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.
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 MgB2 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-stripes, 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 (λ = 810 nm) are first up-converted to blue light (λ = 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. 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):


3. "Fibre-Coupled Single-Photon Detector Based on NbN Superconducting


Patents:


Invited talks and lectures:


10. "Ultrafast, time-resolved dynamics of carriers, spins, and phonons in solid-state materials studied by femtosecond optical pump-probe spectroscopy," (Plenary


Ph. D. theses completed:


3. Ms. Xia Li Cross (Ph. D. Materials Science; 2009) Thesis: "Time-Resolved Optical and Terahertz Characterization of Hg-Based High-Temperature Superconductors."
