J. Bloom, M. Bishof, M. D. Swallows, S. L. Campbell, J. Ye. Comparison of Two Independent Sr Optical Clocks with 1×10^{-17} Stability at 10^3 s, Physical Review Letters, (12 2012): 0. doi: 10.1103/PhysRevLett.109.230801 314,677.00

- 01/07/2014 9 M. D. Swallows, M. J. Martin, M. Bishof, C. Benko, Yige Lin, S. Blatt, A. M. Rey, J. Ye. Operating a ⁸⁷Sr optical lattice clock with high precision and at high density, IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, (03 2012): 0. doi: 10.1109/TUFFC.2012.2210
314,675.00
- 01/07/2014 6 M. Bishof, M. J. Martin, M. D. Swallows, C. Benko, Y. Lin, G. Quémener, A. M. Rey, J. Ye. Inelastic collisions and density-dependent excitation suppression in a ⁸⁷Sr optical lattice clock, Physical Review A, (11 2011): 0. doi: 10.1103/PhysRevA.84.052716
314,671.00
- 01/07/2014 5 S. Blatt, T. L. Nicholson, B. J. Bloom, J. R. Williams, J. W. Thomsen, P. S. Julienne, J. Ye. Measurement of Optical Feshbach Resonances in an Ideal Gas, Physical Review Letters, (08 2011): 0. doi: 10.1103/PhysRevLett.107.073202
314,670.00
- 01/13/2014 49 Yoshitomo Okawachi, Bonggu Shim, Jacob S. Levy, Kasturi Saha, Reza Salem, Adrea R. Johnson, Mark A. Foster, Michael R. E. Lamont, Michal Lipson, Alexander L. Gaeta. Modelocking and femtosecond pulse generation in chip-based frequency combs, Optics Express, (01 2013): 0. doi: 10.1364/OE.21.001335
314,863.00
- 01/13/2014 47 Michael R. E. Lamont, Yoshitomo Okawachi, Alexander L. Gaeta. Route to stabilized ultrabroadband microresonator-based frequency combs, Optics Letters, (09 2013): 0. doi: 10.1364/OL.38.003478
314,861.00
- 01/13/2014 54 Yoshitomo Okawachi, Kasturi Saha, Jacob S. Levy, Y. Henry Wen, Michal Lipson, Alexander L. Gaeta. Octave-spanning frequency comb generation in a silicon nitride chip, Optics Letters, (08 2011): 0. doi: 10.1364/OL.36.003398
314,869.00
- 01/13/2014 53 Adrea R. Johnson, Yoshitomo Okawachi, Jacob S. Levy, Jaime Cardenas, Kasturi Saha, Michal Lipson, Alexander L. Gaeta. Chip-based frequency combs with sub-100 GHz repetition rates, Optics Letters, (02 2012): 0. doi: 10.1364/OL.37.000875
314,868.00
- 01/13/2014 52 R. Halir, Y. Okawachi, J. S. Levy, M. A. Foster, M. Lipson, A. L. Gaeta. Ultrabroadband supercontinuum generation in a CMOS-compatible platform, Optics Letters, (05 2012): 0. doi: 10.1364/OL.37.001685
314,867.00
- 01/13/2014 51 Jacob S. Levy, Kasturi Saha, Yoshitomo Okawachi, Mark A. Foster, Alexander L. Gaeta, Michal Lipson. High-Performance Silicon-Nitride-Based Multiple-Wavelength Source, IEEE Photonics Technology Letters, (08 2012): 0. doi: 10.1109/LPT.2012.2204245
314,865.00
- 04/25/2017 66 S. L. Bromley, B. Zhu, M. Bishof, X. Zhang, T. Bothwell, J. Schachenmayer, T. L. Nicholson, R. Kaiser, S. F. Yelin, M. D. Lukin, A. M. Rey, J. Ye. Collective atomic scattering and motional effects in a dense coherent medium, Nature Communications, (): 11039. doi:
1,040,004.00
- 04/25/2017 72 A.M. Rey, A.V. Gorshkov, C.V. Kraus, M.J. Martin, M. Bishof, M.D. Swallows, X. Zhang, C. Benko, J. Ye, N.D. Lemke, A.D. Ludlow. Probing many-body interactions in an optical lattice clock, Annals of Physics, (): 311. doi:
1,040,010.00
- 04/25/2017 71 B. J. Bloom, T. L. Nicholson, J. R. Williams, S. L. Campbell, M. Bishof, X. Zhang, W. Zhang, S. L. Bromley, J. Ye. An optical lattice clock with accuracy and stability at the 10⁻¹⁸ level, Nature, (): 71. doi:
1,040,009.00
- 04/25/2017 70 X. Zhang, M. Bishof, S. L. Bromley, C. V. Kraus, M. S. Safronova, P. Zoller, A. M. Rey, J. Ye. Spectroscopic observation of SU(N)-symmetric interactions in Sr orbital magnetism, Science, (): 1467. doi:
1,040,008.00
- 04/25/2017 69 T.L. Nicholson, S.L. Campbell, R.B. Hutson, G.E. Marti, B.J. Bloom, R.L. McNally, W. Zhang, M.D. Barrett, M.S. Safronova, G.F. Strouse, W.L. Tew, J. Ye. Systematic evaluation of an atomic clock at 2 × 10⁻¹⁸ total uncertainty, Nature Communications, (): 6896. doi:
1,040,007.00
- 04/25/2017 68 Andrew D. Ludlow, Martin M. Boyd, Jun Ye, E. Peik, P. O. Schmidt. Optical atomic clocks, Reviews of Modern Physics, (): 637. doi:
1,040,006.00

04/25/2017	67 Eugene S. Polzik, Jun Ye. Entanglement and spin squeezing in a network of distant optical lattice clocks, Physical Review A, (): . doi:	1,040,005.00
04/27/2017	73 Hashem Zoubi. Collective light emission of a finite-size atomic chain, EPL (Europhysics Letters), (): 24002. doi:	1,040,304.00
04/27/2017	80 D. Plankensteiner, L. Ostermann, H. Ritsch, C. Genes. Selective protected state preparation of coupled dissipative quantum emitters, Scientific Reports, (): . doi:	1,040,311.00
04/27/2017	79 Martin Hebenstreit, Barbara Kraus, Laurin Ostermann, Helmut Ritsch. Subradiance via Entanglement in Atoms with Several Independent Decay Channels, Physical Review Letters, (): . doi:	1,040,310.00
04/27/2017	77 L. Ostermann, D. Plankensteiner, H. Ritsch, C. Genes. Protected subspace Ramsey spectroscopy, Physical Review A, (): . doi:	1,040,308.00
04/27/2017	76 Thomas Maier, Sebastian Kraemer, Laurin Ostermann, Helmut Ritsch. A superradiant clock laser on a magic wavelength optical lattice, Optics Express, (): 13269. doi:	1,040,307.00
04/27/2017	75 D Plankensteiner, J Schachenmayer, H Ritsch, C Genes. Laser noise imposed limitations of ensemble quantum metrology, Journal of Physics B: Atomic, Molecular and Optical Physics, (): 245501. doi:	1,040,306.00
04/27/2017	74 S. Krämer, L. Ostermann, H. Ritsch. Optimized geometries for future generation optical lattice clocks, EPL (Europhysics Letters), (): 14003. doi:	1,040,305.00
05/02/2017	86 A.M. Rey, A.V. Gorshkov, C.V. Kraus, M.J. Martin, M. Bishof, M.D. Swallows, X. Zhang, C. Benko, J. Ye, N.D. Lemke, A.D. Ludlow. Probing many-body interactions in an optical lattice clock, Annals of Physics, (): 311. doi:	1,040,454.00
05/02/2017	92 M. Schioppo, R. C. Brown, W. F. McGrew, N. Hinkley, R. J. Fasano, K. Beloy, T. H. Yoon, G. Milani, D. Nicolodi, J. A. Sherman, N. B. Phillips, C. W. Oates, A. D. Ludlow. Ultrastable optical clock with two cold-atom ensembles, Nature Photonics, (): 48. doi:	1,040,460.00
05/02/2017	91 T. M Fortier, A. Rolland, F. Quinlan, F. N. Baynes, A. J. Metcalf, A. Hati, A. D. Ludlow, N. Hinkley, M. Shimizu, T. Ishibashi, J. C. Campbell, S. A. Diddams. Optically referenced broadband electronic synthesizer with 15 digits of resolution, Laser & Photonics Reviews, (): 780. doi:	1,040,459.00
05/02/2017	90 Andrew D. Ludlow, Martin M. Boyd, Jun Ye, E. Peik, P. O. Schmidt. Optical atomic clocks, Reviews of Modern Physics, (): 637. doi:	1,040,458.00
05/02/2017	88 K. Beloy, N. Hinkley, N. B. Phillips, J. A. Sherman, M. Schioppo, J. Lehman, A. Feldman, L. M. Hanssen, C. W. Oates, A. D. Ludlow. Atomic Clock with 1×10^{-18} Room-Temperature Blackbody Stark Uncertainty, Physical Review Letters, (): . doi:	1,040,456.00
05/04/2017	96 Philip G. Westergaard, Bjarke T. R. Christensen, David Tieri, Rastin Matin, John Cooper, Murray Holland, Jun Ye, Jan W. Thomsen. Observation of Motion-Dependent Nonlinear Dispersion with Narrow-Linewidth Atoms in an Optical Cavity, Physical Review Letters, (): . doi:	1,040,574.00
05/04/2017	108 D. A. Tieri, Minghui Xu, D. Meiser, J. Cooper, M. J. Holland. Theory of the crossover from lasing to steady state superradiance, ArXiv, (): . doi:	1,040,586.00
05/04/2017	107 Simon B. Jäger, Minghui Xu, Stefan Schütz, Murray J. Holland, Giovanna Morigi. Semiclassical theory of synchronization-assisted cooling, ArXiv, (): . doi:	1,040,585.00

- 05/04/2017 106 Zhe-Xuan Gong, Minghui Xu, Michael Foss-Feig, James K. Thompson, Ana Maria Rey, Murray Holland, Alexey V. Gorshkov. Steady-state superradiance with Rydberg polaritons, ArXiv, (): . doi: 1,040,584.00
- 05/04/2017 103 Peiru He, Phoebe M. Tengdin, Dana Z. Anderson, Ana Maria Rey, Murray Holland. Sub-Doppler Laser Cooling using Electromagnetically Induced Transparency, ArXiv, (): . doi: 1,040,581.00
- 05/04/2017 102 Athreya Shankar, John Cooper, Justin G. Bohnet, John J. Bollinger, Murray Holland. Steady-state spin synchronization through the collective motion of trapped ions, Physical Review A, (): . doi: 1,040,580.00
- 05/04/2017 101 Minghui Xu, Simon B. Jäger, S. Schütz, J. Cooper, Giovanna Morigi, M. J. Holland. Supercooling of Atoms in an Optical Resonator, Physical Review Letters, (): . doi: 1,040,579.00
- 05/04/2017 100 Bjarke T. R. Christensen, Martin R. Henriksen, Stefan A. Schäffer, Philip G. Westergaard, David Tieri, Jun Ye, Murray J. Holland, Jan W. Thomsen. Nonlinear spectroscopy of Sr atoms in an optical cavity for laser stabilization, Physical Review A, (): . doi: 1,040,578.00
- 05/04/2017 99 B Zhu, J Schachenmayer, M Xu, F Herrera, J G Restrepo, M J Holland, A M Rey. Synchronization of interacting quantum dipoles, New Journal of Physics, (): 083063. doi: 1,040,577.00
- 05/04/2017 98 D. A. Tieri, J. Cooper, Bjarke T. R. Christensen, J. W. Thomsen, M. J. Holland. Laser stabilization using saturated absorption in a cavity-QED system, Physical Review A, (): . doi: 1,040,576.00
- 05/04/2017 97 Minghui Xu, M. J. Holland. Conditional Ramsey Spectroscopy with Synchronized Atoms, Physical Review Letters, (): . doi: 1,040,575.00
- 05/04/2017 95 Minghui Xu, D. A. Tieri, E. C. Fine, James K. Thompson, M. J. Holland. Synchronization of Two Ensembles of Atoms, Physical Review Letters, (): . doi: 1,040,573.00
- 05/04/2017 94 S. A. McGee, D. Meiser, C. A. Regal, K. W. Lehnert, M. J. Holland. Mechanical resonators for storage and transfer of electrical and optical quantum states, Physical Review A, (): . doi: 1,040,572.00
- 05/11/2017 109 Joerg Pfeifle, Victor Brasch, Matthias Lauermann, Yimin Yu, Daniel Wegner, Tobias Herr, Klaus Hartinger, Philipp Schindler, Jingshi Li, David Hillerkuss, Rene Schmogrow, Claudius Weimann, Ronald Holzwarth, Wolfgang Freude, Juerg Leuthold, Tobias J. Kippenberg, Christian Koos. Coherent terabit communications with microresonator Kerr frequency combs, Nature Photonics, (): 375. doi: 1,041,029.00
- 05/11/2017 115 Victor Brasch, Erwan Lucas, John D Jost, Michael Geiselmann, Tobias J Kippenberg. Self-referenced photonic chip soliton Kerr frequency comb, Light: Science & Applications, (): . doi: 1,041,035.00
- 05/11/2017 114 Victor Brasch, Michael Geiselmann, Martin H. P. Pfeiffer, Tobias J. Kippenberg. Bringing short-lived dissipative Kerr soliton states in microresonators into a steady state, Optics Express, (): 29312. doi: 1,041,034.00
- 05/11/2017 113 Junqiu Liu, Victor Brasch, Martin H. P. Pfeiffer, Arne Kordts, Ayman N. Kamel, Hairun Guo, Michael Geiselmann, Tobias J. Kippenberg. Frequency-comb-assisted broadband precision spectroscopy with cascaded diode lasers, Optics Letters, (): 3134. doi: 1,041,033.00
- 05/11/2017 112 V. Brasch, M. Geiselmann, T. Herr, G. Lihachev, M. H. P. Pfeiffer, M. L. Gorodetsky, T. J. Kippenberg. Photonic chip-based optical frequency comb using soliton Cherenkov radiation, Science, (): 357. doi: 1,041,032.00

05/11/2017	111	Victor Brasch, Qun-Feng Chen, Stephan Schiller, Tobias J. Kippenberg. Radiation hardness of high-Q silicon nitride microresonators for space compatible integrated optics, Optics Express, (): 30786. doi: 1,041,031.00
05/11/2017	110	T. Herr, V. Brasch, J. D. Jost, I. Mirgorodskiy, G. Lihachev, M. L. Gorodetsky, T. J. Kippenberg. Mode Spectrum and Temporal Soliton Formation in Optical Microresonators, Physical Review Letters, (): . doi: 1,041,030.00
05/18/2015	17	T. M. Fortier, C. W. Nelson, A. Hati, F. Quinlan, J. Taylor, H. Jiang, C. W. Chou, T. Rosenband, N. Lemke, A. Ludlow, D. Howe, C. W. Oates, S. A. Diddams. Sub-femtosecond absolute timing jitter with a 10 ⁷ GHz hybrid photonic-microwave oscillator, Applied Physics Letters, (06 2012): 0. doi: 10.1063/1.4726122 314,685.00
05/18/2015	36	Hashem Zoubi, Helmut Ritsch. Collective electronic excitation coupling between planar optical lattices using Ewald's method, Journal of Physics B: Atomic, Molecular and Optical Physics, (10 2011): 0. doi: 10.1088/0953-4075/44/20/205303 314,714.00
05/30/2017	82	Y. Y. Jiang, A. D. Ludlow, N. D. Lemke, R. W. Fox, J. A. Sherman, L.-S. Ma, C. W. Oates. Making optical atomic clocks more stable with 10 ⁷ 16-level laser stabilization, Nature Photonics, (): 158. doi: 1,040,450.00
05/30/2017	84	Franklyn Quinlan, Tara M. Fortier, Matthew S. Kirchner, Jennifer A. Taylor, Michael J. Thorpe, Nathan Lemke, Andrew D. Ludlow, Yanyi Jiang, Scott A. Diddams. Ultralow phase noise microwave generation with an Er: fiber-based optical frequency divider, Optics Letters, (): 3260. doi: 1,040,452.00
05/30/2017	89	Andrew D. Ludlow, Jun Ye. Progress on the optical lattice clock, Comptes Rendus Physique, (): 499. doi: 1,040,457.00
05/30/2017	116	Wenlan Chen, Jiazhong Hu, Yiheng Duan, Boris Braverman, Hao Zhang, Vladan Vuletić. Carving Complex Many-Atom Entangled States by Single-Photon Detection, Physical Review Letters, (): . doi: 1,042,571.00
05/30/2017	117	Jiazhong Hu, Wenlan Chen, Zachary Vendeiro, Hao Zhang, Vladan Vuletic. Entangled collective-spin states of atomic ensembles under nonuniform atom-light interaction, Physical Review A, (): . doi: 1,042,572.00
05/30/2017	120	Kevin C. Cox, Graham P. Greve, Joshua M. Weiner, James K. Thompson. Deterministic Squeezed States with Collective Measurements and Feedback, Physical Review Letters, (): . doi: 1,042,592.00
05/30/2017	121	Matthew A. Norcia, James K. Thompson. Cold-Strontium Laser in the Superradiant Crossover Regime, Physical Review X, (): . doi: 1,042,593.00
05/30/2017	122	Matthew A. Norcia, James K. Thompson. Strong coupling on a forbidden transition in strontium and nondestructive atom counting, Physical Review A, (): . doi: 1,042,594.00
05/30/2017	118	Kevin C. Cox, Graham P. Greve, Baochen Wu, James K. Thompson. Spatially homogeneous entanglement for matter-wave interferometry created with time-averaged measurements, Physical Review A, (): . doi: 1,042,590.00
05/30/2017	119	M. A. Norcia, M. N. Winchester, J. R. K. Cline, J. K. Thompson. Superradiance on the millihertz linewidth strontium clock transition, Science Advances, (): . doi: 1,042,591.00
05/30/2017	123	Matthew A. Norcia, James K. Thompson. Simple laser stabilization to the strontium ⁸⁸ Sr transition at 707 nm, Review of Scientific Instruments, (): 023110. doi: 1,042,595.00

05/30/2017	125	Kevin C. Cox, Matthew A. Norcia, Joshua M. Weiner, Justin G. Bohnet, James K. Thompson. Reducing collective quantum state rotation errors with reversible dephasing, Applied Physics Letters, (): 261102. doi:	1,042,597.00
05/30/2017	126	Kevin C. Cox, Joshua M. Weiner, James K. Thompson. Phase diagram for injection locking a superradiant laser, Physical Review A, (): . doi:	1,042,598.00
05/30/2017	127	Minghui Xu, D.?A. Tieri, E.?C. Fine, James K. Thompson, M.?J. Holland. Synchronization of Two Ensembles of Atoms, Physical Review Letters, (): . doi:	1,042,599.00
05/30/2017	128	J. G. Bohnet, K. C. Cox, M. A. Norcia, J. M. Weiner, Z. Chen, J. K. Thompson. Reduced spin measurement back-action for a phase sensitivity ten times beyond the standard quantum limit, Nature Photonics, (): 731. doi:	1,042,600.00
05/30/2017	129	Zilong Chen, Justin G. Bohnet, Joshua M. Weiner, Kevin C. Cox, James K. Thompson. Cavity-aided nondemolition measurements for atom counting and spin squeezing, Physical Review A, (): . doi:	1,042,601.00
05/30/2017	130	Justin G. Bohnet, Zilong Chen, Joshua M. Weiner, Kevin C. Cox, James K. Thompson. Linear-response theory for superradiant lasers, Physical Review A, (): . doi:	1,042,602.00
TOTAL:		95	

Number of Papers published in peer-reviewed journals:

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

<u>Received</u>	<u>Paper</u>
01/13/2014 48.00	A. R. Johnson, Y. Okawachi, M. R. E. Lamont, J. S. Levy, M. Lipson, A. L. Gaeta. Microresonator-based comb generation without an external laser source, Optics, (05 2013): 0. doi:
01/13/2014 50.00	K. Saha, Y. Okawachi, J. S. Levy, K. Luke, R. K. W. Lau, M. A. Foster, M. Lipson, and A. L. Gaeta. Broadband parametric frequency comb generation with a 1-?m pump source, Optics Express, (11 2012): 26935. doi:
TOTAL:	2

Number of Papers published in non peer-reviewed journals:

(c) Presentations

A. D. Ludlow, N. D. Lemke, J. von Stecher, J. A. Sherman, A. M. Rey, and C. W. Oates, “Reducing the Uncertainty of the Yb Optical Lattice Clock - the cold collision shift,” 2011 Joint Conference of the IEEE International Frequency Control Symposium/European Frequency and Time Forum (May 2011).

Y. Y. Jiang, A. D. Ludlow, N. D. Lemke, J. A. Sherman, J. von Stecher, R. W. Fox, L. S. Ma, A. M. Rey, C. W. Oates, “Improving the stability and accuracy of the Yb optical lattice clock,” 2011 Joint Conference of the IEEE International Frequency Control Symposium/European Frequency and Time Forum Proceedings pages (2-5 May 2011).

T. M. Fortier, M. S. Kirchner, F. Quinlan, J. A. Taylor, N. Lemke, A. D. Ludlow, Y. Y. Jiang, T. Rosenband, J. C. Bergquist, C. W. Oates, S. A. Diddams, “Photonically Generated 10 GHz Microwaves with Close-to-Carrier Phase Noise <-100 dBc/Hz,” 2011 Joint Conference of the IEEE International Frequency Control Symposium/European Frequency and Time Forum Proceedings pages (2-5 May 2011).

A. D. Ludlow, N. D. Lemke, J. von Stecher, J. A. Sherman, Y. Y. Jiang, A. M. Rey, and C. W. Oates, “Measurement and cancellation of the cold collision shift in the Yb lattice clock,” SYRTE Paris Observatory Seminar (June 2011).

A. D. Ludlow, “Coherent optical carrier transfer via fiber link: Remote distribution of optical clock signals,” BIPM Workshop on Advanced Time and Frequency Transfer techniques (June 28-29 2011).

A. D. Ludlow, “Lattice Stark Effects in the Yb Clock,” Optical Frequency Measurements Group Meeting (Dec 2011).

A. D. Ludlow, “Optical Lattice Clocks,” 37th Annual NIST Time and Frequency Metrology Seminar, 2012.

A. D. Ludlow, J. A. Sherman, N. D. Lemke, K. Beloy, N. Hinkley, M. Pizzocaro, R. W. Fox, C. W. Oates, “Blackbody effects in the Yb Optical lattice clock,” Proceedings of the 2012 International Frequency Control Symposium (May 21-24, 2012, Baltimore).

N. Hinkley, J. Sherman et al., “Ytterbium Optical Lattice Clock,” Meeting of the APS Div. of Atomic, Molecular, and Optical Physics (June 4-8, 2012, Orange County).

K. Beloy et al., “Evaluation of the dynamic correction to the blackbody radiation clock shift in Yb,” International Conference on Atomic Physics (ICAP), Paris, France, July 2012

A. D. Ludlow, “Precision Measurements of the Blackbody Stark Effect in Ytterbium,” The 5th International Workshop on Ultracold Group II atoms (October 2012, Tokyo).

A.D. Ludlow, “The optical lattice clock: quantum metrology of time towards 10⁻¹⁸ level,” Quantum Optics VIII (May 2013, Jachranka, Poland).

A. D. Ludlow, “Optical Lattice Clocks,” 38th Annual NIST Time and Frequency Metrology Seminar, June 2013.

K. Beloy et al., “Pushing the uncertainty of a ytterbium optical lattice clock towards 10–17 fractional frequency” (poster), American Physical Society Division of Atomic, Molecular, and Optical Physics (DAMOP) Meeting, Quebec City, Canada, June 2013.

K. Beloy et al., “Precise realization of the thermal radiation environment for an optical lattice clock” (oral), American Physical Society Division of Atomic, Molecular, and Optical Physics (DAMOP) Meeting, Quebec City, Canada, June 2013

N. Phillips, J. Sherman et al., “Ytterbium Optical Lattice Clock,” International Conference on Laser Spectroscopy (June 9-14, 2013, Berkeley).

A. D. Ludlow, K. Beloy, J. A. Sherman, N. Hinkley, N. Phillips, N. D. Lemke, M. Schioppo, C. W. Oates “Characterizing the blackbody shift in a lattice clock to 1x10⁻¹⁸” 2013 Joint Conference of the IEEE International Frequency Control Symposium/European Frequency and Time Forum (July 2013, Prague, Czech Republic).

A. D. Ludlow, J. A. Sherman, N. B. Phillips, N. Hinkley, K. Beloy, M. Schioppo, C. W. Oates “Precision evaluation on Optical Clock Candidate for Space,” Int. Space Station Research and Development Conference (July 2013, Denver).

A. D. Ludlow, “Blackbody Stark Effects and Clock Instability” NIST Ion Storage Group Lunch Talk (August 2013).

A. D. Ludlow, “Enhancing the tick-tock of an optical atomic clock,” JILA Colloquium (September 2013, Boulder, CO).

A. D. Ludlow, “Enhancing the tick-tock of an optical atomic clock,” UC Berkeley AMO Physics Seminar (December 2013, Berkeley, CA).

K. Beloy, “If you can’t stand the heat: precise realization of a blackbody radiation environment in a Yb optical lattice clock” (oral), Time and Frequency Division Seminar, National Institute of Standards and Technology, Boulder, CO, January 2014.

A. D. Ludlow, “Enhancing the tick-tock of an optical atomic clock,” MIT/Harvard Center for Ultracold Atoms (CUA) Seminar (Cambridge, MA, March 2014).

N. Hinkley et al., International Frequency Control Symposium (May 19-27, 2014, Taiwan).

J. Olson et al., “A calcium optical frequency standard with Ramsey-Borde Interferometry,” Meeting of the APS Div. of Atomic Molecular and Optical Physics (June 2-6, 2014, Madison, WI).

A. D. Ludlow, “Optical Atomic Clocks and Metrology” Annual Meeting of the Division of Atomic, Molecular, and Optical Physics of the American Physical Society (June 2014, Madison, WI).

A. D. Ludlow, K. Beloy, N. Hinkley, J. A. Sherman, M. Schioppo, N. Phillips, J. Lehman, A. Feldman, L. Hanssen, C. W. Oates, “Optical lattice clock measurements at the mHz level,” European Frequency and Time Forum (June 2014, Neuchatel, Switzerland).

A. D. Ludlow, K. Beloy, M. Schioppo, N. Hinkley, J. A. Sherman, N. Phillips, W. McGrew, J. Lehman, A. Feldman, L. Hanssen, C. W. Oates, “Ultra-precise atomic timekeeping with the optical lattice clock,” International Conference on Atomic Physics (August 2014, Washington, D. C.).

K. Beloy et al., “Precise characterization of the blackbody radiation environment in an optical lattice clock” (poster), International Conference on Atomic Physics (ICAP), Washington, D.C., August 2014

A. D. Ludlow, “Optical Lattice Clocks,” 40th Annual NIST Time and Frequency Metrology Seminar, June 2015.

N. Phillips et al., “Lattice Stark shifts in a Ytterbium Optical Lattice Clock,” Joint Meeting of the Int’l. Freq. Control Symposium and European Frequency and Time Forum (April 12-16, 2015, Denver).

J. Olson et al., “Calcium optical frequency standard using Ramsey-Borde interferometry,” Meeting of the APS Div. of Atomic, Molecular, and Optical Physics (June 8-12, 2015, Columbus, Ohio).

W. McGrew et al., “Ytterbium optical lattice clock,” Meeting of the APS Div. of Atomic, Molecular, and Optical Physics (June 8-12, 2015, Columbus, Ohio).

M. Schioppo et al., “Ytterbium optical lattice clock,” Int’l. Conference on Laser Spectroscopy (June 28-July 3, 2015, Singapore).

A. D. Ludlow, K. Beloy, R. Brown, M. Schioppo, N. B. Phillips, N. Hinkley, T. H. Yoon, W. McGrew, R. Fasano, J. A. Sherman, C. W. Oates, “High stability Yb optical lattice clock towards 10-18 level uncertainty” 8th Symposium on Frequency Standards and Metrology (October 2015, Potsdam, Germany).

K. Beloy et al., “Precision measurement and control of Stark shifts in a Yb optical lattice clock” (poster), 8th Symposium on Frequency Standards and Metrology, Potsdam, Germany, October 2015

A. D. Ludlow, “Improving the Tick-Tock of an Atomic Clock: Telling Time to an Accuracy of One Second in the Lifetime of the Universe,” Philosophical Society of Washington Public Lecture (Feb. 5, 2016, Washington, D. C.).

A. D. Ludlow, R. Brown, K. Beloy, M. Schioppo, W. McGrew, N. Hinkley, T. H. Yoon, R. Fasano, N. B. Phillips, D. Nicolodi, G. Milani, J. A. Sherman, C. W. Oates, “Making 10-18 fractional frequency measurements with Yb optical lattice clocks,” International Workshop on Ultracold Group II Atoms (Feb. 2016, Paris, France).

A. D. Ludlow et al., “Yb optical lattice clock: towards fundamental physics in space,” NASA Fundamental Physics Proposers’ Workshop (Apr. 2016, Dana Point, CA).

K. Beloy et al., “Yb optical lattice clock towards low 10–18 standard uncertainty” (oral), Institute of Electrical and Electronics Engineers (IEEE) International Frequency Control Symposium (IFCS), New Orleans, LA, May 2016.

T. H. Yoon et al., “Ytterbium Optical Lattice Clock,” European Frequency and Time Forum (April 4-7, 2016, York, UK).

Robert Fasano et al., “Ytterbium Optical Lattice Clock,” Meeting of the APS Div. of Atomic Molecular and Optical Physics (May 23-27, 2016, Providence).

W. McGrew et al., “Ytterbium Optical Lattice Clock,” Gordon Research Conference – Quantum Science (July 31-Aug 5, 2016, Easton, MA).

N. Hinkley et al., “Ytterbium Optical Lattice Clock,” International Conference on Atomic Physics (July 24-19, 2016, Seoul, Korea).

J. Olson et al., “A calcium optical frequency standard using Ramsey-Borde interferometry,” International Conference on Atomic Physics (July 24-19, 2016, Seoul, Korea).

A. D. Ludlow, M. Schioppo, R. Brown, W. McGrew, N. Hinkley, R. Fasano, K. Beloy, T. H. Yoon, G. Milani, D. Nicolodi, N. B. Phillips, J. A. Sherman, C. W. Oates, “High-resolution optical-clock spectroscopy of ultracold, trapped ytterbium,” International Conference on

Spectral Lineshapes (June 2016, Torun, Poland).

R. Brown et al., "Ytterbium optical lattice clock," American Society for Gravitational and Space Research (October 26-29, 2016, Cleveland).

R. Brown et al., "Ytterbium optical lattice clock," Quantum Metrology Workshop (March 2-4, 2016, Warsaw, Poland).

A. D. Ludlow, "Optical lattice clocks" Frontiers in Matter Wave Optics Summer School (Sep. 2016, Arcachon, France).

A. D. Ludlow, "Improving the Tick-Tock of an Atomic Clock: Optical Lattice Clocks for Next-Generation Timekeeping," Northwestern University Dept. of Physics AMO Seminar (November 2016).

Helmut Ritsch,(invited)

Discussions on Nano & Mesoscopic Optics (El Chalten, Patagonia, Argentina, April 2015

Superradiance and Cascaded Decay. Quantum Assisted Sensing And Readout (QuASAR Program Review, Santa Barbara, 29.08.2012

Optomechanics on the Hudson (keynote tutorial, New York, USA, April, 2-4, 2012)

Hashem Zoubi

Excitons and Polaritons for Optical Lattice Ultracold Atoms in Cavity QED. APS March Meeting, Dallas, Texas, 23.03.2011

Collective light emission of optical lattice ultracold atoms. Max-Planck-Institut für die Physik des Lichts (MPL) / Max Planck Institute for the Science of Light, Erlangen, 04.05.2012

3.3 Laurin Ostermann

Poster at ICAP Summer School (Paris, France; Jul 2012)

Poster at QUASAR Review Meeting (Santa Barbara, CA, USA; Aug 2012)

Talk at Meeting of the Austrian Physical Society (Graz, Austria; Sep 2012)

Talk and Poster at YAO Summer School (Birmingham, UK; Apr 2013)

Poster at SFB Meeting (Innsbruck, Austria; Jul 2013)

Seminar Talk at JILA (Boulder, CO, USA; Aug 2013)

Poster at QUASAR Review Meeting (Santa Cruz, CA, USA; Aug 2013)

Poster at Meeting of Austrian Physical Society (Linz, Austria; Sep 2013)

Talk at Quantum Technologies IV (Warsaw, Poland; Sep 2013)

Talk at SFB Meeting (Innsbruck, Austria; Oct 2013)

Poster at Meeting of Austrian Physical Society (Vienna, Austria; Sep 2015)

Murray Holland:

Contributed talk: David Tieri, Dominic Meiser and Murray Holland, "Cavity QED systems with group II atoms and the crossover between lasing and superradiance", DAMOP annual meeting of the American Physical Society, Atlanta, Georgia June 13-17 (2011).

Contributed talk: Dominic Meiser, Michael Martin, Jun Ye and Murray Holland, "Cavity enhanced nonlinear spectroscopy of ultra-narrow optical transitions", DAMOP annual meeting of the American Physical Society, Atlanta, Georgia, June 13-17 (2011).

Contributed poster: Murray Holland, Dominic Meiser and David Tieri, "Cavity QED with group II atoms", DAMOP annual meeting of the American Physical Society, Atlanta, Georgia, June 13-17 (2011).

Invited talk: Murray Holland, "Prospects for a millihertz linewidth laser", Regional Workshop on Ultracold Atoms, Australian Research Council Centre of Excellence for Quantum-Atom Optics, Kioloa, Australia, 28-30 November (2011).

Invited talk: Murray Holland, "Prospects for a superradiant laser", The 41st Winter Colloquium on the Physics of Quantum Electronics, Snowbird, Utah, Jan 2-6 (2011).

Physics Department Colloquium: Murray Holland "A Sharper Laser", University of Otago, Dunedin, New Zealand, November 22 (2011).

Contributed talk: Justin Bohnet, Zilong Chen, Joshua Weiner, Dominic Meiser, Murray Holland, and James Thompson, "A Superradiant Raman Laser with < 1 Intracavity Photons", DAMOP annual meeting of the American Physical Society, Orange County, June 4-8 (2012).

JILA Colloquium: Murray Holland "There and back again", JILA, University of Colorado Boulder, September 11 (2012).

Physics Department Colloquium: Murray Holland, "Ultrastable light", University of Massey, Auckland, New Zealand, February 16 (2012).

Contributed talk: M. Holland, JILA AMO Physics Frontier Center Meeting, August 2012.

Invited talk: Murray Holland, "Cold atoms and degenerate quantum gases", DAMOP Meeting of the American Physical Society, June 3–7, 2013; Quebec City, Canada.

Contributed talk: Minghui Xu, David Tieri, and Murray Holland, "Ultrastable light sources in the crossover from superradiance to lasing", DAMOP Meeting of the American Physical Society, June 3–7, 2013; Quebec City, Canada.

Research Seminar: Murray Holland "Quantum synchronization and the superradiant laser", University of Innsbruck, Austria, Thursday 4th July, 2013.

Research Seminar: Murray Holland, "Quantum Synchronization and the superradiant laser", University of Pisa, Italy, July 9, 2013.

Physics Colloquium: Murray Holland, "The Superradiant Laser", University of New Mexico, Albuquerque September 12, 2013.

Invited talk: Murray Holland, "Quantum synchronization and the no-photon laser", APS March Meeting 2014, March 3–7, 2014; Denver, Colorado.

Contributed Talk: Bihui Zhu, Juan Restrepo, Ana Maria Rey, Murray Holland, "Quantum synchronization of ultracold atoms with dipole-dipole interactions in an optical lattice", DAMOP Meeting 2014, June 2–6, 2014; Madison, Wisconsin.

Contributed Talk: David Tieri, Jan Thomsen, Jun Ye, Murray Holland, "Collective atomic effects in cavity QED with application to atomic clocks", DAMOP Meeting 2014, June 2–6, 2014; Madison, Wisconsin.

Contributed Talk: Minghui Xu, David Tieri, Effie Fine, James Thompson, Murray Holland, "Quantum Synchronization of Two Ensembles of Atoms", DAMOP Meeting 2014, June 2–6, 2014; Madison, Wisconsin.

Contributed Talk: Peiru He, Minghui Xu, David Tieri, Bihui Zhu, Ana Maria Rey, Kaden Hazzard, Murray Holland, "Quantum synchronization of many coupled atoms for an ultranarrow linewidth laser", DAMOP Meeting 2014, June 2–6, 2014; Madison, Wisconsin.

Invited Talk and Discussion Leader: M. Holland, "Quantum synchronization in atomic clocks and ultrastable lasers", International Workshop on Quantum Coherence and Decoherence II, Medellin, Colombia, August 25-29, 2014.

Contributed Talk: Peiru He, Ana Maria Rey, and Murray Holland, "Quantum Synchronization of Three Level Atoms", DAMOP Meeting 2015, June 8–12, 2015; Columbus, Ohio.

Contributed Talk: Zhexuan Gong, Michael Foss-feig, Minghui Xu, Ana Maria Rey, Murray Holland, Alexey Gorshkov, "Nonclassical millihertz linewidth light source with Rydberg polaritons", DAMOP Meeting 2015, June 8–12, 2015; Columbus, Ohio.

Invited Speaker: Murray Holland, "Supercooling of atoms based on steady-state superradiance", International Conference on Control of Complex Systems and Networks, Heringsdorf, Usedom, Germany, 9/4/2016-9/8/2016.

Invited Speaker: Murray Holland, "Supercooling of atoms based on steady-state superradiance", International Conference on continuous atomic sources and extreme cooling of atoms and molecules: techniques and applications, Les Houches, France, 1/24/2016-1/29/2016.

Contributed Talk: Peiru He, Phoebe Tengdin, Dana Anderson, Ana Maria Rey, and Murray Holland, "Theoretical model for Sub-Doppler Cooling with EIT System", DAMOP Meeting May 23–27, 2016; Providence, Rhode Island.

Contributed Talk: Minghui Xu, Simon Jager, Stefan Schutz, John Cooper, Giovanna Morigi, and Murray Holland, "Supercooling of Atoms in an Optical Resonator", DAMOP Meeting May 23–27, 2016; Providence, Rhode Island.

Contributed Talk: Victor Colussi, Cameron Straatsma, Matthew Davis, Dan Lobser, Murray Holland, Dana Anderson, Eric Cornell, and Heather Lewandowski, "Collapse and revival of the monopole mode of a Bose-Einstein condensate in a spherical harmonic trap", DAMOP Meeting May 23–27, 2016; Providence, Rhode Island.

Kippenberg

Presentations were QuASAR results were presented in full or in-part.

Presenter	Conference	Location	Date	Title	Status
TJ Kippenberg	Frontiers in Optics	FIO Orlando, FL, USA	Oct. 6-10, 2013	Frequency Combs and Ultrashort Laser Pulses Generation via Temporal Solitons in Optical Microresonators	Invited
TJ Kippenberg	Swiss Symposium Zruich, Switzerland	Kyoto	Nov. 21-22, 2013	Chip Scale Optical Frequency Combs	Invited
T. Herr	Super-continuum symposium	Besancon, France	Sept. 20, 2013	Microresonator Frequency Combs	Invited
J. Jost	Physics of Quantum Electronics	Snowbird, UT, USA	Jan. 5-8, 2014	Frequency Comb Generation in Optical Microresonators via Soliton Formation	Invited
T. Herr	Optical Frequency Combs : from sources to applications	2014 Toulouse, France	Feb. 12, 2014	Microresonator frequency combs	Invited
T. Herr	Workshop: Fabrication and Application of Micro-structured Optical Devices	Tokyo, Japan	Feb 27-28, 2014	Microresonator frequency combs	Invited
T. Herr	SPIE Silicon Photonics and Photonic Integrated Circuits	Brussels, Belgium	Apr. 15, 2014	Chip-scale microresonator frequency combs and femtosecond pulse generation	Invited
TJ Kippenberg	Annual Mtg EOS	Berlin, Germany,	Sept 16 -19, 2014	The mechanical properties of light	Invited
TJ Kippenberg	ECOC 2014	Cannes - France	Sept 21 -25, 2014	Microresonator based optical frequency combs and ultra short solitons	Invited
TJ Kippenberg	NOEKS Bremen, Germany		Sept 22- 25 2014	Soliton and frequency comb generation in optical microresonators	Invited
M. Geiselmann	IEEE IPS Benelux	Enschede, Holland	Nov 3 -4 2014	Chip scale optical frequency combs	Invited
TJ Kippenberg	MSU - Moscow				

State University
Seminar Moscow
Russia Nov 18-21
2014 The Physics of High Q optical micro
resonators: from optomechanics to frequency combs Invited

M. Geiselmann PQE-2015 Snowbird UT,
USA Jan 4-9
2015 Optical microresonator based frequency
combs: from soliton Induced Cherenkov radiation to counting the cycles of light Invited

TJ Kippenberg SPIE Photonic
WEST San
Francisco San
Francisco, USA Feb 7-12,
2015 On chip temporal solitons and coherent
dispersive waves in SiN optical micro resonators for octave spanning frequency
combs Invited

M. Geiselmann Integrated
Photonics
Research Boston, USA Jun. 28 -
July 1,
2015 Microresonator based soliton formation Invited

V. Brasch OSA Nonlinear
Optics Meeting
2015 Lihue, USA July 27 –
Aug. 01
2015 Photonic Chip Based Frequency Comb
Using Soliton Induced Cherenkov
Radiation Invited

TJ Kippenberg CLEO US San Jose,
USA May 5 – 15,
2015 Photonic Chip Based Optical Frequency
Comb Using Soliton Induced Cherenkov
Radiation Invited

TJ Kippenberg ITQW 2015,
Workshop on on
Frequency combs technology and applications. Wien, Austria Sept 9 – 11,
2015 The Science of Optical Microresonators:
Chipscale Optical Frequency Combs Invited

TJ Kippenberg Photonic in
Switching- Florence Florence,
Italy Sept, 22-25,
2015 Soliton Cherenkov radiation based
optical frequency combs using a chip scale micro-resonator” Invited

M. Geiselmann post ECOC
workshop Barcelona -
Spain Oct. 2-4,
2015 Cavity-Soliton Kerr Frequency Combs
and their applications Invited

V. Brasch Frontier in Optics San Jose, CA,
USA Oct 8-10,
2015 Broadband Frequency Combs on a
Photonic Chip Using Soliton Induced
Cherenkov Radiation Invited

TJ Kippenberg Optical Frequency
Combs for Space applications -
Keck Institute Caltech, CA,
USA Nov 2-15,
2015 Optical Frequency Combs for Space
applications Workshop Invited

23 TJ Kippenberg Frontiers in Optics
(FiO) 2016 Rochester,
USA Oct, 17-21,
2016 Soliton Kerr Frequency Combs on a Chip Invited
24 TJ Kippenberg Menlo Systems
OFC User Seminar
Program Munich,
Germany Nov, 16-17,
2016 Microresonator-based optical frequency
combs Invited

Prof James Thompson

1. "Breaking Quantum and Thermal Limits," DARPA QUASAR, George Mason Univ., Arlington, VA (Sept. 2016)
2. "Clocks for Probing New Physics," New Pathways for Physics Beyond the Standard Model Workshop, Univ. of California Berkeley, Berkeley, CA (June 2016)
3. "Breaking Quantum and Thermal Limits on Precision Measurements," DAMOP 2016 Invited Talk in Cold Atoms in Optical Cavities session, Providence, RI (May 2016)
4. "Breaking Quantum and Thermal Limits," DARPA QUASAR, JILA, Boulder, CO (April 2016)
5. "Breaking Quantum and Thermal Limits on Precision Measurements," Quantum Optics 2016 Obergurgl, Austria (Feb 2016)
6. "Collective atom counting and first lasing on a millihertz linewidth optical transition," International Workshop on Ultracold Group II atoms, Paris Observatory, Paris, France (Feb 2016)
7. "Breaking Quantum and Thermal Limits," SPIE Photonics West, San Francisco, CA (Feb 2016)
8. "Breaking Quantum and Thermal Limits," AMO Seminar, Stanford University, Palo Alto, CA (Nov. 2015)
9. "Quantum Accuracy and Quantum Fuzziness," Physics Colloquium, UCLA, Los Angeles, CA (Nov. 2015)
10. "Quantum Accuracy and Quantum Fuzziness," Physics Colloquium, Colorado School of Mines, Golden, CO (Nov. 2015)
11. "Breaking Quantum and Thermal Limits," DARPA QUASAR, UCSB, Santa Barbara, CA (Oct 2015)
12. "Overcoming Quantum and Thermal Limits for Precision Measurements," 12th US-Japan Seminar on many body quantum systems, Madison, WI (Sept. 2015)
13. "Breaking Quantum and Thermal Limits," Physics Research Opportunities Seminar, Boulder, CO (Sept. 2015)
14. "Quantum Many-Body States for Precision Measurement," NRC Review Panel, Boulder, CO (Sept. 2015)
15. "Quantum Fuzziness & <1 Photon Laser," REU Summer Program, Boulder, CO (July 2015)
16. "Collective Effects for Precision Measurement," University of Amsterdam, Amsterdam, Netherlands, (May 2015)
17. "Collective Effects for Precision Measurement," Niels Bohr Institute, Copenhagen, Denmark, (May 2015)
18. "Entanglement via Coherence Preserving Measurements," Continuous Variable Entanglement in Atomic Systems, WR Heraeus

Seminar, Bad Honnef, Germany (May 2015)

19. “Quantum Fuzziness and Quantum Certainty,” Saturday Morning Physics, Boulder, CO (April 2015)
20. “Enhancing Clocks with Collective Effects: Spin Squeezing and Superradiance,” IFCS-EFTF IEEE International Frequency Control Symposium & European Frequency and Time Forum, Denver, CO (April 2015)
21. “Collective Effects for Precision Measurements,” DARPA QUASAR, Boston, MA (March 2015)
22. “Table Top Physics in Boulder”, graduate recruiting weekends, Boulder, CO (March and April 2015)
23. “Collective Effects for Precision Measurements,” Physics Frontier Center, Boulder, CO (Feb. 2015)
24. “Quantum Fuzziness and Quantum Certainty,” James Franck Institute 1st Tuesday Colloquium, Univ. of Chicago, Chicago, IL (Oct. 2014)
25. “Collective Effects for Enhancing Frequency Metrology,” DARPA QUASAR, Broomfield, CO (Sept. 2014)
26. “Collective Effects for Enhancing Quantum Metrology,” IMODS/NIST Workshop on Quantum Technologies, NIST, Boulder, CO (June 2014)
27. “Dynamics of a Superradiant Laser,” DAMOP Focus Session, Madison, WI (June 2014)
28. “Table Top Physics in Boulder”, graduate recruiting weekends, Boulder, CO (March and April 2014)
29. “Collective Effects for Enhancing Frequency Metrology,” DARPA QUASAR, Long Beach, CA (Jan. 2014)
30. “10 dB of Observed Squeezing via Collective Measurement,” Physics of Quantum Electronics PQE, Snowbird, UT (Jan. 2014)
31. “Exploring Collective Effects for Precision Measurement,” Physics Colloquium, Dept. of Physics, Univ. of Washington, Seattle, WA (Nov. 2013)
32. “Optical Coherence Times Approaching One Hour,” NIST Colloquium, NIST, Gaithersburg, MD (Nov. 2013)
33. “Exploring Collective Effects for Precision Measurement,” Joint Quantum Institute, Univ. of Maryland, College Park, MD (Oct. 2013)
34. “Breaking Quantum and Thermal Limits,” CU Physics Research Opportunities Seminar, Boulder, CO (Sept. 2013)
35. “Superradiant Lasers for Advanced Communication,” NIST Advanced Communication Workshop, NIST, Boulder, CO (Sept. 2013).
36. “Exploring Collective Effects for Precision Measurement,” 6th International Symposium on Modern Problems of Laser Physics, Novosibirsk, RS (August, 2013)
37. “Exploring Collective Effects for Precision Measurement,” Gordon Research Conference on Atomic Physics, Newport, RI (June, 2013)
38. “A Cold-Atom Laser with <1 Intracavity Photon,” CLEO/QELS2013, San Jose, CA, (June, 2013).
39. “Exploring Collective Effects for Precision Measurement,” AMO Seminar, Univ. of California, Berkeley, CA (May 2013)
40. “Table Top Physics in Boulder”, graduate recruiting weekends, Boulder, CO (March and April 2013)
41. “Superradiant Lasers,” DARPA QuASAR Workshop, JILA, Boulder, CO (March, 2013)
42. “Superradiant Laser with <1 Intracavity Photon,” Physics Frontier Center Talk, JILA, Boulder, CO (November, 2012)
43. “Superradiant Laser with <1 Intracavity Photons,” NIST on a Chip Workshop, Boulder, CO (November, 2012)
44. “Superradiant Laser with <1 Intracavity Photons,” APS Four Corners Sectional Meeting, New Mexico Inst. of Mining and Technology, Socorro, NM (October, 2012)
45. “Ensemble Cavity-QED for Quantum Metrology,” Dept. of Physics Colloquium, Colorado State University, Fort Collins, CO (October, 2012)

46. "A Cold-Atom Superradiant Laser with <1 Intracavity Photon," Frontiers in Optics, Rochester, NY (October, 2012)
47. "Spin Squeezing a Large Atomic Ensemble," Division of Laser Science, Rochester, NY (October, 2012)
48. "Superradiant laser with <1 Intracavity photon", Optical, Electronic, and Quantum Systems Seminar OEQS, U.C. Boulder, CO (September, 2012)
49. "Superradiant laser with <1 Intracavity photon", DARPA QuASAR, Santa Barbara, CA, (August, 2012)
50. "Superradiant laser with <1 Intracavity photon", Hot Topics Session, ICAP, Paris, France (July, 2012)
51. "Superradiant laser with <1 Intracavity photon", Hot Topics Session, DAMOP, Anaheim, CA (June, 2012)
52. "Ensemble Cavity-QED and Precision Metrology", NIST Ion Trapping Group, Boulder, CO (May, 2012)
53. "Table Top Physics in Boulder", graduate recruiting weekends, Boulder, CO (March and April 2012)
54. "Breaking Quantum and Thermal Limits", REU talk, Boulder, CO (July, 2012)
55. "Squeezed Atoms and a Superradiant Laser with <1 Photon", MIT/Harvard Center for Ultracold Atoms, Harvard University, Cambridge, MA (April, 2012)
56. "Ensemble Cavity-QED and Precision Metrology", Southwest Quantum Information and Technology (SQuInT), Albuquerque, NM (Feb, 2012)

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

<u>Received</u>	<u>Paper</u>
01/06/2014	20 R. W. Fox, J. A. Sherman, W. Douglas, J. B. Olson, A. D. Ludlow, C. W. Oates. A high stability optical frequency reference based on thermal calcium atoms, Proceedings of the 2012 IEEE International Frequency Control Symposium. 21-MAY-11, . : ,
01/25/2014	55 Gaeta, A.L., Lipson, M., Okawachi, Y., Saha, K., Levy, J.S., Wen, Y.H.. Silicon-chip-based octave-spanning frequency comb, Conference on Lasers and Electro-Optics (CLEO). 06-MAY-12, . : ,
01/25/2014	63 Zhang, Mian, Cardenas, Jaime, Phare, Chris, Shah, Shreyas, Poitras, Carl B., Lipson, Michal. High Q SiC on silicon microresonators, 2013 Conference on Lasers and Electro-Optics (CLEO), 09-14 June 2013, San Jose, CA.. 09-JUN-13, . : ,
01/25/2014	62 Lamont, Michael R.E., Griffith, Austin, Henry Wen, Y., Okawachi, Yoshitomo, Lipson, Michal, Gaeta, Alexander L., Lau, Ryan K.W.. Mid-infrared supercontinuum generation in silicon waveguides, ., 2013 Conference on Lasers and Electro-Optics (CLEO), 09-14 June 2013, San Jose, CA. 09-JUN-13, . : ,
01/25/2014	61 De Oliveira, Rafael E. P., Lipson, Michal, De Matos, Christiano J. S.. Electrically controlled silicon nitride ring resonator for quasi-phase matched second-harmonic generation, 2012 Conference on Lasers and Electro-Optics (CLEO), 06-11 May 2012, San Jose, CA.. 06-MAY-12, . : ,
01/25/2014	57 Saha, K., Okawachi, Y., Shim, B., Levy, J.S., Foster, M.A., Lipson, M., Gaeta, A.L. On-chip high repetition rate femtosecond source, 2012 Conference on Lasers and Electro-Optics (CLEO). 06-MAY-12, . : ,
01/25/2014	56 Clemmen, S., Van Laer, R., Farsi, A., Levy, J., Lipson, M., Gaeta A.. Towards frequency-coded qdits manipulation using coherent four-wave mixing, Lasers and Electro-Optics (CLEO), 2012 Conference on . 06-MAY-12, . : ,
01/25/2014	60 Fridman, M., Okawachi, Y., Clemmen, S., Menard, M., Lipson, M., Gaeta, A.L.. Optical cross correlator in a silicon waveguide, 2012 Conference on Lasers and Electro-Optics (CLEO), 06-11 May 2012, San Jose, CA.. 06-MAY-12, . : ,
01/25/2014	59 Okawachi, Y., Lipson, M., Gaeta, A.L., Bergman, K., Ophir, N., Padmaraju, K., Menard, M., Lau, R.K.W.. A broadband 1850-nm 40-Gb/s receiver based on four-wave mixing in silicon waveguides, 2012 Conference on Lasers and Electro-Optics (CLEO), 06-11 May 2012, San Jose, CA.. 06-MAY-12, . : ,
01/25/2014	58 Saha, K., Johnson, A.R., Okawachi, Y., Levy, J.S., Cardenas, J., Lipson, M., Gaeta, A.L.. Broadband parametric frequency combs with sub-100-GHz repetition rates, 2012 Conference on Lasers and Electro-Optics (CLEO), 06-11 May 2012, San Jose, CA.. 06-MAY-12, . : ,
05/18/2015	18 Y. Y. Jiang, A. D. Ludlow, N. D. Lemke, J. A. Sherman, J. von Stecher, R. W. Fox, L. S. Ma, A. M. Rey, C. W. Oates. Improving the stability and accuracy of the Yb optical lattice clock, 2011 Joint Conference of the IEEE International Frequency Control Symposium/European Frequency and Time Forum. 02-MAY-11, . : ,

05/18/2015	19	T. M. Fortier, M. S. Kirchner, F. Quinlan, J. A. Taylor, N. Lemke , A. D. Ludlow, Y. Y. Jiang, T. Rosenband, J. C. Bergquist, C. W. Oates, S. A. Diddams. Photonically Generated 10 GHz Microwaves with Close-to-Carrier Phase Noise <-100 dBc/Hz, Proceedings of the 2011 Joint Conference of the IEEE International Frequency Control Symposium/European Frequency and Time Forum. 02-MAY-11, . : ,
05/18/2015	21	J. A. Sherman, N. D. Lemke, K. Beloy, N. Hinkley, M. Pizzocaro, R. W. Fox, C.W. Oates, A. D. Ludlow. Blackbody effects in the Yb lattice clock, 2012 IEEE International Frequency Control Symposium, Baltimore, Maryland, May, 2012. 21-MAY-11, . : ,
TOTAL:		13

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

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

<u>Received</u>	<u>Paper</u>
01/25/2014 64.00	Yoshitomo Okawachi, Reza Salem, Adrea R. Johnson, Kasturi Saha, Jacob S. Levy, Michal Lipson, Alexander L. Gaeta. Single-Shot Characterization of Ultrafast High-Repetition-Rate Signals Using an Asynchronous Time Magnifier, CLEO: Science and Innovations. 09-JUN-13, San Jose, California. : ,
01/25/2014 65.00	Ryan K. Lau, Michael Menard, Yoshitomo Okawachi, Michal Lipson, Alexander L. Gaeta. Four-Wave Mixing in Si3N4-Clad Silicon-on-Insulator Waveguides for the Mid-Infrared Region, CLEO: Science and Innovations. 09-JUN-13, San Jose, California. : ,
TOTAL:	2

(d) Manuscripts

<u>Received</u>	<u>Paper</u>
01/07/2014 26.00	N. Poli, C. W. Oates, P. Gill, G. Tino. Optical Atomic Clocks, La Rivista del Nuovo Cimento (10 2013)
01/07/2014 27.00	A.V. Gorshkov, A. M. Rey, C.V. Kraus, M. J. Martin, M. Bishof, M. D. Swallows, X. Zhang, C. Benko, J. Ye, N.D. Lemke, A.D. Ludlow. Probing many-body interactions in an optical lattice clock, Annals of Physics (11 2013)
01/07/2014 31.00	Minghui Xu, D. A. Tieri, E. C. Fine, James K. Thompson, M. J. Holland. Quantum Synchronization of Two Ensembles of Atoms, PHYSICAL REVIEW LETTERS (08 2013)
TOTAL:	3

Number of Manuscripts:

Books

<u>Received</u>	<u>Book</u>
TOTAL:	

<u>Received</u>	<u>Book Chapter</u>
01/07/2014 8.00	T. Bodiya, R. DeSalvo, G. M. Harry. High-precision Laser Stabilization via Optical Cavities, London : Cambridge University Press, (01 2011)
05/02/2017 81.00	Ritsch, Helmut (with Zoubi, Hashem). Excitons and Cavity Polaritons for Optical Lattice Ultracold Atoms, : Elsevier, ()
TOTAL:	2

Patents Submitted

Patents Awarded

Awards

Jun Ye:

Presidential Rank Award (US), Distinguished, 2015

Gold Medal (Optical Atomic Clock), US Department of Commerce, 2014

Thomson Reuters Highly Cited Researcher (Top 1%), 2002 – 2014, 2015, 2016

Rocky Mountain Eagle Award, 2014

Elected member, National Academy of Sciences (US), 2011

Andrew Ludlow

1. Presidential Early Career Award for Scientists and Engineers (PECASE, 2016, Andrew Ludlow)

2. U.S. Department of Commerce Gold Medal Award (2015, Andrew Ludlow and Chris Oates)

3. Rocky Mountain Eagle Award for Scientific Achievement (2014, Andrew Ludlow and Chris Oates)

4. IEEE Ultrasonics, Ferroelectric, and Frequency Control (UFFC) Society Outstanding Paper Award (2013)

5. European Frequency and Time Forum (EFTF) Young Scientist Award (2013, Andrew Ludlow)

Helmut Ritsch

L. Ostermann: EPL Poster Prize at Meeting of the Austrian Physical Society (Linz, AT; Sep 2013)

Kippenberg:

Dr. Tobias Herr was chosen by the Quantum Electronics and Photonics (QEP) Group of the Institute of Physics (IOP) for the best 2013 thesis on one of the topics of the group.

Vladan Vuletic

Marko Jaric Prize, Serbia (2013);

Fellow of the American Physical Society (2012);

James Thompson

Department of Commerce Bronze Medal (Aug. 2013)

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	<u>DISCIPLINE</u>
S. Blatt	0	Physics
T.L. Nicholson	0	Physics
M.J. Martin	0	Physics
M. Bishof	0	Physics
B. Bloom	0	Physics
Akio Kawasaki	5,000	physics
Hao Zhang	5,000	physics
Boris Braverman	5,000	physics
S. Blatt	2,500	physics
M.J. Martin	5,000	physics
T.L. Nicholson	5,000	physics
M. Bishof	2,500	physics
B. Bloom	5,000	physics
S. Campbell	3,000	physics
S. Bromley	5,000	physics
R. Hutson	5,000	physics
Laurin Ostermann	10,000	physics
Thomas Maier	7,500	physics
David Plankensteiner	0	physics
Nathan Hinkley	5,000	physics
Gianmaria Milani	5,000	physics
William McGrew	5,000	physics
David Tieri	10,000	physics
Minghui Xu	10,000	physics
John Bartolotta	5,000	physics
Haonan Liu	5,000	physics
Athreya Shankar	5,000	physics
Justin Bohnet	2,500	physics
Kevin Cox	2,500	physics
Justin Weiner	2,500	physics
Matthew Norcia	2,500	physics
Graham Greve	2,500	physics
FTE Equivalent:	1,280.00	
Total Number:	32	

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	<u>Discipline</u>
Nathan Hinkley	50.00	
Mahdi Hosseini	5.00	
M. Swallows	15.00	
J. Williams	30.00	
X. Zhang	20.00	
G.E. Marti	15.00	
S. Kolkowitz	5.00	
Hashem Zoubi	50.00	
Laurin Ostermann	5.00	
Nathaniel Phillips	25.00	
Marco Schioppo	25.00	
Dominic Meiser	100.00	
FTE Equivalent:	345.00	
Total Number:	12	

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Helmut Ritsch	0.00
Jun Ye	0.00
Andrew Ludlow	20.00
Murray Holland	8.30
Tobias Kippenberg	0.00
Vladan Vuletic	0.00
James Thomson	0.00
FTE Equivalent:	28.30
Total Number:	7

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	<u>DISCIPLINE</u>
R. McNally	10,000	physics
N.D. Oppong	2,500	physics
FTE Equivalent:	125.00	
Total Number:	2	

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: 3.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 3.00

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:..... 3.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 3.00

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: 1.00

Names of Personnel receiving masters degrees

<u>NAME</u>
Thomas Maier
David Plankensteiner
Total Number:
2

Names of personnel receiving PhDs

<u>NAME</u>	
Laurin Ostermann	
S. Blatt	
M.J. Martin	
T.L. Nicholson	
M. Bishof	
B. Bloom	
S. Campbell	
Nathan Hinkley	
Marco Pizzocaro	
Nathan Lemke	
Minghui Xu	
David Tieri	
Victor Brasch	
Justin Bohnet	
Kevin Cox	
Justin Weiner	
Total Number:	16

Names of other research staff

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Richard Fox	10.00
Tiago Moarles	10.00
FTE Equivalent:	20.00
Total Number:	2

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Jun Ye:

Developing the first quantum degenerate gas based optical lattice clock in a three dimensional lattice. This work represents the first important step towards realization of the full potential on the Sr lattice clock: using 1 millions atoms with a coherence time of 160s. This ultimate system will represent performance improvement over current systems by 4 orders of magnitude. (2) Development of the first proposal of space-based gravitational wave detection using Sr optical lattice clocks, with an emphasis on the unique features of this atom technology based detection approach. (3) A comprehensive study of coherence of scattered light and collective emission in a driven gas of cold strontium-88 atoms, highlighting that light scattering from a dense coherent medium is determined by the interplay of dispersive and radiative dipole-dipole interactions. (4) Provide a new physical platform to study spin-orbit coupling physics in a fermionic optical lattice clock. Spin-orbit coupling is both generated and probed using a direct ultra-narrow optical clock transition between two electronic levels. The stability of the clock system allows control of all relevant quantum degrees of freedom. The system can access unexplored phenomena, including the direct observation of van Hove singularities (divergences in the density of states) in a spin-orbit coupled band structure and many-body correlations resulting from the interplay between SOC and interactions. (5) Development of the world's most stable lasers, with laser linewidth approaching 10 mHz. New reference cavity configurations and new high quality optical coating methods have been developed and characterized.

Ludlow:

1. We realized multiple world-record advances in atomic clock stability, including the demonstration of the world's most stable/precise atomic clock. These advances, distributed in time throughout the QuASAR program, include demonstrating clock instability in the low 10-16 range at one second and demonstrating the first atomic clock to realize 10-18 instability at any timescale. Furthermore, by merging two optical lattice clock systems into a single hybrid clock, we demonstrated further record-breaking optical clock stability at all timescales measured, from 6×10^{-17} at one second, to 1×10^{-18} in a mere few thousand seconds of operation.

2. We carried out a detailed study of atomic collision processes in an ytterbium lattice clock, elucidating key collision-induced frequency shifts in lattice clocks and how these shifts can be controlled. This study further revealed evidence of many-body interactions in an optical lattice.

3. We carried out a detailed study of all effects contributing to the largest systematic effect in most optical lattice clocks, the blackbody Stark effect. This study included a very high accuracy measurement of the differential clock static polarizability in ytterbium, an experimental and theoretical investigation to tightly constrain higher-order dynamic corrections to the blackbody Stark shift, and the design and characterization of a highly-emissive radiative enclosure surrounding the lattice-trapped ultracold atoms. This work culminated in the first characterization of all blackbody Stark effects at the 1×10^{-18} clock uncertainty level at room temperatures.

4. We carried out a detailed study of lattice Stark effects in an ytterbium optical lattice clock. Next to the blackbody radiation shift, this is easily the most significant systematic effect impacting optical lattice clock uncertainty when targeting state-of-the-art performance. This study included characterization of high-order Stark effects, such as hyperpolarizability and magnetic dipole and electric quadrupole polarizabilities. This was the first study in any optical lattice clock system to consider in detail finite temperature effects on the lattice Stark shift, which can have significant implications for 10-18 uncertainty.

5. We carried out studies of a range other systematic effects impacting the total uncertainty of the ytterbium optical lattice clock. This included several novel studies, such as experimental measure of background gas collisions and residual Doppler effects, as well as more traditional effects such as Zeeman shifts and static Stark shifts. The total uncertainty of the ytterbium lattice clock has now been characterized in the low 10-18 range.

6. Using the state-of-the-art cavity-stabilized lasers developed for the ytterbium lattice clock, ultra-low-noise optical signals were divided down with an optical frequency comb to generate new performance levels in ultra-low-noise microwave signals, useful in a variety of applications such as phase noise metrology and radar.

Ritsch:

Our work theoretically studied the modified decay behavior introduced by dipole-dipole interaction in extended arrays of two-level emitters with a particular focus on improving atomic clock accuracy. This phenomenon comes to life due to the inherent interaction amongst atomic transition dipoles that is mediated by vacuum

fluctuations in the electromagnetic field. Our

work has intensely investigated collective decay by means of analytical and numerical methods, both in small-scale toy systems (OpEx2012) as well as in realistically large systems relying on numerical approximation and simulation techniques (EPL2016). Our main results are the fact that sub-radiant states can be used effectively in order to increase measurement time in Ramsey spectroscopy, thus improving sensitivity (PRL2013, PRA2014) and that square and hexagonal lattice geometries in ultra-cold optical lattice atomic clocks are more favorable with respect to suppressing collective decay than others (EPL2016). In related studies we envisioned a scheme to prepare sub-radiant states directly (ScRep2015) and extended our analysis to a thematically related system, the super-radiant laser (OpEx2014). In a very recent

work, we found that decay in multi-level systems can be inhibited by virtue of preparing particular highly entangled states, that themselves are a useful resource in quantum information (PRL2017).

Murray Holland:

We developed a theory of motion-dependent nonlinear dispersion with narrow linewidth atoms in an optical cavity. This project was performed in collaboration with Jan Thomsen's experimental group at the University of Copenhagen in Denmark. During the period of this award we published both an experimental and a theoretical Physical Review A article, and a collaborative experiment/theory Physical Review Letters article. We were able to develop a detailed understanding of the importance of Doppleron resonances in the saturation spectroscopy physics associated with nonlinear absorption using alkaline Earth atoms that contain narrow intercombination-line transitions.

In a separate project, we have developed a theoretical framework and understanding of conditional Ramsey spectroscopy in an ensemble of two-level atoms in a cavity, with the atoms actively pumped. The principal idea here was that in conventional Ramsey spectroscopy, dephasing processes remove atoms from the coherent ensemble leading to a loss of visibility in the Ramsey fringe contrast. However, we showed that the active pumping leads to quantum synchronization of the dipoles, so that the effect of dephasing is greatly reduced and the fringe visibility persists for much longer times. This work was published in Physical Review Letters.

We have also continued to explore all aspects of the theory of the crossover from the standard quantum theory of the laser in the good cavity regime, to the regime of steady-state superradiance. This work has been performed using a variety of theoretical approaches, including exact SU(4) methods, quantum Langevin equations, and various factorization methods. A long article is being prepared for submission in 2016 on this topic.

Recently we showed a large viscosity appears in cavity QED systems with ultranarrow linewidth atoms that can move along the cavity axis in the regime of steady-state superradiance, and showed that this has potential for extremely efficient laser cooling in a collective regime. This work was published in Physical Review Letters.

Finally, in collaboration with John Bollinger at NIST, we have developed a theory of ion-trap superradiance in analogy with cavity-QED systems. This work was published in Physical Review A.

Kippenberg: see attachment

Vuletic:

We have built an optical-transition atomic clock inside an optical resonator for clock performance below the standard quantum limit. The ytterbium atoms are cooled in a magneto-optical trap and then transferred to a magical-wavelength trap inside an optical resonator. The peak single-atom cooperativity of the resonator is 30, the maximum collective cooperativity observed is several thousand.

We have invented a scheme for spin squeezing on the atomic clock transition for ^{171}Yb . The spin squeezing is accomplished between the nuclear magnetic sublevels in the atomic ground state via interaction with light coupling to the $3P_1$ state, and then transferred onto the optical-clock transition with a π pulse by the clock laser. We have partly implemented this scheme and already observed spin moderate spin squeezing between the nuclear ground states. The squeezing is accomplished in two different ways: i) by direct collective measurement of the spin state populations via the cavity and ii) by cavity feedback squeezing where laser light inside the resonator interacting with the atoms induces an effective coupling between the components of the atomic collective spin, resulting in entanglement and spin squeezing.

Thompson

There were numerous scientific advances and accomplishments, however, the two most significant scientific advances were (1) the direct observation of extremely large levels of entanglement (18 dB relative to the standard quantum limit) and (2) the first observation of superradiant laser pulses on a mHz linewidth optical clock transition.

Spin squeezed states are entangled states in which the atoms conspire with one another to be quieter than they can be on their own. We have learned to create and directly observe as much as 18 dB of squeezing below the Standard Quantum Limit (i.e. quieter in noise variance by a factor of 60) on a microwave transition in Rb. This means that the same precision can be achieved using 60 times fewer atoms (good for reducing technical requirements and for reducing atom number dependent systematic errors) or 60 times less sensing time (good for enhanced measurement bandwidth of time varying signals and for reducing system size requirements in atom interferometers.) We have demonstrated the application of real time feedback to steer the atomic system toward user targeted squeezed states. We have developed a technique to overcome the detrimental effects of the standing wave probe for future atom interferometers, and techniques for reducing rotation-associated added noise. We have also performed proof-of-principle collective measurements in Sr that show the feasibility of using a spin-forbidden optical transition to create squeezed states on a mHz linewidth optical clock transition for future enhancements in optical lattice clocks.

We built from scratch a Sr cavity-QED system in which we essentially turned an optical lattice clock into a laser gain

medium with the goal of making a narrow linewidth laser that would be 100,000 times less sensitive to the technical and fundamental thermal vibrations of optical reference cavities that limit the performance of the best lasers to date. We succeeded in observing pulsed superradiance on the mHz linewidth transition and began a promising frequency comparison campaign between the pulsed light source and Jun Ye's cavity-stabilized lasers. We also demonstrated lasing crossing over from the bad to good cavity limit using the 7.5 kHz transition, and showed that the system could be optically repumped to obtain more than one photon per atom. We observed a collective vacuum Rabi splitting on the 7.5 kHz transition, and also developed a new spectroscopy technique for creating narrow spectroscopic features called magnetically induced transparency. We discovered and began to understand a new laser-cooling mechanism based on sweeping the cooling lasers across atomic resonance. This technique became a workhorse for loading atoms on a daily basis, also appears to work to form robust magneto optical traps, and may be applicable to cooling molecules in the future.

Technology Transfer

Ludlow:

1. Starting in 2016, we began a collaborative effort with Draper Laboratories and Stable Laser Systems to develop calcium Ramsey-Borde optical clocks for time and navigation DoD applications. This effort is a technology transfer of the calcium Ramsey-Borde clock research we carried out as part of the QuASAR program. The collaboration with Draper Laboratories and Stable Laser Systems was funded in the context of the DARPA STOIC program.

2. We had various discussions with multiple DoD scientists interested in transferring optical lattice clocks and technology to potential DoD projects and applications. These discussions focused on optical lattice clock performance, reliability, and designs for portability.

Kippenberg:

There has been an incorporated startup company based in part on QuASAR research

o LiGen Tec SA. - www.ligentec.com

Ligentec is an expert in offering photonic chips with silicon nitride thickness above 600nm maintaining very low propagation loss. Our thick nitride is transparent from the visible to mid-IR and does not suffer from two photon absorption. Due to its good confinement thick nitride waveguides and resonators have low bending losses and excel in high power applications even in the mid-IR.

The main application areas using thick silicon nitride integrated photonics include coherent telecommunication, filters, supercontinuum generation, pulse generation, spectroscopy, sensing and microwave photonics.

With its silicon nitride chips Ligentec enables products based on integrated photonics for fabless companies and research institutions to be able to work with silicon nitride.

Scientific progress and accomplishments.

Major accomplishments in the QuASAR program during the reporting period.

Discover of Temporal Solitons in Microresonators

“Temporal solitons in optical microresonators”, T. Herr, et al., **NATURE PHOTONICS**, Vol: 8 Issue: 2, 145 (2014).

Temporal dissipative solitons in a continuous-wave laser-driven nonlinear optical microresonator were observed. The solitons were generated spontaneously when the laser frequency was tuned through the effective zero detuning point of a high-Q resonance, which led to an effective red-detuned pumping. Transition to soliton states were characterized by discontinuous steps in the resonator transmission. The solitons were stable in the long term and their number could be controlled via pump-laser detuning. These observations are in agreement with numerical simulations and soliton theory. Operating in the single-soliton regime allows the continuous output coupling of a femtosecond pulse train directly from the microresonator. This approach enables ultrashort pulse syntheses in spectral regimes in which broadband laser-gain media and saturable absorbers are not available. In the frequency domain the single-soliton states correspond to low-noise optical frequency combs with smooth spectral envelopes, critical to applications in broadband spectroscopy, telecommunications, astronomy and low noise microwave generation.

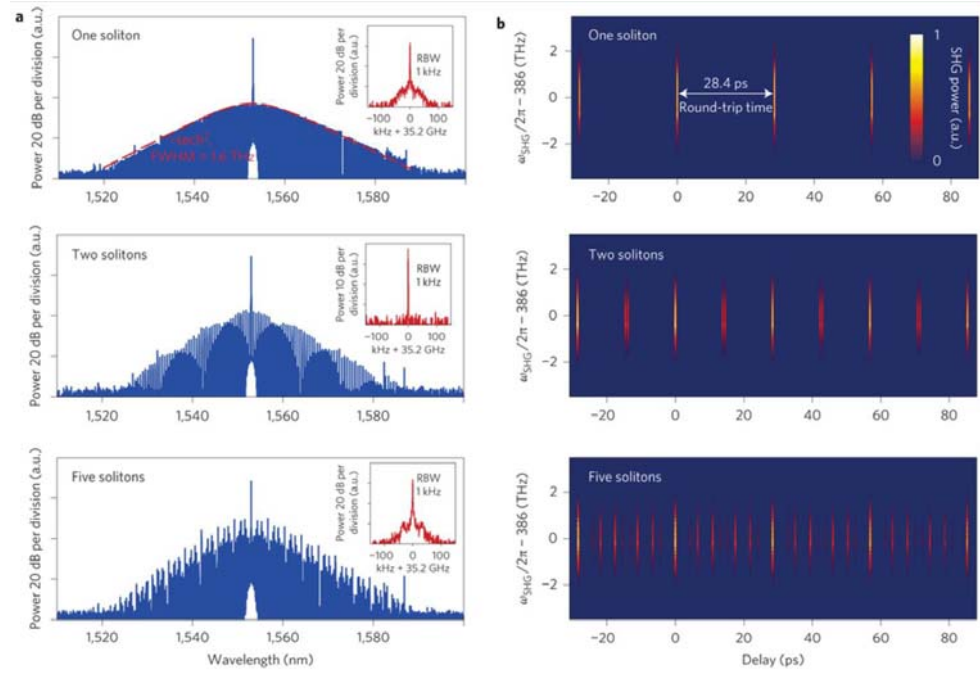


Figure 1: a, Optical spectra of three selected states with one, two and five solitons, respectively. The insets show the RF beatnote, which is resolution-bandwidth limited to a 1 kHz width in all cases. The dashed red line in the optical spectrum of the one-pulse state shows the spectral sech2 envelope expected for solitons with a 3 dB bandwidth of 1.6 THz. b, FROG traces of the states in a that display the signal of the single and multiple pulses.

Coherent Chip-Based Optical Frequency Using Cherenkov Radiation

“Photonic chip-based optical frequency comb using soliton Cherenkov radiation”, V. Brasch, et al., *SCIENCE*, Volume: 351 Issue: 6271 Pages: 357-360 (2015)

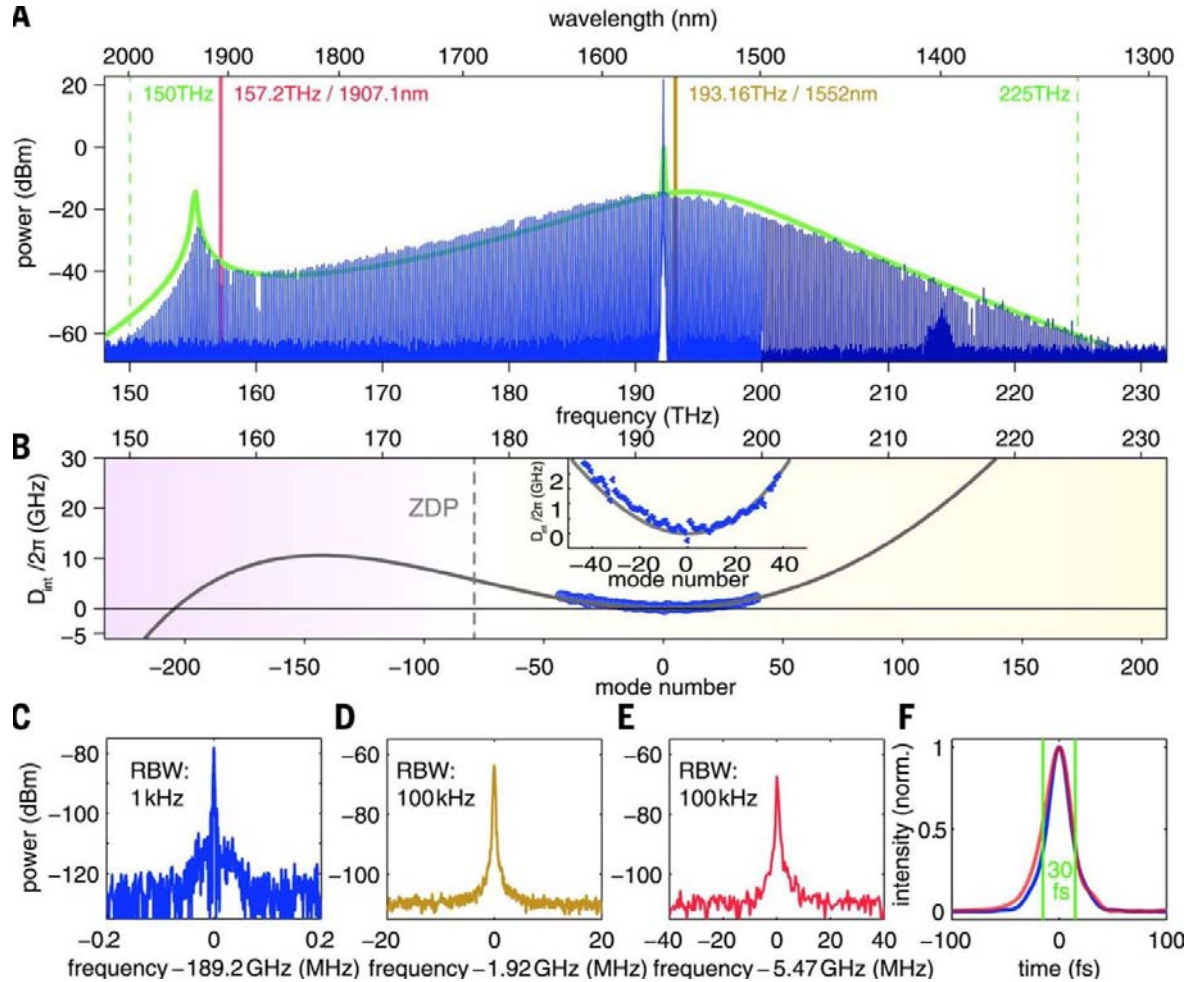


Figure 2: (A) The optical spectrum shows the sech2 shape of a single soliton (with a 3-dB width of 10.8 THz) and the soliton Cherenkov radiation at 155 THz. The green dashed lines mark a span of two-thirds of an octave. The green solid line denotes the simulated spectral envelope. The different blue colors indicate measurements done with two different optical spectrum analyzers. (B) The integrated dispersion D_{int} from finite element simulations for the measured resonator geometry (gray solid line). The gray dashed line indicates the zero dispersion point. The blue dots around 0 (inset shows a zoom-in) are measured positions of around 80 resonances which show good agreement with the simulated dispersion. (C) The repetition rate beat note of the frequency comb at the line spacing of 189.22 GHz shows a narrow linewidth of ~1 kHz. (D and E) The measured beat note of the generated frequency comb with a narrow linewidth reference laser positioned at 1552.0 nm [(D), orange line in (A)] and at 1907.1 nm [(E), red line in (A)]. (F) The intensity profile of the soliton pulse inside the resonator estimated from the measured spectrum (blue) and taken directly from the numerical simulation, with full width at half maximum (FWHM) below 30 fs. The red profile shows a small asymmetry due to the effect of the Cherenkov radiation.

Optical solitons are propagating pulses of light that retain their shape because nonlinearity and dispersion balance each other. In the presence of higher-order dispersion, optical solitons can emit dispersive waves via the process of soliton Cherenkov radiation. This process underlies supercontinuum generation and is of critical importance in frequency metrology. Using a continuous wave-pumped, dispersion-engineered, integrated silicon nitride microresonator, we generated continuously circulating temporal dissipative Kerr solitons. The presence of higher-order dispersion led to the emission of red-shifted soliton Cherenkov radiation. The output

corresponds to a fully coherent optical frequency comb that spans two-thirds of an octave and whose phase we were able to stabilize to the sub-Hertz level. By preserving coherence over a broad spectral bandwidth, our device offers the opportunity to develop compact on-chip frequency combs for frequency metrology or spectroscopy.

First Self-Referenced Chip Based Optical Frequency Comb Without External Broadening

“Self-referenced photonic chip soliton Kerr frequency comb”, V. Brasch, et al., *LIGHT-SCIENCE & APPLICATIONS*, Volume: 6, Article Number: e16202 (2017)

Self-referencing turns pulsed laser systems into self-referenced frequency combs. Such frequency combs allow counting of optical frequencies and have a wide range of applications. The required optical bandwidth to implement self-referencing is typically obtained via nonlinear broadening in optical fibers. Recent advances in the field of Kerr frequency combs have provided a path toward the development of compact frequency comb sources that provide broadband frequency combs, exhibit microwave repetition rates and are compatible with

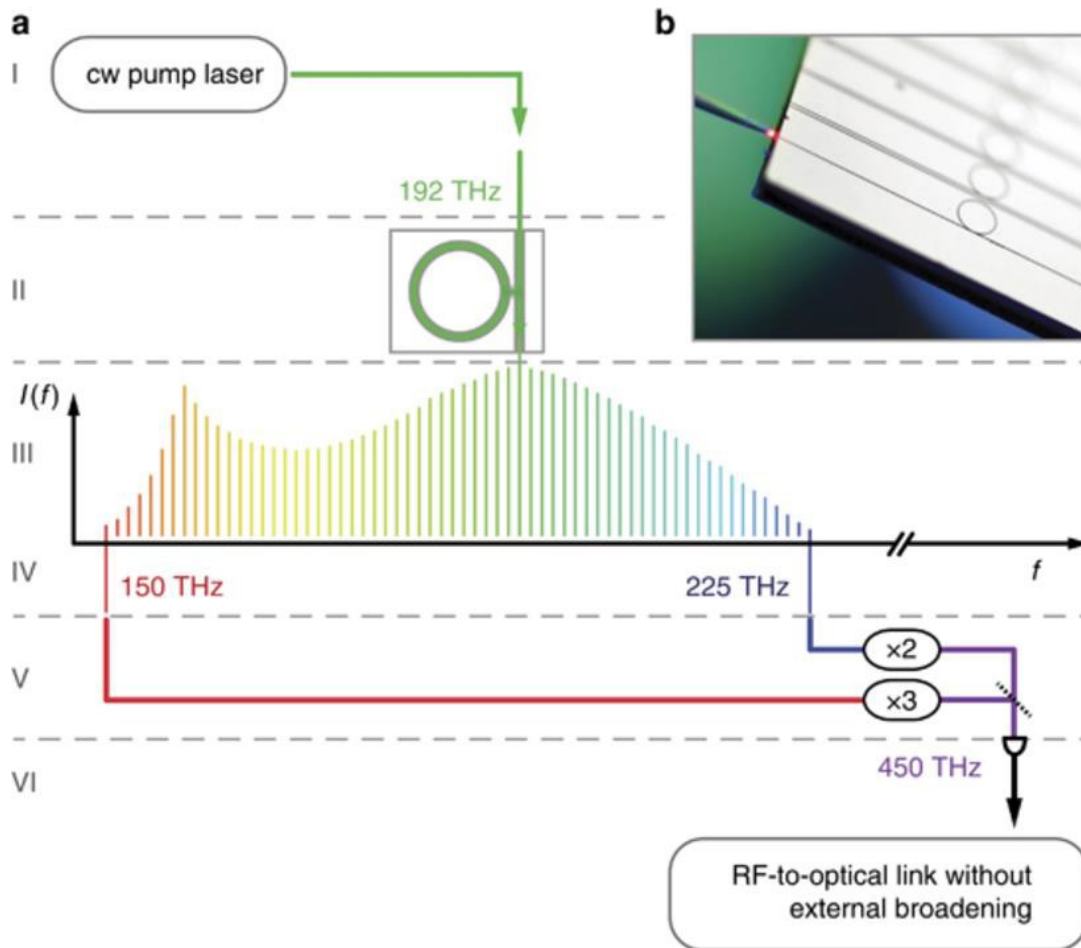


Figure 3: Schematic illustration of a self-referenced Kerr frequency comb. (a) The soliton Kerr frequency comb is generated from a continuous wave laser (I) coupled to a silicon nitride microresonator (II). With a spectral width of two-thirds of an octave, the resulting Kerr frequency comb (III) is sufficiently broad to allow for the measurement of its offset frequency (that is, the carrier envelope offset frequency). To do so, two transfer lasers (IV) are phase-locked to the frequency comb and doubled and tripled in frequency via nonlinear crystals (V). The heterodyne beat note of the two lasers allows the measurement of the offset frequency (f_{CEO}) of the Kerr frequency comb (VI). (b) A photograph of a chip with integrated silicon nitride microresonators (240 μm diameter) and bus waveguides. Also shown is a lensed fiber used to couple light (in this photograph a red laser) into the waveguides on the chip.

on-chip photonic integration. These devices have the potential to significantly expand the use of frequency combs. Yet to date, self-referencing of such Kerr frequency combs has only been attained by applying conventional, fiber-based broadening techniques. We demonstrated external broadening-free self-referencing of a Kerr frequency comb. An optical spectrum spanning two-thirds of an octave is directly synthesized from a continuous wave laser-driven silicon nitride microresonator using temporal dissipative Kerr soliton formation and soliton Cherenkov radiation. Using this coherent bandwidth and two continuous wave transfer lasers in a $2f$ – $3f$ self-referencing scheme, we are able to detect the offset frequency of the soliton Kerr frequency comb. By stabilizing the repetition rate to a radio frequency reference, the self-referenced frequency comb is used to count and track the continuous wave pump laser's frequency. This work demonstrates the principal ability of soliton Kerr frequency combs to provide microwave-to-optical clockworks on a chip.