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Modeling and Design of IR Laser Sources, Nonlinear Sources, and Devices

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Curtis R. Menyuk

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14. ABSTRACT

We summarize activities that we carried out during the grant period in collaboration with scientists at the Naval Research Laboratory. Our joint research focused on two activities. The first was the study of propagation in chalcogenide fibers and materials and focused on supercontinuum generation, negative curvature fibers, and motheye structures. We found ways to achieve a broad bandwidth in chalcogenide fibers and to maximize the transmission into and out of these fibers. The second was the study of high-current photodetectors and focused on determining the sources of nonlinearity and methods to mitigate them.

15. SUBJECT TERMS

Optical fibers, chalcogenides, infrared devices, photodetectors

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FINAL REPORT: N00173-09-2-C016

Modeling and Design of IR Laser Sources, Nonlinear Sources, and Devices

Curtis R. Menyuk

In this report, I will be summarizing the activities that we carried out on grant N00173-09-2-C016, Modeling and Design of IR Laser Sources, Nonlinear Sources, and Deviceswhich covered the period from 09/28/2009 – 03/31/2015. 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 two general activities. The first was the study of propagation in chalcogenide optical fibers and materials. This work included studies of supercontinuum generation, studies of negative curvature fibers, and studies of propagation into and out of chalcogenide fibers that have motheye structure super-imposed on the surface. The second activity examined nonlinearity in photodetectors and examined ways to compensate for the nonlinearity. We had not found good approaches for mitigating nonlinearity at the point that this grant ended, but we continued to look for mitigation techniques in the current grant and have been successful.

This work also led to two PhD dissertations, one of which is within this contract period and is listed here. The other PhD degree was awarded in 2016. The student who received the PhD degree in 2015 is now working at the Naval Research Laboratory.

The list of publications and presentations follows:

Archival journal publications

1. J. Hu, C. R. Menyuk, L. B. Shaw, J. S. Sanghera, and I. D. Aggarwal, "Maximizing the Bandwidth of Supercontinuum Generation in As_2Se_3 Chalcogenide Fibers," Opt. Express **18**, 6722–6739 (2010).
[doi:10.1364/OE.18.006722]

2. J. Hu, C. R. Menyuk, L. B. Shaw, J. S. Sanghera, and I. D. Aggarwal, "Computational Study of a 3–5 μm Source Created By Using Supercontinuum Generation in As_2Se_3 Chalcogenide Fibers With a Pump at 2 μm," Opt. Lett. **35**, 2907–2909 (2010).
[doi:10.1364/OL.35.002907]

3. R. J. Weiblen, A. Docherty, J. Hu, and C. R. Menyuk, "Calculation of the Expected Bandwidth for a Mid-Infrared Supercontinuum Source Based on As_2Se_3 Chalcogenide Photonic Crystal Fibers," Opt. Express **18**, 26666–26674 (2010). [Invited paper]
[doi:10.1364/OE.18.026666]

4. J. Hu, C. R. Menyuk, L. B. Shaw, J. S. Sanghera, and I. D. Aggarwal, "A Mid-IR Source With Increased Bandwidth Using Tapered As_2S_3 Chalcogenide Photonic

Crystal Fibers," Opt. Comm. **293**, 116–118 (2013).
[doi:10.1016/j.optcom.2012.11.021]

5. J. J. Butler, A. S. Bowcock, S. R. Sueoka, S. R. Montgomery, S. R. Flom, E. J. Friebele, B. M. Wright, J. R. Peele, R. G. S. Pong, J. S. Shirk, J. Hu, C. R. Menyuk, and T.F. Taunay, "Optical Properties of Solid-Core Photonic Crystal Fibers Filled With Nonlinear Absorbers," Opt. Express **21**, 20707–20712 (2013).
[doi:10.1364/OE.21.020707]

6. R. J. Weiblen, A. Docherty, C. R. Menyuk, L. B. Shaw, J. S. Sanghera, and I. D. Aggarwal, "Calculation of the Expected Output for a Mid-Infrared Supercontinuum Source Based on As_2S_3 Chalcogenide Photonic Crystal Fibers," Opt. Express **22**, 22220–22231 (2014).
[doi:10.1364/OE.22.022220]

7. Y. Hu, B. S. Marks, C. R. Menyuk, V. J. Urick, and K. J. Williams, "Modeling Sources of Nonlinearity in a Simple p-i-n Photodetector," J. Lightwave Technol. **32**, 3710–3720 (2014).
[doi:10.1109/JLT.2014.2315740]

8. C. Wei, R. A. Kuis, F. Chenard, C. R. Menyuk, and J. Hu, "Higher-Order Mode Suppression in Chalcogenide Negative Curvature Fibers," Opt. Express **23**, 15825–15832 (2015).
[doi:10.1364.OE.23.015825]

9. Y. Hu, T. F. Carruthers, C. R. Menyuk, M. N. Hutchinson, V. J. Urick, and K. J. Williams, "Simulation of a Partially Depleted Absorber (PDA) Photodetector," Opt. Express **23**, 20402–20417 (2015).
[doi:10.1364/OE.23.020402]

10. J. Hu, C. R. Menyuk, C. Wei, L. B. Shaw, J. S. Sanghera, and I. D. Aggarwal, "Highly Efficient Cascaded Amplification Using Pr^{3+}-Doped Mid-Infrared Chalcogenide Fiber Amplifiers," Opt. Lett. **40**, 3687–3690 (2015).
[doi:10.1364/OL.40.003687]

11. R. J. Weiblen, C. M. Florea, L. E. Busse, L. B. Shaw, C. R. Menyuk, I. D. Aggarwal, and J. S. Sanghera, "Irradiance Enhancement and Increased Laser Damage Threshold in As_2S_3 Moth-Eye Antireflective Structures," Opt. Lett. **40**, 4799–4802 (2015).
[doi:10.1364/OL.40.004799]

Invited conference presentation

1. C. R. Menyuk, R. J. Weiblen, J. Hu, I. D. Aggarwal, L. B. Shaw, and J. S. Sanghera, "Maximizing the Bandwidth While Minimizing the Spectral Fluctuations Using Supercontinuum Generation in Photonic Crystal Chalcogenide Fibers," IEEE Summer Topical Meetings, Nassau, Bahamas (July 13–15, 2015), paper ME3.2.

Reviewed conference presentations

1. Y. Hu, C. R. Menyuk, M. Hutchinson, V. J. Urick, and K. J. Williams, "Impact of the Coulomb Interaction on the Franz-Keldysh Effect in a High-Current Photodetector," Conference on Lasers and Electro-Optics, San Jose, CA (May 10–15, 2015), paper STh3F.6.

2. C. Wei, J. Hu, and C. R. Menyuk, "Bending-Induced Mode Coupling in Chalcogenide Negative Curvature Fibers," OSA Advanced Photonics Meeting, Boston, MA (June 27–July 1, 2015), paper NT2C.5.

3. C. Wei, F. Chenard, C. R. Menyuk, and J. Hu, "Design of Chalcogenide Negative Curvature Fibers," IEEE Summer Topicals Meeting, Nassau, Bahamas (July 13–15, 2015), paper MP7.

4. C. Wei, O. Alvarez, F. Chenard, C. Menyuk, and J. Hu, IEEE Summer Topicals Meeting, "Empirical Glass Thickness for Chalcogenide Negative Curvature Fibers," IEEE Summer Topicals Meeting, Nassau, Bahamas (July 13–15, 2015), paper TuE3.3.

5. 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.

6. 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 WI1.4.

Ph.D. dissertation

1. R. J. Weiblen, *Light Propagation Into, Out of, and Through Mid-Infrared Optical Fibers* (Ph.D. Dissertation, November 2015).