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Dear Sirs/Madams:

You will find enclosed the final technical report for grant no. N00173-15-1-G905, "Modeling of Low-Noise IR Transmitting Fibers, Sources, and Detectors."

Sincerely,

Curtis R. Menyuk

REPORT DOCUMENTATION PAGE

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FINAL REPORT: N00173-15-1-G905

Modeling of Low-Loss IR Transmitting Fibers, Sources, and Detectors

Curtis R. Menyuk

In this report, I will be summarizing the activities that we carried out on grant N00173-15-1-G905, Modeling of Low-Loss IR Transmitting Fibers, Sources, and Detectors, which covered the period from 06/12/2015 – 06/11/2021. This grant involved a close working relationship with the Naval Research Laboratory that led to many joint publications, including archival journal publications, as well as invited and peer-reviewed conference presentations. We communicated on at least a monthly basis with scientists at the Naval Research Laboratory and often more frequently to review progress.

Our activities focused on three general activities. The first was the study of propagation in optical fibers, with a strong focus on negative curvature fibers and supercontinuum generation. The second was a study of propagation into and out of motheye structures that are super-imposed on glass surfaces. These two activities included a collaboration with Prof. Jonathan Hu of Baylor University. The third activity examined nonlinearity in photodetectors with a strong focus on frequency combs and included a collaboration with Dr. Franklyn Quinlan

This work also led to two PhD dissertations. One of the awardees is currently employed at SubCom, while the other is a post-doctoral research associate at the University of Central Florida. Both are now US permanent residents.

The list of publications and presentations follows:

Archival journal publications

1. Y. Hu, C. R. Menyuk, M. N. Hutchinson, V. J. Urick, and K. J. Williams, "Impact of the Coulomb Interaction on the Franz-Keldysh Effect in High-Current Photodetectors," *Opt. Lett.* **41**, 456–459 (2016).
[doi:10.1364/OL.41.000456]
2. R. J. Weiblen, C. R. Menyuk, L. E. Busse, L. B. Shaw, J. S. Sanghera, and I. D. Aggarwal, "Optimized Moth-Eye Anti-Reflective Structures for As₂S₃ Chalcogenide Optical Fibers," *Opt. Express* **24**, 10172–10187 (2016).
[doi:10.1364/OE.24.010172]
3. R. J. Weiblen, C. R. Menyuk, R. R. Gattass, L. B. Shaw, and J. S. Sanghera, "Fabrication Tolerances for As₂S₃ Negative-Curvature Antiresonant Fibers," *Opt. Lett.* **41**, 2624–2627 (2016).
[doi:10.1364/OL.41.002624]
4. C. Wei, C. R. Menyuk, and J. Hu, "Bending-Induced Mode Non-Degeneracy and Coupling in Chalcogenide Negative Curvature Fibers," *Opt. Express* **24**, 12228–12239 (2016).
[doi:10.1364/OE.24.012228]

5. C. Wei, C. R. Menyuk, and J. Hu, "Impact of Cladding Tubes in Chalcogenide Negative Curvature Fibers," *IEEE Phot. J.* **8**, 2200509 (2016).
[doi:10.1109/JPHOT.2016.2577711]
6. C. Wei, J. Hu, and C. R. Menyuk, "Comparison of Loss in Silica and Chalcogenide Negative Curvature Fibers as the Wavelength Varies," *Frontiers Phys.* **4**, 30 (22 July 2016). [Invited paper]
[doi:10.3389/fphy.2016.00030]
7. S. E. Jamali Mahabadi, Y. Hu, M. A. Talukder, T. F. Carruthers, and C. R. Menyuk, "A Comprehensive Model of Gain Recovery Due to Unipolar Electron Transport After a Short Optical Pulse in Quantum Cascade Lasers," *J. Appl. Phys.* **120**, 154502 (2016).
[doi:10.1063/1.4964939]
8. R. R. Gattass, D. Rhonehouse, D. Gibson, C. C. McClain, R. Thapa, V. Q. Nguyen, S. S. Bayya, R. J. Weiblen, C. R. Menyuk, L. B. Shaw, and J. S. Sanghera, "Infrared Glass-Based Negative-Curvature Anti-Resonant Fibers Fabricated Through Extrusion," *Opt. Express* **24**, 25697–25703 (2016).
[doi:10.1364/OE.24.025697]
9. Y. Hu, C. R. Menyuk, M. N. Hutchinson, V. J. Urick, and K. J. Williams, "Frequency Dependent Harmonic Powers in a Modified Uni-Traveling Carrier Photodetector," *Opt. Lett.* **42**, 919–922 (2017).
[doi:10.1364/OL.42.000919]
10. Y. Hu, C. R. Menyuk, X. Xie, M. N. Hutchinson, V. J. Urick, J. C. Campbell, and K. J. Williams, "Computational Study of Amplitude-to-Phase Conversion in a Modified Unitraveling Carrier Photodetector," *IEEE Phot. J.* **9**, 5501111 (2017).
[doi:10.1109/JPHOT.2017.2682251]
11. C. Wei, R. J. Weiblen, C. R. Menyuk, and J. Hu, "Negative Curvature Fibers," *Adv. Opt. Phot.* **9**, 504–561 (2017). [Review paper]
[doi:10.1364/AOP.9.000504]
12. C. Wei, C. R. Menyuk, and J. Hu, "Polarization-Filtering and Polarization-Maintaining Low-Loss Negative Curvature Fibers," *Opt. Express* **26**, 9528–9540 (2018).
[doi.org/10.1364/OE.26.009528]
13. C. Wei, C. R. Menyuk, and J. Hu, "Geometry of Chalcogenide Negative Curvature Fibers for CO₂ Laser Transmission," *Fibers* **6**, 74 (2018).
[doi.org/10.3390/fib6040074]
14. S. E. Jamali Mahabadi, S. Wang, T. F. Carruthers, C. R. Menyuk, F. J. Quinlan, M. N. Hutchinson, J. D. McKinney, and K. J. Williams, "Calculation of the Impulse Response and Phase Noise of a High-Current Photodetector Using the Drift-Diffusion

- Equations,” *Opt. Express* **27**, 3717–3730 (2019).
[doi.org/10.1364/OE.27.003717]
15. C. Wei, J. T. Young, C. R. Menyuk, and J. Hu, “Temperature Sensor Based on Liquid-Filled Negative Curvature Fibers,” *OSA Continuum* **2**, 2123–2130 (2019).
[doi.org/10.1364/OSAC.2.002123]
 16. S. E. Jamali Mahabadi, T. F. Carruthers, C. R. Menyuk, J. D. McKinney, and K. J. Williams, “Comparison of the Impact of Nonlinearity in a *p-i-n* and an MUTC Photodetector on Electro-Optic Frequency Combs,” *Opt. Lett.* **46**, 813–816 (2021).
[doi.org/10.1364/OL.414026]
 17. S. E. Jamali Mahabadi, T. F. Carruthers, C. R. Menyuk, J. D. McKinney, and K. J. Williams, “Impact of Nonlinearity Including Bleaching in MUTC Photodetectors on RF-Modulated Electro-Optic Frequency Combs,” *Opt. Express* **29**, 11520–11532 (2021).
[doi.org/10.1364/OE.420096]
 18. S. E. Jamali Mahabadi, T. F. Carruthers, C. R. Menyuk, J. D. McKinney, and K. J. Williams, “Impact of Nonlinearity Including Bleaching in *p-i-n* photodetectors on RF-Modulated Electro-Optic Frequency Combs,” *IEEE Phot.* **13**, 6800107 (2021).
[doi.org/10.1109/JPHOT.2021.3091039]
 19. C. Tu, J. Hu, C. R. Menyuk, T. F. Carruthers, L. B. Shaw, L. E. Busse, and J. S. Sanghera, “Optimized Two-Layer Motheye Structures for MgAl₂O₄ Spinel Ceramic Windows,” *Continuum* **4**, 2143–2153 (2021) [Editor’s Pick].
[doi.org/10.1364/OSAC.428319]

Invited conference presentation

1. C. R. Menyuk, C. Wei, R. J. Weiblen, J. Hu, R. R. Gattass, L. Brandon Shaw, and J. S. Sanghera, “Chalcogenide Negative Curvature Fibers,” SPIE European Security and Defense Meeting, Warsaw, Poland (Sept. 11-14, 2017), paper 10435-18.

Reviewed conference presentations

1. Y. Hu, T. F. Carruthers, and C. R. Menyuk, “Modeling Nonlinearity in a Modified Uni-Traveling-Carrier (MUTC) Photodetector,” IEEE Photonics Conference, Reston, VA (Oct. 4–8, 2015), paper TuC2.4.
2. R. J. Weiblen, C. Florea, C. R. Menyuk, I. D. Aggarwal, L. E. Busse, L. B. Shaw, and J. S. Sanghera, “Ideal Cusp-Like Motheye Antireflective Structures for Chalcogenide Optical Fibers,” IEEE Photonics Conference, Reston, VA (Oct. 4–8, 2015), paper W11.4.

3. C. Wei, R. A. Kuis, F. Chenard, C. R. Menyuk, and J. Hu, "Mode Coupling in Chalcogenide Negative Curvature Fibers," Conference on Lasers and Electro-Optics, San Jose, CA (June 5–10, 2016), paper JTu5A.93.
4. Y. Hu, C. R. Menyuk, X. Xie, M. Hutchinson, V. Urick, J. Campbell, and K. Williams, "Numerical Modeling of Amplitude-to-Phase Conversion in Uni-Traveling Carrier (MUTC) Photodetector," Conference on Lasers and Electro-Optics, San Jose, CA (June 5–10, 2016), paper JW2A.117.
5. J. Hu, C. R. Menyuk, C. Wei, L. B. Shaw, J. S. Sanghera, and I. D. Aggarwal, "Pr³⁺-doped Mid-Infrared Chalcogenide Fiber Amplifiers Using Cascaded Amplification," Conference on Lasers and Electro-Optics, San Jose, CA (June 5–10, 2016), paper STh1O.7.
6. R. J. Weiblen, C. R. Menyuk, R. R. Gatass, L. B. Shaw, and J. S. Sanghera, "Multiple Nested Elements in As₂S₃ Anti-Resonant Negative-Curvature Tube-Lattice Fibers," OSA Advanced Photonics Congress, Vancouver, BC, Canada (July 18–20), paper SoM3F.7.
7. C. Wei, C. R. Menyuk, and J. Hu, "Higher-Order Mode Suppression in Chalcogenide Negative Curvature Fibers with Gaps Between Cladding Tubes," OSA Advanced Photonics Congress, Vancouver, BC, Canada (July 18–20), paper JTu4A.32.
8. S. E. Jamali Mahabadi and C. R. Menyuk, "Calculation of the response of PIN and MUTC photodetectors using the drift-diffusion equations," OSA Frontiers in Optics, Washington, DC (Sept. 17–20, 2017), paper JTu2A.53.
9. C. Wei, C. R. Menyuk, and J. Hu, "Bent Negative Curvature Fibers Using Circular or Elliptical Cladding Tubes," OSA Frontiers in Optics, Washington, DC (Sept. 17–20, 2017), paper JW4A.9.
10. C. Wei, J. Young, C. R. Menyuk, and J. Hu, "Temperature Sensor Using Fluid-Filled Negative Curvature Fibers," Conference on Lasers and Electro-Optics, San Jose, CA (May 13–18, 2018), paper JW2A.179.
11. C. Wei, C. R. Menyuk, and J. Hu, "Polarization-Filtering Negative Curvature Fibers," Frontiers in Optics/Laser Science Conference, Washington, DC Sept. 16–20, 2018), paper JTu3A.1.
12. C. Tu and C. R. Menyuk, "Anti-Reflecting Surfaces Using Two-Layer Motheye Structures for Spinel Ceramic Windows," Frontiers in Optics/Laser Science Conference, Washington, DC Sept. 16–20, 2018), paper JW4A.18.
13. C. Wei, C. R. Menyuk, and J. Hu, "Optimization of Chalcogenide Negative Curvature Fibers for CO₂ Laser Transmission," Conference on Lasers and Electro-Optics, San Jose, CA (May 7–9, 2019), paper JW2A.122.

14. S. E. Jamali-Mahabadi, T. F. Carruthers, and C. R. Menyuk, "Modeling Phase Noise in High-Power Photodetectors," Nineteenth International NUSOD Conference, Ottawa, Canada (July 8–12, 2019), paper TuB2.
15. C. Wei, J. Young, C. R. Menyuk, J. Hu, "Impact of the Glass Thickness in Fluid-Filled Negative Curvature Fibers for Temperature Sensing," Frontiers in Optics/Laser Science Conference, Washington, DC (Sept. 16–19, 2019), paper JW4A.5.
16. S. E. Jamali-Mahabadi, T. F. Carruthers, C. R. Menyuk, M. N. Hutchinson, J. D. McKinney, and K. J. Williams, "Impact of Nonlinearity in an MUTC Photodetector on an RF-Modulated Frequency Comb," IEEE Photonics Conference, San Antonio, TX (Sept. 29–Oct. 3, 2019), paper MC4.6.
17. S. E. Jamali-Mahabadi, T. F. Carruthers, C. R. Menyuk, M. N. Hutchinson, J. D. McKinney, and K. J. Williams, "Impact of Nonlinearity on RF-Modulated Frequency Combs with Different Modulation Depths in an MUTC Photodetector," 2019 International Topical Meeting on Microwave Photonics, Ottawa, Canada (Oct. 7–10, 2019), paper Tu1.4.
18. C. Wei, F. Chenard, C. R. Menyuk, and J. Hu, "Negative Curvature Fibers for Gas-Filled Lasers," SPIE Workshop on Specialty Optical Fibers and Their Applications, Charleston, SC (Nov. 6–8, 2019).
19. C. Tu, R. M. Sood, D. Bamford, D. Woolf, J. Hensley, T. F. Carruthers, C. R. Menyuk, and F.-S. Choa, "Motheye Structures Antireflective Coatings for Enhancing GaAs Transmission Performance at Mid-Infrared Wavelengths," Conference on Lasers and Electro-Optics, Washington, DC (Virtual) (May 10–15, 2019), paper JTu2B.16.
20. R. M. Sood, C. Tu, D. Bamford, J. Hensley, D. Woolf, and C. R. Menyuk, "Reproducible Array Image Translation and Recreation in Nano Photolithography," SPIE Photonics West OPTO Meeting, San Francisco, CA (Feb. 1–6, 2020), paper 11288-26.
21. C. Wei, C. R. Menyuk, and J. Hu, "Bend Loss in Negative Curvature Fibers with Truncated Cladding Tubes," OSA Novel Optical Materials and Applications Conference in Advanced Photonics Congress, Washington, DC (Virtual) (July 13–16, 2020), paper NoM4G.7.
22. S. E. Jamali Mahabadi, T. F. Carruthers, C. R. Menyuk, J. D. McKinney, and K. J. Williams, "Impact on Frequency Combs of Nonlinearity Including Bleaching in *p-i-n* Photodetectors," IEEE Photonics Summer Topicals Meeting (Signal Reconstruction Using Photonics), Cabo San Lucas, Mexico (Virtual) (July 13–15, 2020).
23. C. Tu, C. R. Menyuk, L. B. Shaw, J. S. Sanghera, and L. E. Busse, "Optimized Cone-Shape Motheye Structures for Fused Silica Glass Windows," Frontiers in Optics/Laser Science Conference, Washington, DC (Virtual) (Sept. 14–17, 2020), paper JM6B.31.

Ph.D. dissertations

1. Y. Hu, *Modeling Nonlinearity and Noise in High-Current Photodetectors* (Ph.D. Dissertation, April 2017).
2. S. E. Jainali Mahabadi, *Modeling Phase Noise and Nonlinearity in Photodetectors* (Ph.D. Dissertation, November 2020).