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AFRL-SR-AR-TR-09-0235

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1. REPORT DATE (DD-MM-YYYY) 01-04-2009			2. REPORT TYPE Final Performance Report		3. DATES COVERED (From - To) 01-08-2006 - 30-11-2008	
4. TITLE AND SUBTITLE Quantum Key Distribution Using Polarized Single Photons				5a. CONTRACT NUMBER FA9550-06-1-0348		
				5b. GRANT NUMBER		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Sobolewski, Roman				5d. PROJECT NUMBER		
				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Rochester Department of Electrical and Computer Engineering Rochester, NY 14627-0231				8. PERFORMING ORGANIZATION REPORT NUMBER n.a.		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Office of Scientific Research AFOSR/NE 875 N. Randolph St., Suite 325, Room 3112 Arlington, VA 22203-1768				10. SPONSOR/MONITOR'S ACRONYM(S) AFOSR		
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified Unlimited						
13. SUPPLEMENTARY NOTES none						
14. ABSTRACT Exhaustive research, development, and testing studies were performed on novel superconducting single-photon detectors (SSPDs), based on NbN, meander-type, nano-stripe structures. The fiber-coupled SSPD receivers, designed for quantum key distribution telecommunication networks, were successfully operated without interruption for over a 2-month period inside a liquid-helium Dewar. The developed SSPD receivers possessed both the photon-energy and photon-number resolving capabilities. The phenomenon of dark/unwanted counts in our SSPDs was extensively studied and it was demonstrated that the transient resistive state was due to depairing of vortex-antivortex pairs. An efficient source for generation of entangled-photon pairs for ultrafast quantum cryptography, using a spontaneous down conversion effect and femtosecond optical pulses was designed and experimentally tested. A significant research progress was achieved in the area of novel photon-detector concepts based on MgB2 and Hg-Ba-Ca-Cu-O high-temperature superconducting materials, and ferromagnet/superconductor nano-bilayer structures.						
15. SUBJECT TERMS Quantum communications, quantum cryptography, quantum key distribution, optical single-photon detection, superconducting single-photon detectors, NbN and high-temperature superconductors, entangled photon pairs, femtosecond lasers.						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 7	19a. NAME OF RESPONSIBLE PERSON Sobolewski, Roman	
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (Include area code) 585 275 1551	

20090724231

FA9550-FINAL PERFORMANCE REPORT

To: technicalreports@afosr.af.mil
Subject: Final Performance Report to Dr. Harold Weinstock

Contract/Grant Title: Quantum Key Distribution Using Polarized Single Photons
Contract/Grant #: FA9550-06-1-0348
Reporting Period: 1 August 2006 to 30 November 2008

Program achievements: (200 words max):

Exhaustive research, development, and testing studies were performed on novel superconducting single-photon detectors (SSPDs), based on NbN, meander-type, nano-stripe structures. The fiber-coupled SSPD receivers, designed for quantum key distribution networks for 1550-nm-wavelength, telecommunication systems, were successfully kept and operated without interruption for over a two-month period inside a standard, liquid-helium transport Dewar and, from an operator's point-of-view, could be regarded as room-temperature-like devices. The developed SSPD receivers possessed both the photon-energy and photon-number resolving capabilities. The phenomenon of dark (unwanted) counts in our SSPDs and nano-bridges was extensively studied and it was demonstrated that the transient resistive state, causing the dark-count pulses, was due to depairing of vortex-antivortex pairs induced by the applied bias current. A new, efficient source for generation of entangled-photon pairs for ultrafast quantum cryptography, using a spontaneous down-conversion effect and femtosecond optical pulses was designed and experimentally tested. A significant research progress was achieved in the area of novel photon-detector and device concepts based on high-temperature superconducting materials and ferromagnet/superconductor NiCu/Nb nano-bilayer structures. Time-resolved photoresponse and photoimpedance studies showed the ultrafast performance of detectors based on MgB_2 and Hg-Ba-Ca-Cu-O superconductors, and confirmed attractiveness of these materials for the next-generation photon counters.

Main accomplishments:

1. Fiber-coupled SSPD receivers

We have developed and exhaustively tested a novel, two-channel, single-photon receiver based on two fiber-coupled SSPDs consisting of nanostructured NbN superconducting meanders and designed for quantum key distribution networks for 1550-nm-wavelength, telecommunication systems. Coupling between the NbN detector and optical fiber was achieved using a micromechanical photoresist ring placed directly over the SSPD, holding the fiber in place. With this arrangement, we obtained coupling efficiencies up to ~30%. Our experimental results showed that the best receiver had a near-infrared system quantum efficiency of 0.33% at 4.2 K. The quantum efficiency increased exponentially with the photon energy increase, reaching a few percent level for visible-light photons. The photoresponse pulses of our devices were limited by the meander high kinetic

inductance and had the rise and fall times of approximately 250 ps and 5 ns, respectively. The receiver's timing jitter was in the 37- to 58-ps range, approximately 2 to 3 times larger than in our older free-space-coupled SSPDs. We stipulate that this timing jitter was in part due to optical fiber properties. The two-detector was also implemented in quantum correlation experiments.

2. Dark-count and photon-energy resolving capabilities of SSPD receivers

Dark counts in SSPDs manifest themselves as spontaneous, transient voltage pulses, typically indistinguishable from photon counts. We designed and engineered a new readout technique based on integrating in liquid helium the SSPD with a low-noise, cryogenic high-electron-mobility transistor (HEMT) with high-input impedance. This arrangement allowed us to achieve amplitude resolution of the recorded output transients. In two-dimensional superconducting nano-strips, the physics of photon counting is based on the hotspot formation mechanism, while the dark counts correspond to voltage transients triggered by the vortex-antivortex motion and/or phase-slip centers. Thus, their respective transients can be distinguished by comparing the output pulse amplitude distributions. Our scheme also allowed us to perform photon-energy-resolution studies by comparing the SSPD output pulse amplitude distributions (the mean pulse amplitude and the distribution width) collected for incident single photons with different energies. The HEMT integrated read-out should be also useful for the photon-number-resolving SSPD experiments.

3. Source of entangled photons for quantum cryptography applications

We built an experimental setup for generation of entangled-photon-pairs via spontaneous parametric down conversion, based on the femtosecond pulsed laser. Our entangled-photon source utilizes a 76-MHz repetition rate, 100-fs pulse width, mode-locked ultrafast femtosecond laser, which can produce, on average, more photon pairs than a cw laser of an equal pump power. The output infrared pump photons ($\lambda = 810$ nm) are first up-converted to blue light ($\lambda = 405$ nm), and subsequently, down-converted in a 1.5-mm-thick type-II BBO crystal, via spontaneous down conversion. The resulting entangled pairs can be efficiently counted by a pair of high quantum efficiency, single-photon detectors. The total down conversion efficiency of our system, corresponding criterion of the pump power for real entangled coincident events, has been calculated to be 0.86×10^{-6} .⁹ Our apparatus can be used as an efficient source/receiver system for the quantum communications and quantum key distribution applications.

4. Hg-based high-temperature superconductors as optical photodetectors

We performed the time-resolved, femtosecond optical photoresponse and photoimpedance, as well as ultrafast THz-pulse time-domain spectroscopy studies of Hg-Ba-Ca-Cu-O (HBCCO) high-temperature, superconducting thin films. Our 500-nm-thick films were prepared by rf-magnetron sputtering of Re-Ba-Ca-Cu-O precursor films, followed by an *ex-situ*, high-temperature mercuration process. The resulting films were *c*-axis oriented with a predominant Hg-1212 (plus some Hg-1223) phase. Their transition

temperature T_c had an onset at 122 K and zero resistance at 110 K. The THz TDS measurements demonstrated a sharp drop in the transmitted THz signal when the sample temperature was decreased below T_c , which we directly related to a change in the imaginary component of the film complex conductivity. Simultaneously, the peak of the temperature-dependent real part of the conductivity was shifted toward lower frequencies at lower temperatures. The time-resolved THz spectroscopy experiments showed that the quasiparticle relaxation process exhibited an intrinsic single-picosecond dynamics with no phonon bottleneck, which is a unique feature among superconductors and makes the HBCCO material promising for ultrafast radiation detector applications.

5. Transient photoimpedance studies of MgB_2 microbridges

We performed time- and temperature-dependent experimental studies of transient photoimpedance signals, generated in current-biased superconducting MgB_2 microbridge structures. We have found that despite the intrinsic two-gap nature of this material, a conventional description of nonequilibrium superconductivity, based either on the Rothwarf and Taylor equations or a two-temperature model, is valid. We demonstrated that the superconducting recovery dynamics in MgB_2 was governed by a phonon-bottleneck mechanism, which time evolution was limited by both the anharmonic decay of phonons and their escape to the substrate. Observation of 50-ps-wide transient photoimpedance signals at temperatures well above those for conventional metallic superconductors (e.g., 20 K) showed that MgB_2 nanostructures a promising system for ultrafast radiation detectors and photon counters operating at the liquid-hydrogen temperature range.

6. Ultrafast photoresponse of superconductor/ferromagnet nanostructures

Heterogeneous nanostructures, such as proximized superconductor/normal metal and superconductor/ferromagnet (S/F) bilayers, are very promising, since they exhibit the ultrafast Cooper-pair and quasiparticle dynamics. We have characterized Nb/NiCu, NbN/NiCu, YBaCuO/Au/NiCu, and YBaCuO/LaSrMnO proximized S/F nano-bilayers, using time-resolved, all-optical, femtosecond pump-probe spectroscopy measurements down to 4 K. The weak ferromagnetic nature of an ultrathin NiCu film makes it possible to observe the dynamics of the nonequilibrium superconductivity in S/F hybrids through time-resolved measurements of a near-surface optical reflectivity change and analyze within a nonequilibrium two-temperature electron-heating model. We observed that the NiCu overlay significantly reduced the slow, bolometric contribution present in the photoresponse on a pure Nb film, resulting in a strong enhancement of the nonequilibrium, kinetic-inductive component of the transient photoimpedance, measured as a ~ 700 -ps-wide voltage waveform generated across an optically excited, current-biased NiCu/Nb bilayer microbridge. Our experiments have demonstrated that these bilayer heterostructures are suitable for novel, “engineered” ultrafast superconducting photodetectors, as well as can find applications in spintronics. Moreover, our time-resolved studies of the carrier dynamics in oxide-based S/F structures opened the way to novel basic-physics investigations of nonequilibrium effects in correlated systems.

Archival publications (published and accepted):

23. "Novel superconducting proximized heterostructures for ultrafast photodetection," (invited) G. P. Pepe, L. Parlato, N. Marrocco, V. Pagliarulo, G. Peluso, A. Barone, F. Tafuri, U. Scotti di Uccio, F. Miletto, M. Radovic, D. Pan, and R. Sobolewski, *Cryogenics*, accepted (2009).
22. "Ultrafast photoresponse of superconductor/ferromagnet hybrid nanostructures," (invited) G. P. Pepe, D. Pan, V. Pagliarulo, L. Parlato, N. Marrocco, C. De Lisio, G. Peluso, A. Barone, U. Scotti di Uccio, A. Casaburi, F. Tafuri, M. Khafizov, T. Taneda, and R. Sobolewski, *IEEE Trans. Appl. Supercon.*, accepted (2009).
21. "Pulsed-THz Characterization of Hg-Based High-Temperature Superconductors," X. L. Cross, X. Zheng, P. D. Cunningham, L. M. Hayden, Š. Chromik, M. Sojkova, V. Štrbík, P. Odier, and R. Sobolewski, *IEEE Trans. Appl. Supercon.*, accepted (2009).
20. "HEMT-based Read-Out Technique for Dark and Photon Count Studies in NbN Superconducting Single-Photon Detectors," J. Kitaygorsky, S. Dorenbos, E. Reiger, R. Schouten, V. Zwiller, and R. Sobolewski, *IEEE Trans. Appl. Supercon.*, accepted (2009).
19. "Measurements of amplitude distributions of dark counts and photon counts in NbN superconducting single-photon detectors integrated with the HEMT read-out," J. Kitaygorsky, R. Schouten, S. Dorenbos, E. Reiger, V. Zwiller, and R. Sobolewski, in: *Special Issue on Single-Photon: Sources, Detectors, Applications, and Measurement Methods, J. Mod. Opt.*, accepted (2009).
18. "Layered ferromagnet/superconductor heterostructures: time-resolved femtosecond carrier dynamics and photodetector applications," D. Pan, G. P. Pepe, V. Pagliarulo, C. De Lisio, L. Parlato, M. Khafizov, I. Komissarov, and R. Sobolewski, *Phys Rev B*, **78**, 174503 (2008).
17. "Easy Vortex Motion in an Artificial Channel of YBa₂Cu₃O₇ Superconducting Films," A. Jukna, I. Barboy, G. Jung, A. Abrutis, X. Li, D. Wang, and R. Sobolewski, *Acta Phys. Pol. A*, **113**, 959-962 (2008).
16. "Dynamics of Hotspot Formation in Nanostructured Superconducting Stripes Excited with Single Photons," A. Jukna, J. Kitaygorsky, D. Pan, A. Cross, A. Perlman, I. Komissarov, O. Okunev, K. Smirnov, A. Korneev, G. Chulkova, I. Milostnaya, B. Voronov, G.N. Gol'tsman, and R. Sobolewski, *Acta Phys. Pol. A*, **113**, 955-958 (2008).
15. "Hg-based cuprate superconducting films patterned into structures for ultrafast photodetectors," S. Chromik, M. Valerianova, V. Strbik, S. Gazi, P. Odier, X. Li, Y. Xu, R. Sobolewski, F. Hanic, G. Plesch, S. Benacka, *Appl. Surf. Sc.*, **154**, 3638-3642 (2008).
14. "Time-resolved optical characterization of proximized nano-bilayers for ultrafast photodetector applications," L. Parlato, G. P. Pepe, D. Pan, C. De Lisio, V. Pagliarulo, A. Cosentino, N. Marrocco, D. Dalena, G. Peluso, A. Barone, and R. Sobolewski, *J. Phys. Conf. Series*, **97**, 012317 (2008).
13. "Registration of infrared single photons by a two-channel receiver based on fiber-coupled superconducting single-photon detectors," O. Okunev, G. Chulkova, I. Milostnaya, A. Antipov, K. Smirnov, D. Morozov, A. Korneev, B. Voronov, G. Gol'tsman, W. Słysz, M. Węgrzecki, J. Bar, P. Grabiec, M. Górská, A.

- Pearlman, A. Cross, J. Kitaygorsky, and R. Sobolewski in Second International Conference on Advanced Optoelectronics and Lasers, ed. by I. A. Sukhoivanov, V. A. Svich, and Y. S. Shmaliy, *Proc. of SPIE*, **7009**, 70090V, (2008).
12. "Spectroscopy with Nanostructured Superconducting Single Photon Detectors," E. Reiger, S. Dorenbos, V. Zwiller, A. Korneev, G. Chulkova, I. Milostnaya, O. Minaeva, G. Gol'tsman, W. Słysz, J. Kitaygorsky, D. Pan, A. Jukna, and R. Sobolewski, *J. Sel. Topics Quan. Elec. – Special Issue on "Single Photon Counting: Detectors and Applications"*, **13**, 934 (2007).
 11. "Middle-Infrared to Visible-Light Ultrafast Superconducting Single-Photon Detectors," (invited) G. Gol'tsman, O. Minaeva, A. Korneev, M. Tarkhov, I. Rubtsova, A. Divochiy, I. Milostnaya, G. Chulkova, N. Kaurova, B. Voronov, D. Pan, J. Kitaygorsky, A. Cross, A. Pearlman, I. Komissarov, W. Słysz, M. Wegrzecki, P. Grabiec, and R. Sobolewski, *IEEE Trans. Appl. Supercon.* **17**, 246 (2007).
 10. "Dark Counts in Nanostructured NbN Superconducting Single-Photon Detectors and Bridges," J. Kitaygorsky, I. Komissarov, A. Jukna, O. Minaeva, N. Kaurova, A. Korneev, B. Voronov, I. Milostnaya, G. Gol'tsman, and R. Sobolewski, *IEEE Trans. Appl. Supercon.* **17**, 275 (2007).
 9. "Mechanism of light detection by superconducting current-biased MgB_2 microbridges," M. Khafizov, X. Li, Y. Cui X. X. Xi, and R. Sobolewski, *IEEE Trans. Appl. Supercon.* **17**, 2867 (2007).
 8. "Ultrafast Photoresponse Dynamics of Current-Biased Hg-Ba-Ca-Cu-O Superconducting Microbridges," X. Li, M. Khafizov, S. Chromik, V. Strbik, M. Valerianova, P. Odier, and R. Sobolewski, *IEEE Trans. Appl. Supercon.* **17**, 3648 (2007).
 7. "Time-Resolved Carrier Dynamics and Electron–Phonon Coupling Strength in Proximized Weak Ferromagnet/Superconductor Nanobilayers," T. Taneda, G. P. Pepe, L. Parlato, A. A. Golubov, and R. Sobolewski, *Phys. Rev. B* **75**, 174507 (2007).
 6. "Fiber-Coupled NbN Superconducting Single-Photon Detectors for Quantum Correlation Measurements," W. Słysz, M. Wegrzecki, J. Bar, P. Grabiec, M. Gorska, E. Reiger, S. Dorenbos, V. Zwiller, I. Milostnaya, O. Minaeva, A. Antipov, O. Okunev, A. Korneev, K. Smirnov, B. Voronov, N. Kaurova, G. Gol'tsman, D. Pan, J. Kitaygorsky, and R. Sobolewski, in Photon Counting Applications, Quantum Optics, and Quantum Cryptography, ed. by I. Prochazka, A. L. Migdall, A. Pauchard, M. Dusek, M. S. Hillery, and W. P. Schleich, *Proc. of SPIE*, **6583**, 65830J, (2007).
 5. "Femtosecond Laser-Pumped Source of Entangled Photons for Quantum Cryptography applications," D. Pan, W. R. Donaldson, and R. Sobolewski, in Photon Counting Applications, Quantum Optics, and Quantum Cryptography, ed. by I. Prochazka, A. L. Migdall, A. Pauchard, M. Dusek, M. S. Hillery, and W. P. Schleich, *Proc. of SPIE*, **6583**, 65830K, (2007).
 4. "Ultrafast and High Quantum Efficiency Large-Area Superconducting Single-Photon Detectors," A. Korneev, O. Minaeva, A. Divochiy, A. Antipov, N. Kaurova, V. Seleznev, B. Voronov, G. Gol'tsman, D. Pan, J. Kitaygorsky, W. Słysz, and R. Sobolewski, in Photon Counting Applications, Quantum Optics, and Quantum Cryptography, ed. by I. Prochazka, A. L. Migdall, A. Pauchard, M. Dusek, M. S. Hillery, and W. P. Schleich, *Proc. of SPIE*, **6583**, 65830I, (2007).
 3. "Fibre-Coupled Single-Photon Detector Based on NbN Superconducting

- Nanostructures for Quantum Communications," W. Słysz, M. Węgrzecki, J. Bar, P. Grabiec, M. Górski, V. Zwiller, C. Latta, P. Bohi, A. J. Pearlman, A. S. Cross, D. Pan, J. Kitaygorsky, I. Komissarov, A. Verevkin, I. Milostnaya, A. Korneev, O. Minayeva, G. Chulkova, K. Smirnov, B. Voronov, G. Gol'tsman, and R. Sobolewski, in Special Issue on Single-Photon: Sources, Detectors, Applications, and Measurement Methods, *J. Mod. Opt.* **54**, 315 (2007).
2. "Ultrafast Photoresponse of Superconductor/Ferromagnet Nb/NiCu Heterostructures," G. P. Pepe, M. Amanti, C. De Lisio, R. Latempa, N. Marrocco, L. Parlato, G. Peluso, A. Barone, T. Taneda, and R. Sobolewski, *Phys. Stat. Sol. (c)*, **3**, 2968 (2006).
 1. "Fiber-Coupled Single-Photon Detectors Based on NbN Superconducting Nanostructures for Practical Quantum Cryptography and Photon-Correlation Studies," W. Słysz, M. Węgrzecki, J. Bar, P. Grabiec, M. Gorska, V. Zwiller, C. Latta, P. Bohi, I. Milostnaya, A. Korneev, O. Minayeva, G. Chulkova, K. Smirnov, B. Voronov, G. Gol'tsman, A. Pearlman, A. Cross, I. Komissarov, A. Verevkin, and R. Sobolewski, *Appl. Phys. Lett.* **88**, 261113 (2006).

Patents:

2. "A method of coupling of single- or multi-mode fiber with an optical detector or emitter," P. Grabiec, W. Słysz, M. Węgrzecki, J. Bar, R. Sobolewski, A. Verevkin, G. Gol'tsman, and W. Milczrek, Polish Patent - PL-367391, pending.
1. "Superconducting Single Photon Detector," R. Sobolewski, G. N. Gol'tsman, A. Semenov, O. Okunev, K. Wilsher, and S. Kasapi - US Patent - 7 049 593 (2006).

Invited talks and lectures:

14. "Superconducting Single-Photon Detectors: Operation and Applications," R. Sobolewski, presented at the Quantum-Limited Imaging Detectors, IT Collaboratory 2009 Research Symposium, Rochester Institute of Technology, Rochester, NY, March 2009.
13. "Novel superconducting proximized heterostructures for ultrafast photodetection," G. P. Pepe, D. Pan, V. Pagliarulo, L. Parlato, N. Marrocco, C. De Lisio, G. Peluso, A. Barone, U. Scotti di Uccio, A. Casaburi, F. Tafuri, M. Khafizov and R. Sobolewski, presented at the International Workshop on Solid State Surfaces and Interfaces, Smolenice, Slovak Republic, November 2008.
12. "Optical response of superconductor/ferromagnet hybrid nanostructures," G. P. Pepe and R. Sobolewski, presented at the Euroflux2008 Conference, Naples, Italy, September 2008.
11. "Ultrafast photoresponse of ferromagnet/superconductor nano-layered hybrids," G. P. Pepe, D. Pan, V. Pagliarulo, L. Parlato, N. Marrocco, C. De Lisio, G. Peluso, A. Barone, U. Scotti di Uccio, A. Casaburi, F. Tafuri, M. Khafizov, T. Taneda, and R. Sobolewski, presented at the Applied Superconductivity Conference (ASC'08), Chicago, IL, August 2008.
10. "Ultrafast, time-resolved dynamics of carriers, spins, and phonons in solid-state materials studied by femtosecond optical pump-probe spectroscopy," (Plenary

- Paper), R. Sobolewski, presented at the Second International Workshop on Advanced Spectroscopy and Optical Materials (IWASOM'08), Gdańsk, Poland, July 2008.
9. Lecture Series on Single Photons: Physics and Applications: (1) Physics of Single Photons: Their Generation and Detection, (2) Operation of Semiconducting and Superconducting Single-Photon Detectors, and (3) Quantum Cryptography Based on Single-Photon Communications, R. Sobolewski, presented at Università di Napoli Federico II, Napoli, Italy, June 2008.
 8. "Novel superconducting proximized heterostructures for ultrafast photodetection," G. P. Pepe, L. Parlato, N. Marrocco, A. Barone, F. Tafuri, U. Scotti di Uccio, F. Miletto, D. Pan, and R. Sobolewski, presented at the Eighth International Workshop on Low Temperature Electronics (WOLTE-8) Jena/Gabelbach, June 2008.
 7. "Quantum Key Distribution Using Single Photons," presented during the AFOSR Research Review Meeting, San Francisco, CA, March 2008.
 6. "Superconducting Single-Photon Detectors for Quantum Optics," J. Kitaygorsky, V. Zwiller, E. Reiger, R. Schouten, D. Pan, G. Gol'tsman, and R. Sobolewski, presented at the Single Photon Workshop (SPW2007), Torino, Italy, October 2007.
 5. "Quantum Key Distribution Using Single Photons," presented during the AFOSR Research Review Meeting, San Francisco, CA, August 2007.
 4. "Quantum Cryptography: Unbreakable Code under the Laws of Physics," presented at the Department of Physics REU Lunch Meeting Series, University of Rochester, Rochester, NY, June, 2007.
 3. "Superconducting single-photon detectors: the state-of-the-art and applications," R. Sobolewski, W. Slysz, V. Zwiller, and G. Gol'tsman, presented at the SPIE Europe Congress: Symposium on Photon Counting Applications, Prague, The Czech Rep., April 2007.
 2. "Nanostructured Superconducting Single-Photon Optical Detectors and Their Applications," presented at the Department of Physics Seminar Series, University of Naples "Federico II," Naples, Italy, February 2007.
 1. "Nanostructured Superconducting Single-Photon Detectors and Their Applications," presented at the Department of Physics, University of Maryland Baltimore County, Baltimore, MD, Dec. 2006.

Ph. D. theses completed:

4. Dong Pan (Ph. D. Physics; 2009) Thesis: "Ultrafast Photoresponse of Ferromagnet/Superconductor Nano-Bilayers and Nanostructures."
3. Ms. Xia Li Cross (Ph. D. Materials Science; 2009) Thesis: "Time-Resolved Optical and Terahertz Characterization of Hg-Based High-Temperature Superconductors."
2. Ms. Jennifer Kitaygorsky (Ph. D. Electrical and Computer Engineering; 2008) Thesis: "Photon and Dark Counts in NbN Superconducting Single-Photon Detectors and Nanostripes."
1. Marat Khafizov (Ph. D. Physics; 2007) Thesis: "Photoresponse Mechanism of Superconducting MgB₂."