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14. ABSTRACT
Collaborative work that was carried out by the research groups of Dr. Weimin Zhou at the US Army Research Laboratory (ARL) and by the University of Maryland Baltimore County (UMBC) is described. This work focused on the generation and transfer of low-noise radio frequencies using photonics. In its earliest stage, this work focused on optoelectronic oscillators. Later, the focus was on using frequency combs for free-space transfer. We have also carried out work on microresonator combs and the ARL group anticipates doing experiments on these combs with theoretical support from UMBC.

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FINAL REPORT

Cooperative Research Agreement: W911NF-13-2-0010

University of Maryland Baltimore County, Baltimore, MD
and
US Army Research Laboratory, Adelphi, MD

Research on RF Photonics Devices

Curtis R. Menyuk
Recipient Program Manager, UMBC

Weimin Zhou
Cooperative Agreement Manager, ARL

Technical Discussion

The work during this contract period was marked by a close technical cooperation between the research group of Dr. Curtis Menyuk (RPM) at UMBC and the research group of Dr. Weimin Zhou (CAM) at ARL. In particular, Dr. Menyuk and members of his group interacted closely with Dr. James Cahill. This technical cooperation led to numerous joint publications that are detailed in the publication section of this report and included 1–2 presentations in the IEEE-sponsored International Frequency Control Symposium every year.

At the start of contract period, the focus of the work was understanding the Rayleigh scattering process that limited the attainable length and hence the close-in phase noise that can be obtained using an optoelectronic oscillator. This work was successfully completed, and we found successful strategies for overcoming this limit. However, we also concluded that this technology is not competitive with frequency comb technology, and the focus of our work shifted as a consequence.

Within the first year of this contract and up to the present time, the focus of our work was on using frequency combs to transfer frequencies. Our original focus was on optical fibers. However, we always had in mind that the ultimate application would be to free-space transfer, in order to support soldiers operating in the field. The ultimate goal is to obtain compact, fieldable frequency sources with low phase noise. Within the past two years, much of the work at ARL has focused on a building a free-space demonstration testbed, and during the past year the UMBC work transitioned in part to the development of FPGA controllers for the free-space demonstration. This effort—funded by a different cooperative agreement—is being led by Dr. Tinoosh Mohsenin.

Until two years ago, the work at ARL was supported in part by a Coalition Warfare Program (CWP) that included the participation of Dr. Moshe Horowitz at the Technion as part of the agreement between ARL and the Israeli Ministry of Defense (IMOD). There was a significant overlap between the goals of the CWP and the goals of the cooperative agreement with UMBC, which was focused on the transfer of low-noise radio frequency (RF) data. As a consequence, Dr. Menyuk participated in this joint work.

During almost the entire contract period, Dr. Menyuk participated in the DARPA PULSE program as a performer with the group led by Dr. Nathan Newbury at NIST, while Drs. Zhou and Cahill participated as government monitors. The focus of Dr. Menyuk's participation was to develop models of the fiber lasers that Dr. Newbury's group was developing. That work is not directly relevant to this cooperative agreement; however, it led to work on microresonators that is directly relevant. Dr. Prem Kumar, the DARPA program manager asked Dr. Menyuk to investigate the physical processes that lead to frequency combs in microresonators. While this work was mostly supported by DARPA, work in Dr. Menyuk's group by a research professor, Dr. Giuseppe D'Aguanno, was supported in part by this cooperative agreement. This work led to a series of high-impact publications, culminating recently in a paper that was published in *Optica*. These papers are included in the publication section of this report. Given the promise of microresonators as a compact source of frequency combs, Drs. Cahill and Zhou recently began a program to investigate

their use experimentally with theoretical support from Dr. Menyuk's group.

During this contract period, there have been significant personnel changes. At its start, Dr. Cahill was a SMART student, working under the direct supervision of Dr. Olukayode Okusaga. In 2015, Dr. Okusaga left ARL, and Dr. Cahill graduated. At that time, Dr. D'Aguanno began working in Dr. Menyuk's group at UMBC. He was forced to leave Dr. Menyuk's group in 2017 due to a lack of sufficient research funds to support him. He is currently working at the Johns Hopkins Applied Physics Laboratory and collaborating with Dr. Menyuk's group as a visiting professor on a voluntary basis. At about the same time, Mr. Patrick Sykes began working with Dr. Menyuk's group on a project supported by Raytheon to investigate the limits that optical fiber processes impose on time transfer through optical fibers and compare them to environmental effects. Mr. Sykes graduated with an M.S. in 2017. At the end of his M.S. thesis work, he was supported in part by this cooperative agreement. He recently won a SMART student fellowship and is working on free-space optical frequency transfer under the mentorship of Dr. Cahill.

A new cooperative agreement between Dr. Zhou's group at ARL and Dr. Menyuk's group at UMBC is in already in place, and we anticipate that the close cooperation and technical successes that were achieved during the previous cooperative agreement will continue into the future.

Publications

A. Journal Articles

1. O. Okusaga, J. P. Cahill, A. Docherty, C. R. Menyuk, and W. Zhou, "Spontaneous Inelastic Rayleigh Scattering in Optical Fibers," Opt. Lett. **38**, 549–551 (2013). [doi:10.1364/OL.38.000549]
2. A. Docherty, C. R. Menyuk, J. P. Cahill, O. Okusaga, and W. Zhou, "Rayleigh-Scattering-Induced RIN and Amplitude-to-Phase Conversion as a Source of Length-Dependent Phase Noise in OEOs," IEEE Phot. J. **5**, 5500514 (2013). [doi:10.1109/JPHOT.2013.2250940]
3. Y. K. Chembo and C. R. Menyuk, "Spatiotemporal Lugiato-Lefever Formalism for Kerr-Comb Generation in Whispering-Gallery-Mode Resonators," Phys. Rev. A **87**, 053852 (2013). [doi:10.1103/PhysRevA.87.053852]
4. A. Coillet, I. Balakireva, R. Henriet, K. Saleh, L. Larger, J. M. Dudley, C. R. Menyuk, and Y. K. Chembo, "Azimuthal Turing Patterns, Bright and Dark Cavity Solitons in Kerr Combs Generated With Whispering-Gallery-Mode Resonators," IEEE Phot. J. **5**, 6100409 (2013). [doi:10.1109/JPHOT.2013.2277882]
5. O. Okusaga, J. P. Cahill, A. Docherty, C. R. Menyuk, W. Zhou, and G. M. Carter, "Suppression of Rayleigh-Scattering-Induced Noise in OEOs," Opt. Express **21**, 22255–22262 (2013). [doi:10.1364/OE.21.022255]
6. J. P. Cahill, O. Okusaga, W. Zhou, C. R. Menyuk, and G. M. Carter, "Superlinear Growth of Rayleigh Scattering-Induced Noise in Single-Mode Fibers," Opt. Express **23**, 6400–6407 (2015). [doi:10.1364/OE.23.006400]
7. M. Fleyer, J. P. Cahill, M. Horowitz, C. R. Menyuk, and O. Okusaga, "Comprehensive Model for Studying Noise Induced by Self-Homodyne Detection of Backward Rayleigh Scattering in Optical Fibers," Opt. Express **23**, 25635–25652 (2015). [doi:10.1364/OE.23.025635]
8. G. D'Aguanno and C. R. Menyuk, "Nonlinear Mode Coupling in Whispering-Gallery-Mode Resonators," Phys. Rev. A **93**, 043820 (2016). [doi:10.1103/PhysRevA.93.043820]
9. J. P. Cahill, W. Zhou, and C. R. Menyuk, "Additive Phase Noise of Fiber-Optic Links Used in Photonic Microwave-Generation Systems," Appl. Opt. **56**, B18–B25 (2017). [doi:10.1364/AO.56.000B18]
10. Z. Qi, G. D'Aguanno, and C. R. Menyuk, "Nonlinear Frequency Combs Generated by Cnoidal Waves in Microring Resonators," J. Opt. Soc. Am. B **34**, 785–794 (2017). [doi:10.1364/JOSAB.34.000785]

11. G. D'Aguanno and C. R. Menyuk, "Coupled Lugiato-Lefever Equation for Nonlinear Frequency Comb Generation at an Avoided Crossing of a Microresonator," Eur. Phys. J. D **71:74**, 70705 (2017).
[doi:10.1140/epjd/e2017-70705-x]

12. J. P. Cahill, W. Zhou, and C. R. Menyuk, "Self-Stabilization of an Optical Frequency Comb Using a Short-Path-Length Interferometer," Opt. Lett. **42**, 1680–1683 (2017).
[doi:10.1364/OL.42.001680]

13. A. Coillet, Z. Qi, I. V. Balakireva, G. Lin, C. R. Menyuk, and Y. K. Chembo, "On the Transition to Secondary Kerr Combs in Whispering-Gallery Mode Resonators," Opt. Lett. **44**, 3078–3081 (2019).
[doi.org/10.1364/OL.44.003078]

14. Z. Qi, S. Wang, J. Jaramillo-Villegas, M. Qi, A. M. Weiner, G. D'Aguanno, T. F. Carruthers, and C. R. Menyuk, "Dissipative Cnoidal Waves (Turing Rolls) and the Soliton Limit in Microring Resonators," Optica **6**, 1220–1232 (2019).
[doi.org/10.1364/OPTICA6.001220]

B. Proceedings Articles

1. J. P. Cahill, G. M. Carter, C. R. Menyuk, J. Pritchett, R. Sorenson, M. Berman, O. Okusaga, and W. Zhou, "Inverse Relationship Between the OEO Q-Factor and Vibration Sensitivity," *Proceedings of the 2013 Joint European Frequency and Time Forum and the IEEE International Frequency Control Symposium* (IEEE, Piscataway, NJ, 2013).
[doi:10.1109/EFTF-IFC.2013.6702215].

2. O. Okusaga, J. Pritchett, R. Sorenson, W. Zhou, M. Berman, J. P. Cahill, G. M. Carter, and C. R. Menyuk, "The OEO as an Acoustic Sensor," *Proceedings of the 2013 Joint European Frequency and Time Forum and the IEEE International Frequency Control Symposium* (IEEE, Piscataway, NJ, 2013).
[doi:10.1109/EFTF-IFC.2013.6702238].

3. J. P. Cahill, O. Okusaga, W. Zhou, C. R. Menyuk, and G. M. Carter, "Optimization of Modulation Techniques for Suppression of GEMRS in Frequency Transfer Systems," *Proceedings of the IEEE Frequency Control Symposium* (IEEE, Piscataway, NJ, 2014).
[doi:10.1109/FCS.2014.6859985].

4. C. R. Menyuk and OPN Editors, "Frequency Combs: Optimization for Precision Metrology," Interview in Opt. Photon. News, April 2015, pp. 20–21.

5. C. R. Menyuk, "Transmission of a Frequency Channel Through a Long-Haul Optical Fiber Communications Link," Proc. 2015 Joint Conf. IEEE Frequency Control Symposium and European Time and Frequency Forum (IEEE, Piscataway, NJ, 2015), pp. 736–741.
[doi:10.1109/FCS.2015.7138946].

6. J. P. Cahill, O. Okusaga, W. Zhou, C. R. Menyuk, and G. M. Carter, "Comparison of Forward- and Backward-Propagation Optical-Fiber-Induced Noise for Application to

Optical Fiber Frequency Transfer," Proc. 2015 Joint Conf. IEEE Frequency Control Symposium and European Time and Frequency Forum (IEEE, Piscataway, NJ, 2015), pp. 765–768.
[doi:10.1109/FCS.2015.7138954]

7. J. P. Cahill, W. Zhou, and C. R. Menyuk, "Self-Delay-Line-Referenced Optical Frequency Comb for Low-Phase-Noise Microwave Generation," Proc. 2016 IEEE International Frequency Control Symposium (IEEE, Piscataway, NJ, 2016).
[doi:10.1109/FCS.2016.7563537]
8. A. Coillet, N. Yu, C. R. Menyuk, and Y. K. Chembo, "Dynamical Regimes in Kerr Optical Frequency Combs: Theory and Experiments," in *Nonlinear Cavity Dyamics*, edited by P. Grelu (Wiley, 2016), Chap. 7, pp. 163–188.
9. J. P. Cahill, W. Zhou, and C. R. Menyuk, "Short-Length Homodyne Interferometer for Self-Stabilization of an Optical Frequency Comb," Proc. 2017 Joint Conf. European Frequency and Time Forum and IEEE Frequency Control Symposium (IEEE, Piscataway, NJ, 2017), pp. 425–426.
[doi:10.1109/FCS.2017.8088912]
10. P. G. Sykes, C. Tu, and C. R. Menyuk, "Nonlinear Interaction Between Neighboring Data Channels and a Frequency Signal in a Commercial Optical Fiber Communication System," Proc. 2018 IEEE Frequency Control Symposium (IEEE, Piscataway, NJ, 2018).
[doi:10.1109/FCS.2018.8597498]
11. J. P. Cahill, W. Zhou, and C. R. Menyuk, "Microwave Frequency Generation Using a Non-Octave-Spanning Optical Frequency Comb," Proc. 2018 IEEE Frequency Control Symposium (IEEE, Piscataway, NJ, 2018).
[doi:10.1109/FCS.2018.8597465]
12. J. P. Cahill, W. Zhou, and C. R. Menyuk, "Shot Noise in Self-Stabilized Optical Frequency Combs," Proc. 2019 Joint Conference of the European Frequency and Time Forum and the IEEE Frequency Control Symposium (IEEE, Piscataway, NJ, 2019).
[doi:10.1109/FCS.2019.8856077]

C. Conference Presentations

1. J. P. Cahill, J. Pritchett, R. Sorenson, M. Berman, O. Okusaga, W. Zhou, G. M. Carter, and C. R. Menyuk, "Inverse Relationship Between OEO Q-Factor and g-Sensitivity," Joint European Forum on Frequency and Time Transfer and IEEE Frequency Control Symposium, Prague, Czech Republic (July 21–25, 2013), paper IFCS-EFTF2-A2-6.
2. O. Okusaga, J. P. Cahill, J. Pritchett, R. Sorenson, W. Zhou, M. Berman, G. M. Carter, and C. R. Menyuk, "The Optoelectronic Oscillator as an Acoustic Sensor," Joint European Forum on Frequency and Time Transfer and IEEE Frequency Control Symposium, Prague, Czech Republic (July 21–25, 2013), paper IFCS-EFTF4-C2-2.
3. J. P. Cahill, O. Okusaga, W. Zhou, C. R. Menyuk, and G. M. Carter, "Effect of Optical Scattering on One-Way RF and Microwave Frequency Transfer Over Optical

Fibers," Precise Time and Time Interval Systems and Applications Meeting, Bellevue, WA (Dec. 2–5, 2013).

4. J. P. Cahill, O. Okusaga, W. Zhou, C. R. Menyuk, and G. M. Carter, "Optimization of Modulation Techniques for Suppression of GEMRS in Frequency Transfer Systems," IEEE Frequency Control Symposium, Taipei, Taiwan (May 19–22, 2014), session C2L-A.
5. C. R. Menyuk, "Transmission of a Frequency Channel Through a Long-Haul Optical Fiber Communication Link," Joint Conference of the IEEE International Frequency Control Symposium and the European Time and Frequency Forum, Denver, CO (Apr. 12–16, 2015), session C4L-C.
6. J. P. Cahill, O. Okusaga, W. Zhou, C. R. Menyuk, and G. M. Carter, "Comparison of Forward- and Backward-Propagating Optical-Fiber-Induced Noise for Application to Optical Fiber Frequency Transfer," Joint Conference of the IEEE International Frequency Control Symposium and the European Time and Frequency Forum, Denver, CO (Apr. 12–16, 2015), session D1L-C.
7. J. P. Cahill, W. Zhou, and C. R. Menyuk, "Correlation of Double Rayleigh Scattering in Single-Mode Fibers," IEEE Photonics Conference, Reston, VA (Oct. 4–8, 2015), paper WC3.1.
8. J. P. Cahill, W. Zhou, and C. R. Menyuk, "Self-Delay-Line- Referenced Optical Frequency Comb for Low-Phase-Nose Microwave Generation," IEEE International Frequency Control Symposium, New Orleans, LA (May 9–12, 2016), session B3P-K(132).
9. Z. Qi, G. D'Aguanno, and C. R. Menyuk, "Cnoidal Waves in Microresonators," Conference on Lasers and Electro-Optics, San Jose, CA (June 5–10, 2016), paper FM2A.7.
10. G. D'Aguanno and C. R. Menyuk, "Coupled Bright Solitons in the Normal Dispersion Regime in Whispering-Gallery-Mode Resonators," Conference on Lasers and Electro-Optics, San Jose, CA (June 5–10, 2016), paper JW2A.48.
11. J. P. Cahill, W. Zhou, and C. R. Menyuk, "Short-Length Homodyne Interferometry for Self-Stabilization of an Optical Frequency Comb," Joint Conference of the European Frequency and Time Forum and IEEE Frequency Control Symposium, Besançon, France (July 9–13, 2017), session B3P-L.
12. Z. Qi, G. D'Aguanno, and C. R. Menyuk, "Dark Solitons and Cnoidal Waves in Microresonators with Normal Dispersion," OSA Frontiers in Optics, Washington, DC (Sept. 17–20, 2017), paper JTu3A.14.
13. C. R. Menyuk, S. Wang, and T. F. Carruthers, "A Dynamical Perspective on Noise in Passively Modelocked Lasers," OSA Frontiers in Optics, Washington, DC (Sept. 17–20, 2017), paper JTu3A.57.
14. Z. Qi, S. Wang, J. Jaramillo-Villega, M. Qi, A. M. Weiner, G. D'Aguanno, and C. R. Menyuk, "Stability of cnoidal wave frequency combs in microresonators," Conference on Lasers and Electro-Optics, San Jose, CA (May 13–18, 2018), paper SF2A.6.
15. P. G. Sykes, C. Tu, and C. R. Menyuk, "Nonlinear Interaction between Neighboring

Data Channels and a Frequency Signal in a Commercial Optical Fiber Communication System," IEEE International Frequency Control Symposium, Lake Tahoe, CA (May 21–24, 2018).

16. J. P. Cahill, W. Zhou, and C. R. Menyuk, "Microwave Frequency Generation Using a Non-Octave-Spanning Optical Frequency Comb," IEEE International Frequency Control Symposium, Lake Tahoe, CA (May 21–24, 2018).
17. J. P. Cahill, W. Zhou, and C. R. Menyuk, "Shot Noise in Self-Stabilized Optical Frequency Combs," Joint Conference of the European Frequency and Time Forum and IEEE Frequency Control Symposium, Orlando, FL (April 14–18, 2019).
18. Z. Qi and C. R. Menyuk, "Soliton Frequency Combs in Dual Microresonators," Frontiers in Optics/Laser Science Conference, Washington, DC (Sept. 16–19, 2019), paper JTu4A.118.

D. Theses and Dissertations

1. J. P. Cahill, *Rayleigh-Scattering-Induced Noise in Analog RF-Photonic Links* (Ph.D. Dissertation, March 2015).
2. P. G. Sykes, *Nonlinear Interaction Between a Frequency Signal and Neighboring Data Channels in a Commercial Optical Fiber Communication System* (M.S. Thesis, November 2018).