MRI: Development of Integrated Multi-Access Entangled-Photon Sources and Single-Photon Detector Array for Interdisciplinary Quantum Information Research

We propose a Track 1 development instrument that will for the first time remove the barrier to the generation and maintenance of quantum resources for a broad scientific and student audience, i.e., entangled-photon sources (EPSs) and single photon detectors (SPDs) will be assembled in an accessible platform that can communicate over a unique fiber-based network at the University of Arizona (UA), between buildings, colleges, and scientific disciplines. The development of the **IN**terdisciplinary **QU**antum **I**nformation **RE**search (INQUIRE) instrument (Figure 1) will leverage UA's highly successful photonics research and development expertise, specifically, in the NSF Engineering Research Center for Integrated Access Networks (CIAN). It will involve four major technical tasks (MTTs): 1) development of three high-brightness EPSs operating at telecommunication wavelengths; 2) deployment of fiber optic links over a significant fraction of the UA campus, linking five different buildings and disciplines; 3) integration of the EPSs, SPDs, and fiber network and installation of optical switching to route entangled photons to multiple users; and 4) development of a robust, safe, and accessible user and administrator software interface. The INQUIRE instrument will provide for a means to deliver unique light sources to multiple scientific disciplines and offers a first-of-its-kind platform for exploring the beginnings of quantum information sharing and processing. **The INQUIRE instrument will be the world's first shared major facility as a test-bed to foster interdisciplinary research and student training in quantum information science (QIS), an area identified as both a national and NSF-wide priority.**

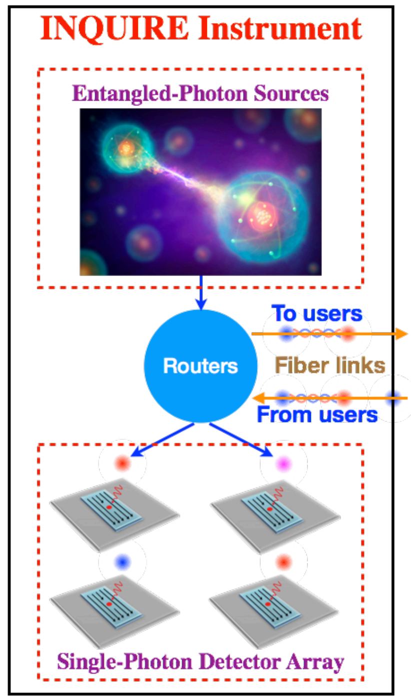

Figure 1. Architecture of the INQUIRE instrument for interdisciplinary QIS research.

The triumph of quantum mechanics in the 20th century has given birth to QIS that leverages quantum mechanical effects at a macroscopic level to greatly exceed the performance of classical approaches. QIS has heretofore required specialized, expensive expertise that are exclusive in many laboratories, which holds back a broad pursuit of QIS-enabled science and technology. The INQUIRE instrument will enable the convergence of QIS and diverse fields such as materials science, biomedical engineering, physics, computer science, optical science, and electrical engineering on the UA campus—an emerging Hispanic Serving Institution and an American Indian and Alaska Native-Serving Institution. This unique instrument will allow researchers to readily harness state-of-the-art QIS tools at the boundaries of science and technology to realize unprecedented sensing, imaging, communication, and computing capabilities.

We anticipate that at least 25 senior personnel (SP), 10 postdoctoral (PD) researchers, 20 graduate (GS) students, and 20 undergraduate (UG) students will benefit directly from research and research training with the instrument in the UA Colleges of Engineering, Optical Sciences, and Sciences, together with UA teaching laboratories and visiting researchers from Arizona State University (ASU), the University of New Mexico (UNM), and University of California, Riverside (UCR).

Planned Instrument Development. Development of the INQUIRE instrument entails four MTTs. Each MTT comprises multiple components that can be individually built. The advantage of such a multi-task, multi-component plan is threefold for: 1) managing the complexity of the entire project; 2) reducing development risk as users will start to benefit from the INQUIRE instrument once one of the EPSs for MTT-I is complete; and 3) controlling the overall project cost. Such a plan will enable the INQUIRE instrument to begin to create a major scientific impact within a short timeframe (~17 month). Briefly, the four MTTs are:

<u>MTT-I: Development of entangled-photon sources (for additional details refer to Section III.1).</u> We will build three EPSs: 1) **EPS1**, a 1550-nm polarization EPS to generate 800,000 pairs/s and >90% collection efficiency; 2) **EPS2**, a bright 1550-nm time-energy EPS to generate 7.8×10^9 broadband pairs/s; and 3) **EPS3**, a bright 1340-nm time-energy EPS to generate 1.2×10^{11} pairs/s. To measure entangled photons, we will procure and install an array of superconducting nanowire SPDs (SNSPDs) with >80% quantum efficiency and a high-temporal resolution, 8-channel, time-tagging device.

<u>MTT-II: Deployment of fiber links (Section III.2).</u> The INQUIRE instrument's central location will be at the Electrical and Computer Engineering (ECE) Building. We will deploy fiber links to the College of Optical Sciences (Meinel Building), BIO5 Institute (Keating Building), Physics-Atmospheric Sciences Building, and Department of Materials Science and Engineering (Mines Building).

<u>MTT-III: Integration of EPSs and fiber links (Section III.3).</u> We will connect the EPSs and the SNSPD array to the deployed fiber links and use optical switches to route photons to different users.

<u>MTT-IV: Development of user and administrator interface (Section III.4).</u> We will implement a software interface for users to easily configure the EPS properties and monitor the INQUIRE instrument's state. Users can also remotely connect to the SNSPD array to perform real-time measurements. Administrators control users' access to the INQUIRE instrument to enable time sharing and ensure safe operation.

I- Information about the Proposal

I.1 Instrument Location and Type

<u>Instrument Location:</u> Rm. 111, ECE Building, the University of Arizona
<u>Instrument:</u> Integrated, multi-access entangled photon sources and single-photon detector array.

I.2 Justification for Submission as a Development Proposal

How will the end result of the effort be a stable shared-use research instrument, rather than technology development, a device, a product or a technique/protocol? We will equip the central INQUIRE instrument with state-of-the-art QIS tools for easy access—via optical fibers and a friendly software interface—by multiple users with no/minimal QIS expertise. Our instrument design will ensure long-term stability. As such, the INQUIRE instrument will be the world's first shared, campus-wide major research and research training tool that converges QIS with diverse science fields.

What significant new capabilities, not available in an instrument provided by a vendor, will the new instrument provide? The INQUIRE instrument will be unique, providing three different types of efficient EPSs, an array of SNSPDs with > 80% system efficiency and < 100 Hz dark-count rate, and an easy-to-use software interface for QIS non-experts. No commercial instrument of this type exists.

Does the instrument development effort build capacity for instrument development activities within an MRI submission-eligible organization(s)? The INQUIRE instrument will strengthen the UA faculty's capabilities to build nonclassical light sources, establish low-loss quantum networks, and integrate stable hardware and software platforms to be leveraged in future instrument development activities.

In what way does the instrument development require design and development work that must be undertaken or has been undertaken in-house, rather than through readily available/published designs found in the literature? The INQUIRE instrument will optimize the use of pump lasers between three EPSs. In addition, the instrument requires an optimal optics design to maximize the flux of EPS1. A user-friendly software interface will enable seamless switching and routing of the photons from the EPSs, and allow users to remotely take measurements at the single-photon level. Such unique capabilities require new, in-house designs.

To what extent does the instrument development require/benefit from a team of scientists/engineers/technicians that bring a variety of skills to the project? Our interdisciplinary UA team comprises: 1) quantum-optics experts to design and build the EPSs; 2) optical-communication experts to establish the fiber network; 3) electrical engineers to implement the control hardware; and 4) software engineers to develop a user-friendly interface.

For what activities does the instrument development require a significant number of person-hours, more so than simple "assembly" of purchased parts? These activities include: 1) building and characterizing the pumps and the EPSs; 2) deploying fiber links and implementing the routing infrastructure; and 3) developing the software interface and control hardware.

To what extent does the instrument development require time-frames for completion that are longer than are required for plug-and-play or assembled instruments? The full integration of EPSs with fiber links requires 1 year, the software interface development requires 0.5 year, and the dry runs require 1 year. All these efforts need significant timeframes.

Does the instrument development require the use of a machine shop or a testbed to fabricate/test unique components? We will use a machine shop to fabricate a robust housing for the bulk crystal used in EPS1 along with other customized optical elements. The deployed fiber network will serve as a testbed to measure the loss incurred in entanglement distribution and enable the subsequent optimization of the operating conditions for the pump lasers and EPSs.

Does the instrument development effort involve risks in achieving the required specifications, and what is the risk mitigation plan? To mitigate risk, we divide the project into a pre-MTT activity, four MTTs, and alpha and beta dry runs. Each MTT comprises modules that are independently developed and tested. We will execute the EPS Development Task (MTT-I) and the Fiber-Link Deployment Task (MTT-II) in parallel, and then integrate to minimize the risk. Upon the completion of one of the EPSs, we will start to serve the first group of users to produce groundbreaking results. See Sections III and V for full details.

II- Research Activities to be Enabled

II.1 Broadband Quantum Communication Network (2 SP, 1 PD, 2 GS & 3 UG; Funding: General Dynamics & NSF pending): PI Z. Zhang (UA Materials Science & Engineering) and co-PI I. Djordjevic (UA Electrical & Computer Engineering) will leverage the INQUIRE instrument's EPS2 to develop and implement a gigabit-per-second (Gbit/s) multi-access quantum key distribution (QKD) network that does not rely on the trusted-nodes mode, thereby offering unmatched rate and security for a QKD network. Figure 2 illustrates the proposed broadband multi-access QKD network that leverages both: 1) the multimode encoding scheme of Floodlight-QKD [Zhang2017]; and 2) the highly successful orthogonal frequency-division multiple access (OFDMA) method employed in classical optical communications [Shieh2010]. In the proposed experiment, Alice utilizes an amplified spontaneous emission (ASE) source for key generation and the entangled photons generated from the INQUIRE instrument for security monitoring. Users also utilize the SNSPDs in the INQUIRE instrument to perform time tagging measurements that quantify an eavesdropper's intrusion. All users encode on the same quantum stream using the OFDMA method widely applied in classical networking to maximize the spectral efficiency and secret-key rate (SKR). Notably, only Alice can decode all users' encoding. With an encoding rate of 10 Gbit/s and an optical bandwidth of 2.5 THz, Zhang and Djordjevic estimate that all users share a 4 Gbit/s

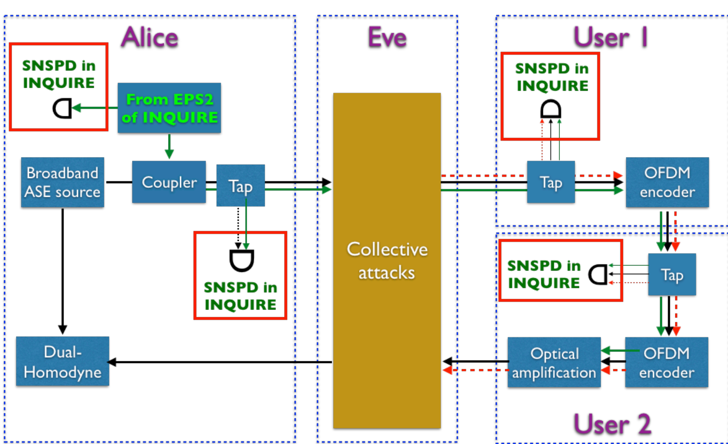

Figure 2. Experimental schematic of a broadband multi-access quantum communication network without the trusted-nodes assumption. *Black*, *green*, and *red lines* denote photons from the ASE source, EPS2 of the INQUIRE instrument, and Eve. The SNSPDs in the INQUIRE instrument, marked in *red boxes*, constitute the channel monitor that verifies the integrity of the channel. As shown, only the photons in the *green curves* contribute to the coincidence with the idler. The channel monitor derives the strength of Eve's intrusion.

SKR. Such a high rate is on par with what classical optical-communication network affords. The proposed experiment thus opens a path to quantum-secured communication network at Gbit/s-class rates with strong security, i.e., no need to resort to the trusted-nodes model.

II.2 Quantum Information Processing with Nano Materials and Devices (2 SP, 2 PD, 2 GS & 3 UG; Funding: AFOSR, planned NSF RAISE): J. Schaibley (UA Physics) and P. Wei (UCR Physics) will utilize single photons generated by the INQUIRE instrument's EPS3 to perform quantum information processing in transmission metal dichalcogenides (TMDs) and their heterostructures. As illustrated in Figure 3, Schaibley will utilize heralded single photons to characterize a single-photon switching devices based on surface-plasmon polaritons (SPPs) in conducting single-walled carbon nanotubes (SWCNTs) coupled to single quantum emitters (SQEs) in a monolayer semiconductor (WSe_2). Such a device has been highly sought after for applications in quantum information processing, where quantum nonlinear optics can be used to perform logic operation [Chang2007; Chang2014; Gorniaczyk2014; Tiarks2014]. Schaibley will investigate the fundamental small-size limit for nanoscale waveguides by confining the SPPs to single SWCNTs, and then integrating them with nonlinear atom-like systems. Specifically, Schaibley will take advantage of the 1340-nm photons produced in EPS3, in conjunction with a tunable quantum frequency converter comprising a PPKTP waveguide device, to obtain 10^6 entangled-photon pairs/s. Schaibley will subsequently perform single-photon pump-probe measurements.

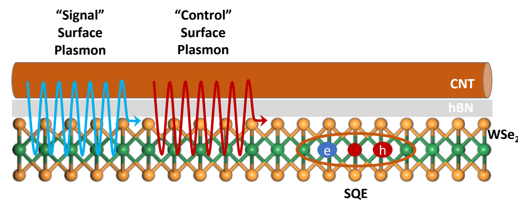

Figure 3. Single-plasmon transistor based on a SWCNT/hBN/WSe_2 heterostructure. In this experiment, the presence or absence of the "control" plasmon (*red*), which couples to the SQE, will determine the transmission of the "signal" plasmon (*blue*) through the nonlinear response of the SQE in the WSe_2. Either the "control" plasmon or the "signal" plasmon is excited by a single photon originating from the INQUIRE instrument.

Wei will leverage molecular beam epitaxy in an ultra-vacuum environment [Wei2013] to engineer heterostructures of $MoSe_2$ and $MoTe_2$ with a material bandgap matching the 1310-nm telecommunication band. Wei will then pursue the creation of TMD-heterostructure quantum dots [Luo2017] to directly couple with telecommunication photons generated by EPS3, without resorting to quantum wavelength conversion. Both Schaibley and Wei will use the INQUIRE instrument's SNSPDs to measure at the single-photon level.

II.3 Entanglement-Enhanced Brain Imaging (1 SP, 1 PD, 1 GS & 2 UG; Funding: NIH): Co-PI M. Romanowski (UA Biomedical Engineering) will demonstrate the application of entangled photons for intraoperative deep brain tissue imaging, allowing for better delineation of cancer to improve a patient's outcome. Romanowski, in collaboration with the UA College of Medicine, has developed intraoperative imaging instrumentation at 650–950 nm for fluorescence-guided surgery in the brain [Martirosyan2015, Watson2015]. While providing high sensitivity and spatial resolution, this spectral range is limited by light scattering and absorption in the tissue. Particularly promising are low-scattering spectral windows at 1100–1350 nm and 1600–1870 nm [Horton2013, Shi2016a]. Inspired by recent work with polarization-entangled photons at 802 nm in a transmitted light mode [Shi2016b], Romanowski will use all of the INQUIRE instrument's EPSs and SNSPD array to further improve imaging sensitivity and develop a system operating in the reflected-light mode: for better compatibility with surgical procedures in brain (Figure 4). Photons at 1340 nm (EPS3) and 1550 nm (EPS1 & 2) will increase the tissue penetration depth. Romanowski will test polarization vs. time-energy entanglement to determine the modality that yields the highest signal-to-noise ratio. In comparison with

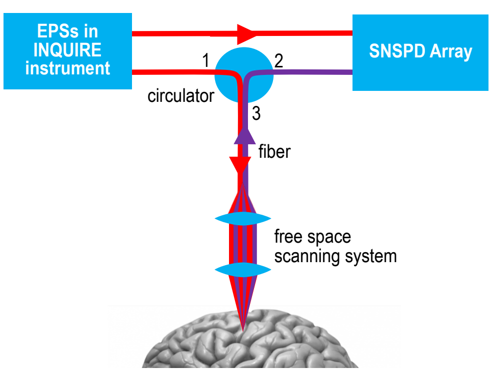

Figure 4. Deep brain intraoperative imaging using infrared entangled photons operating in a reflected light mode.

multiphoton fluorescence techniques, the proposed modality uses lower NA optics to enable greater working distances compatible with image guided interventions. Characterization of photon entanglement will provide information about tissue pathology without exogenous contrast agents.

I.4 Photonic Quantum Computing (2 SP, 2 PD, 2 GS & 2 UG; Funding: UA & pending Corning Corp.): Co-PI N. Peyghambarian (UA College of Optical Sciences) and PI Zhang will employ the high-quality polarization entangled photons generated from the INQUIRE instrument's EPS1 in low-loss optical fibers to construct a highly scalable platform for multi-photon quantum walk experiment: a primitive of an all-photonic quantum-computing neuron network. The experimental schematic is depicted in Figure 5. The signal (idler) photon is coupled into dispersion-shifted fiber and is guided to the left (right) all-optical low-loss switch, which in turn routes the photon into the left (right) cavity. The round-trip times in the two fiber cavities are set to $T_L, T_R \sim 500$ ns with $T_L - T_R = 10$ ns. The photons in one cavity can hop into the other through a low-loss 50/50 evanescent coupler, and can be routed out from the fiber cavities by applying pump pulses to the switches at desired times. The photon-arrival time statistics are measured on two SNSPDs in the INQUIRE instrument through the out$_1$ ports to derive the photon-number distribution of the quantum walk. Losses in the proposed scheme arise from the evanescent coupler, the all-optical switch, and fiber propagation are, respectively, 0.1 dB, 0.9 dB, and 0.3 dB/km. As such, the overall loss per layer is ~ 1 dB, which is lower than those in previous schemes based on integrated photonics [Sansoni2012]. Moreover, the active switches allow for deterministic readout of the photon distribution at any layer, thereby substantially reducing the required acquisition time.

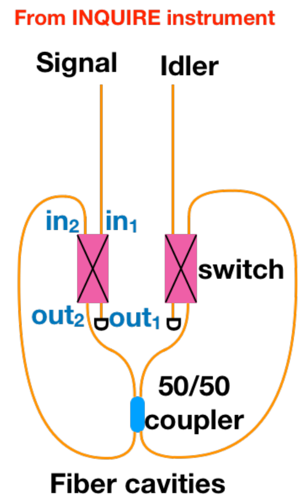

Figure 5. Schematic for quantum walk in fibers using entangled photons.

II.5 Biomedical Imaging and Sensing Using Entangled Photons (1 SP, 1 PD, 1 GS & 1 UG; Funding: NIH): Co-PI J. Barton (UA BIO5 Institute) will harness EPS3 to develop high-resolution and sensitivity optical imaging methods for applications ranging from early detection of cancer to precision surgery. The purpose is to examine and characterize the transmission of entangled photons through single, multimode, and photonic-crystal fibers. In fluorescence microscopy, entangled photons have reduced the illuminating power by ten orders of magnitude [Varnavski2017], opening a route for photobleaching-free noninvasive imaging. However, endoscopes are necessary to deliver and return light from organs deep in the body due to the limited penetration depth of photons. As illustrated in Figure 6, Barton will use fiber-based endoscopes to travel natural orifices in the body such as the colon, bronchi, or fallopian tubes for high-resolution optical imaging [Leung2015; Keenan2017; Welge2017]. The use of entangled photons in endoscopes could offer substantial advantages over laser light by virtue of a pair's correlation in both the time and the frequency domains. Also, the lower peak power required for multiphoton processes may mitigate potential fiber damage. Barton will compare the output intensity, dispersion, and multiphoton excitation efficiency to the non-fiber-coupled case. The entangled photons delivered from the INQUIRE instrument are well suited to such endeavors. The ultimate goal is to determine the effectiveness of quantum light sources for endoscopic medical applications.

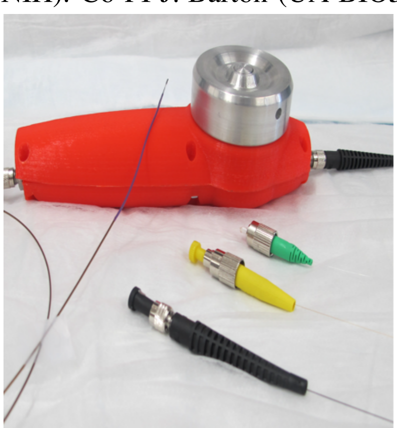
Figure 6. 0.8-mm diameter falloposcope with optical coherence tomography and fluorescence imaging capability, designed for early detection of ovarian cancer.

II.6 Additional Users: There are 14 additional users for the INQUIRE instrument (see 'Statements from Individuals'):

E. Becerra, UNM (1 SP, 1 GS & 1 UG; Funding: UNM Physics & AFOSR): Becerra will investigate measurements with EPS1, EPS2, and the SNSPD array to characterize quantum states of photons in high dimensions. These methods will require the minimum amount of resources based on compressed sensing tomography, which utilize prior information about quantum states.

S. Goodnick, ASU (1 SP, 0.25 PD & 0.5 GS; Funding: NSF/DOE Quantum Energy and Sustainable Solar Technologies, DOE ARPA-E & NASA): Goodnick will use EPS2, EPS3, and the SNSPD array to characterize material defects, structural properties of nanostructured materials, and ultrafast carrier relaxation dynamics in relation to advanced concept photovoltaic devices. Goodnick will also investigate materials and structural properties of semiconductors such as self-assembled InGaAs and InGaSb quantum dots for intermediate-band solar cells, and study the associated quantum entanglement.

P. Lucas, UA (1 SP, 1 GS & 1 UG; Funding: pending NSF EPMD): Lucas will design, fabricate, and test (with EPS2 and the SNSPD array) chalcogenide glass, low-loss optical fibers that carry entangled photons in the infrared domain. Such entangled photons can couple with molecular vibrations and offer a broad range of new opportunities to develop the next generation of high-efficiency optical sensors.

E. McLeod, UA (1 SP, 1 GS & 1 UG; Funding: Arizona TRIF): McLeod will use entangled photons (from EPS3) in combination with nanostructured photonic metamaterials to develop and demonstrate super-resolution imaging devices. These 3D photonic metamaterials will comprise nanoscale dielectric and/or metallic building blocks.

O. Monti, UA (1 SP, 2 GS, 0.25 PD & 1 UG; Funding: NSF ECCS): Monti will use the INQUIRE instrument EPS3 and the SNSPD array to investigate how to transfer and manipulate photon entanglement to pseudo-spin states in heterostructures of two-dimensional transition metal dichalcogenides.

R. Norwood, UA (1 SP, 2 GS, 1 PD & 1 UG; Funding: AIM Photonics, NSF, ONR & AFOSR): Norwood will develop nonlinear photonics devices based on the Si/SiN photonics platform, including electro-optic and all-optical modulators, frequency generation devices, and integrated chips for quantum photonics. Norwood will use EPS1, EPS2, and the SNSPD array to explore the limits of these integrated photonic devices, in coordination with existing photonic chip testing and optical networking testbeds.

J. Schroeder, UA (1 SP, 1 GS & 1 UG; Funding: NIH): Schroeder will use EPS3 and the SNSPD array to investigate Receptor Tyrosine Kinase trafficking during development and cancer progression. In particular, Schroeder will implement novel imaging processes to understand how internalization and retrograde trafficking of membrane bound receptors is altered during these processes by revealing nanoscale details regarding protein-protein interactions and movements.

U. Utzinger, UA (1 SP, 1 GS & 1 UG; Funding: Moore Foundation & NIH): Utzinger will use entangled photons from EPS3 in fluorescence imaging to: 1) operate at pico- to nano-watt excitation power; and 2) reduce the effect of scattering on the two-photon (2P) absorption cross section. Deep brain imaging with the 1300-nm entangled photons will image Alex680 in the red, and also evaluate several dyes in the Alexa and Vivo Tag series for compatibility with entangled 2P excitation fluorescence microscopy.

W. Wang, UA (1 SP, 1 GS & 1 PD; Funding: NSF & SRC): Wang pursues spintronics as a promising route to realize ultra-low energy information storage and process in future computational devices. Wang will study interaction between spins and entangled photons with EPS3 and the SNSPD array.

Other Users:

M. Fallahi, UA, communication & sensing
K. Hickenbottom, UA, characterizing membranes
K. Kieu, **UA**, communication & sensing
A. Mafi, UNM, quantum devices
A. Sandhu, UA, study of ultrafast dynamics

II.7 Results from Prior NSF Support

EEC-0812072: $36,528,818; 9/1/08–8/31/19; *Center for Integrated Access Networks*. **PI N. Peyghambarian**. Intellectual Merit: The vision for the Center for Integrated Access Networks (CIAN) is to deliver network services at data rates up to 100 Gbit/s anytime and anywhere at low cost and with high energy efficiency. Broader Impacts: CIAN has made significant impacts in both fundamental and applied research in areas ranging from quantum optics in nanoscale materials to network architectures and intelligent control systems. Publications/Products: *Nature Photon*. **8**, 153 (2014); *Opt. Express* **17**, 8237 (2009); *Opt. Express* **20**, 16410 (2012); *IEEE Photon. Tech. Lett*. **22**, 1656 (2010); *Chem. Mater*. **23**, 416 (2011); *ACS Nano* **7**, 8441 (2013); *Opt. Express* **18**, 21350 (2010); *Opt. Mat. Express* **3**, 1358 (2013).

CCF-0952711: $399,546; 9/1/10–8/31/15; *NSF* CAREER. *Enabling Technologies for Beyond 1 Tb/s per Wavelength Optical Transport*. **PI I. Djordjevic**. Intellectual Merit: A study of the different approaches to overcome the limitations of heterogeneous optical networks, enabling serial 1 Tb/s optical transport while employing the components operating at lower speeds. Broader Impacts: The broader impacts include solving technological challenges faced beyond 1 Tb/s optical transport and the next generation of heterogeneous optical networks. Publications/Products: *Advanced Optical Communications and Networks*. *Artech House* (2013); *Opt. Express* **23**, 14501 (2015); *IEEE Trans. Commun*. **62**, 3262 (2014); *IEEE Trans. on Commun*. **62**, 2507 (2014); *IEEE Sig. Proc. Mag*. **31**, 104 (2014); *J. Lightw. Technol*. **30**, 2846 (2012).

CBET-085392: $307,658; 7/15/09–9/30/13; *Degradable plasmon-resonant gold nanoshells*. **PI M. Romanowski**. Intellectual Merit: Deposition of gold on the liposome core enabled control of electronic, optical, and thermal properties of this composite material. Broader Impacts: Biological compatibility and small size of this composite material enable new uses in medical diagnostic and therapeutic methods, or in augmentation of impaired functions of the body. Publication/Products: *Adv. Funct. Mat*. **21** 1113 (2011); *ACS Nano* **6**, 9383 (2012); *Adv. Mat*. **24**, 6380 (2012); *Theranostics* **2**, 1020 (2012); *Dekker Encyclopedia Nanosci. Nanotech 3rd ed.,* 336 (2014).

III- Description of the Research Instrument and Needs

III.1 Development of EPSs (MTT-I)

We will build three state-of-the-art EPSs to serve different applications, as summarized in Table 1. For all three EPSs, the designs will optimize between long-term stability and performance.

Table 1. List of Entangled-Photon Sources in the INQUIRE Instrument

Sources	Crystal	Pump	Mode	Flux	Applications
EPS1 1550-nm polarization entanglement	Type-II PPKTP bulk	Frequency-doubled 1550-nm fiber lasers (NPP)	pulsed or c.w.	800,000 pairs/s	Teaching labs, biomedical imaging/sensing, quantum communications, quantum computing
EPS2 1550-nm time-energy entanglement	Type-0 PPLN bulk	Frequency-doubled 1550-nm fiber laser (NPP)	c.w.	7.8×10^{9} pairs/s	Teaching labs, quantum communications, biomedical imaging/sensing
EPS3 1340-nm time-energy entanglement	Type-0 PPLN waveguide	Amplified 670-nm diode laser (Toptica)	c.w.	1.2×10^{11} pairs/s	Biomedical imaging/sensing, materials studies

III.1.1 Pump Management: Figure 7 illustrates the pump generation and sharing scheme. EPS1 and EPS2 will share a c.w. 775-nm pump, produced via frequency doubling of a c.w. >2 W 1550-nm fiber laser (FL) via a 10-cm-long pigtailed PPLN waveguide (WG) device (HCPhotonics). Such a fiber-in-fiber-out device enjoys long-term stability essential for the INQUIRE instrument. EPS1 can also operate in a pulsed mode, achieved by switching to a pulsed 755-nm pump generated via frequency doubling of a >2 W 3-ps pulsed 1550-nm fiber laser via a PPKTP bulk device (AdvR). The residue 1550-nm pump photons are rejected by a 780/1550-nm wavelength-division multiplexing (WDM) filter (> 50 dB directivity, Haphit). Two fiber taps collect 1% of the 775-nm light for power monitoring (mon).

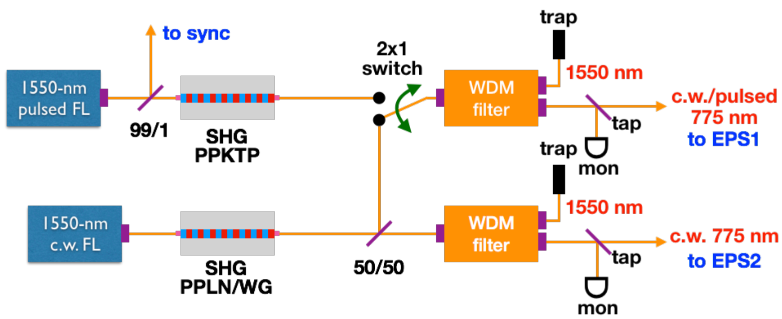

Figure 7. Pump generation and sharing scheme. EPS1 employs a low-loss 2x1 switch (Thorlabs OSW12-780-SM) to select its operating modes. A 99/1 coupler produces a synchronization (sync) signal. A WDM filter rejects 1550-nm photons.

III.1.2 EPS1 1550-nm Polarization Entanglement: We will adopt the design of the single-pass deterministic polarization EPS used in NIST's milestone experiment for the strong loophole-free test of local realism [Shalm2015]. Compared to the conventional bidirectional polarization EPS in a Sagnac setting, NIST's scheme enjoys long-term stability and minimal optical realignment—both highly desirable features for the INQUIRE instrument.

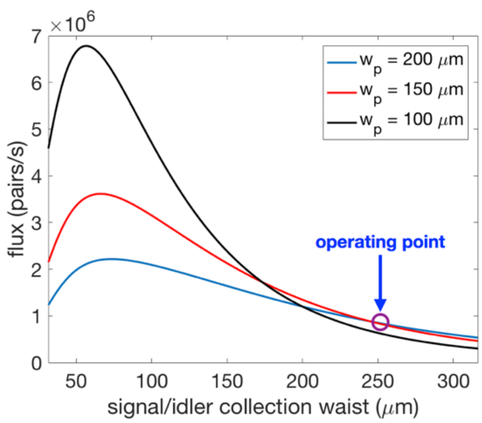

Figure 8. Optimization of flux by adjusting signal/idler collection waist at different pump waists w_p.

We used Bennink's approach [Bennink2010] to simulate EPS1's produced flux at different pump waists and signal/idler collection waists, subject to the constraints on the dimension of the setup. We chose the lenses and collimators based on these results shown in Figure 8. Figure 9 illustrates the EPS1 design: a 775-nm pump laser (c.w. or pulsed, 300 mW maximum power) couples to free space through a collimator (Thorlabs F230FC-780). Two short-pass dichroic mirrors reject residue 1550-nm photons to first filter the free-space pump. A 75-cm focal-length lens then focuses the free-space pump down to a type-II PPKTP bulk crystal (AdvR). Between the lens and the crystal are a polarizer, followed by a half-wave plate (HWP) to rotate the polarization. A beam displacer (BD) then separates the horizontal (H) and vertical (V) polarizations.

A semicircular HWP rotates the polarization of the bottom beam so that both beams are H-polarized prior to entering the crystal. With a small probability, due to the indistinguishability between two spontaneous parametric down-conversion (SPDC) processes a pair of degenerate orthogonally-polarized photons—centered at 1550 nm—generate in a superposition state of being in both the top and bottom arms. A second BD (BD2) placed after the crystal separates the H- and V-polarized components of the two arms. Two semicircular HWPs rotate the polarizations of the photon in the first and third arms, while the polarizations of the second and fourth arms are unchanged. The third and fourth arms then pass through a HWP. A third BD (BD3) combines the first two arms and the last two arms. A silicon filter eliminates all pump photons. Two 50-cm-focal-length lenses collect the photons. Two motorized mirrors fine tune the coupling of the two beams into two single-mode fibers via two collimators (Thorlabs F230FC-1550).

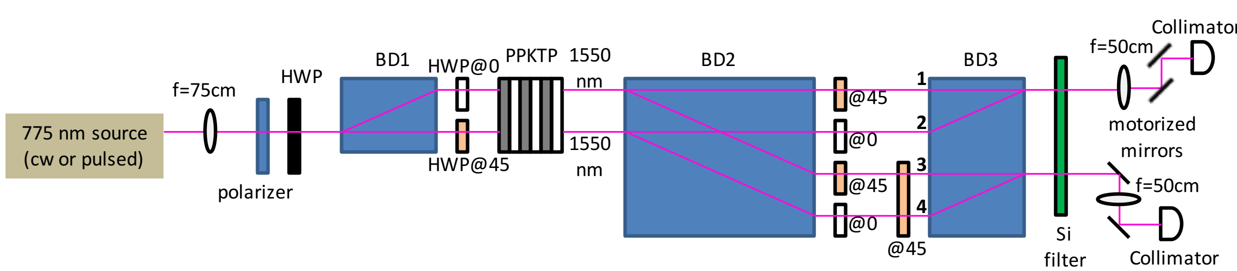

Figure 9. Schematic of EPS1 to produce polarization entangled photons at 1550 nm.

III.1.3 Time-Energy EPS at 1550 nm: As illustrated in Figure 10 (*left*), we will adopt an all-fiber design for EPS2. We couple a c.w. 775-nm pump with up to 300 mW power into a pigtailed PPLN bulk crystal device (HCPhotonics) via a polarization maintaining (PM) fiber. The produced SPDC photons centered at 1550 nm couple into a PM fiber. A built-in filter rejects the 775-nm pump photons. A 780/1550nm WDM filter (Haphit) further eliminates all pump photons. The PPLN device's temperature is tuned by an external controller so that the center wavelengths of the SPDC signal and idler photons can be adjusted.

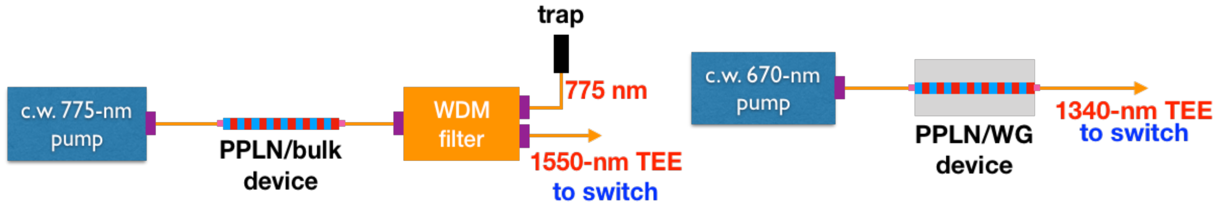

Figure 10. (*left*) schematic of EPS2 to generate time-energy entanglement (TEE) at 1550 nm. (*right*) schematic of EPS3 to generate time-energy entanglement at 1340 nm.

III.1.4 Time-Energy EPS at 1340 nm: As illustrated in Figure 10 (*right*), the EPS3 design will be similar to EPS2 [Tanzilli2002]. A c.w. 670-nm pump laser (Toptica DLC TA Pro 670) with up to 60-mW power drives a pigtailed 10-cm-long PPLN/WG device (HCPhotonics) via a PM fiber. The created SPDC photons centered at 1340 nm couple into a fiber, and reach the user target via a switch. 670-nm pump photons are suppressed during the transmission in single-mode fibers to a user's terminal. Since materials studies and biomedical imaging/sensing use 1340-nm TEE photons, EPS3 users are responsible for utilizing a silicon window to completely eliminate residue 670-nm photons, as described in the management plan (Section V).

III.2 Deployment of Fiber Links (MTT-II)

As depicted in Figure 11, UA will install single-mode optical fiber cabling in a star topology from the ECE Building each to the Meinel Building, Mines Building, Physics-Atmospheric Sciences Building, and Keating Building. Additionally, in the Meinel and Keating Buildings, UA will install optical fiber cabling from the building entrance point to three and two interior labs, respectively.

Figure 11. UA campus optical fiber network map for the INQUIRE instrument.

Between buildings, existing underground conduit and tunnel pathways will house the optical fiber cables. The outside fiber will be outdoor rated, water-blocked, with armored construction. The inside-building fiber cable will be indoor rated and non-armored construction. The single-mode optical fiber will be OS2 rated, and specifically: 1) Corning SMF-28e optical fiber with nominal loss of 0.3 dB/km linking the Keating and Physics Buildings at 1310/1383 nm to minimize the dispersion at 1340 nm; and 2) Corning LEAF fiber with 0.19 dB/km and 4 ps/nm/km chromatic dispersion at 1550 nm for the other links. The cross-connect point on the run between the ECE and Physics-Atmospheric Sciences Buildings will have a nominal loss of approximately 0.75 dB based on industry standard guidelines. FC/PC connectors will terminate the fiber.

III.3 Integration of EPSs and Fiber Links (MTT-III)

The INQUIRE instrument will entail five outbound ports (EPS1: signal, idler, sync; EPS2: SPDC photons; EPS3: SPDC photons) to deliver entangled photons and the sync signal to the initial eight users. We hook each output port to a low-loss (0.6 dB) 1x8 switch (Agiltron LBSA-0080111132) and software control the switches as described in Section III.3. The INQUIRE instrument also has an array of eight SNSPDs (Quantum Opus) with > 80% efficiency, ~ 30 ns dead time, and ~ 100 ps timing jitter.

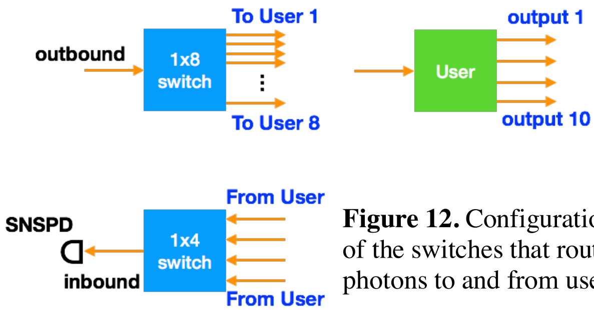

Figure 12. Configuration of the switches that route photons to and from users.

As illustrated in Figure 12, to allow each user to access at maximal four SPSNDs, each SNSPD connects to a low-loss (0.6 dB) 1x4 switch (Agiltron LBSA-0040111132), and the switch outputs guide to different users. In summary, the configurations of the switches and user terminal fiber bundles are five 1x8 switches with inputs from the signal of EPS1, idler of EPS1, sync of EPS1, EPS2, and EPS3. The eight outputs for each 1x8 switch go to eight users; eight 1x4 switches, the output port of each 1x4 switch goes to an SNSPD. For the first to fourth 1x4 switch, their input ports connect Users 1–4. For the fifth to eighth 1x4 switch, their input ports connect Users 5–8. Each user's terminal has a bundle of 10 fibers (Figure 12, *green box*), and each fiber connects with EPS1: signal, idler, sync, EPS2, EPS3, four SNSPDs, and one reserved port.

III.4 Development of User and Administrator Interface (MTT-IV)

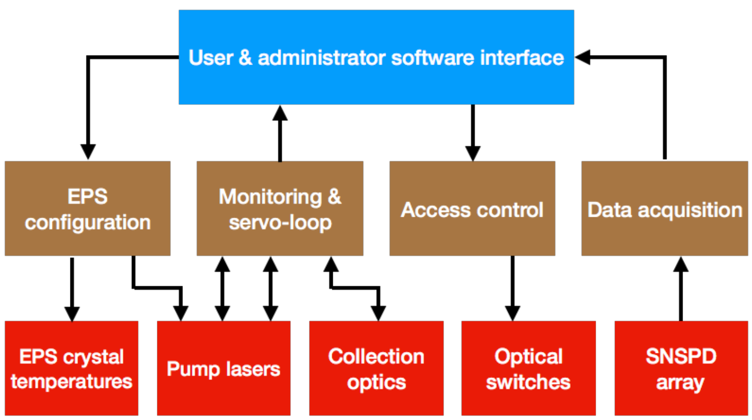

Figure 13. Architecture for the user and administrator interface that offers the functionalities of EPS configurations, system monitoring, access control, and data acquisition. Servo-loops will ensure the long-term stability of the INQUIRE instrument.

We will ensure long-term robustness of the INQUIRE instrument and offer users a friendly interface to access the QIS resources. To this end, we will develop a fully automated hardware feedback system to optimize the pump lasers' operating conditions.

We will develop a software interface for users to remotely measure at the single-photon level. To do so, we will work with the time-tagging device manufacturer (Swabian Instrument) to customize our web-based, data-acquisition platform. Swabian Instrument's 8-channel Time Tagger Ultra device has data acquisition software embedded in an Internet browser. We will integrate the Time Tagger Ultra data acquisition module with INQUIRE instrument's software interface so that users can readily access the EPSs and SNSPDs in a unified environment.

The hardware feedback system comprises monitoring detectors that measure the pump lasers' power and wavelengths via length-stabilized cavity mirrors. The error signals then feed back to the laser drivers to lock the output power and wavelengths. Four motorized mirrors in EPS1 optimize the collection efficiencies of the SPDC signal and idler photons. A program controls the hardware feedback system, and provides a software interface for users to conveniently and safely tune the brightness, operating modes (c.w. vs pulsed), and center wavelengths of the sources. The software interface also allows the INQUIRE instrument administrator to configure the switches, and to grant different users access to specific instrument components. Figure 13 illustrates the architecture for our proposed control hardware and software interface.

III.5 Performance Analysis (Preliminary Data)

We have performed an extensive analysis on the coupling efficiencies, insertion losses of different devices, and losses induced by fiber transmissions to precisely estimate the performance of the EPSs and derive the flux at each User's terminal. We summarize the estimated losses in Table 2.

Table 2. Performance estimate of the flux of INQUIRE instrument EPSs at different buildings.

EPS #	max raw flux (pairs/s)	coupling & filtering loss	switch loss	**ECE** loss/flux	**Meinel** loss/flux	**Keating** loss/flux	**Physics** loss/flux	**Mines** loss/flux
				0.05 dB	0.2 dB	0.4 dB	1.1 dB	0.07 dB
1	800,000	0.55 dB	0.6 dB	460,000	430,000	391,820	283,850	456,000
2	7.8×10^{9}	5.1 dB	0.6 dB	5.5×10^{8}	5.2×10^{8}	4.7×10^{8}	3.4×10^{8}	5.5×10^{8}
3	1.2×10^{11}	4.1 dB	0.6 dB	1.35×10^{10}	1.3×10^{10}	1.2×10^{10}	8.3×10^{9}	1.3×10^{10}

We have also investigated the effect of dispersion on the broadening of the bi-photon correlation time. We find that for within campus distances, the effect of dispersion on correlation broadening is insignificant. Note that correlation broadening will be substantially reduced when two photons are diverted to narrowband channels. Moreover, we can employ a dispersion compensating technique for experiments with stringent requirement on sharp bi-photon correlation time. Table 3 summarizes the bi-photon temporal correlation.

Table 3. Performance estimate of bi-photon temporal correlation time at different buildings.

EPS #	optical bandwidth	original bi-photon corr. time	**ECE**	**Meinel**	**Keating**	**Physics**	**Mines**
			dispersion	dispersion	dispersion	dispersion	dispersion
			corr. time	corr. time	corr. time	corr. time	corr. time
1	2 nm	2.49 ps	~0	4.12 ps/nm	22.8 ps/nm	20.6 ps/nm	1.48 ps/nm
			2.49 ps	11.7 ps	62.6 ps	58 ps	4.9 ps
2	40 nm	125 fs	~0	4.12 ps/nm	22.8 ps/nm	20.6 ps/nm	1.48 ps/nm
			125 fs	233 ps	574 ps	1.3 ns	83.7 ps
3	13 nm	287 fs	~0	-16 ps/nm	2.68 ps/nm	2.44 ps/nm	-5.55 ps/nm
			287 fs	285 ps	49.2 ps	44.8 ps	102.1 ps

IV- Broader Impacts (Including Impact on Research and Training Infrastructure)

IV.1 QIS Teaching Laboratories: QIS is envisaged to drive a forthcoming scientific and technological revolution. It is imperative for the next-generation workforce of scientists and engineers to grasp the essential concepts of QIS and be able to apply such knowledge in their own fields. Quantum mechanical effects, however, are counterintuitive, creating a challenge in QIS education. The INQUIRE instrument is an ideal platform to demonstrate to students the otherwise obscure QIS concepts, and to inspire STEM and underrepresented minority students to pursue quantum science education and careers. Specifically, we propose to deliver entangled photons to UA undergraduate and graduate teaching laboratories located in the Meinel Building so that students can perform hands-on, proof-of-concept QIS experiments as invaluable research training. Figure 14 illustrates our three initially planned teaching experiments. *Violation of the Clauser-Horne-Shimony-Holt (CHSH) inequality experiment*: Two fiber ports receive polarization entangled signal and idler photons from EPS1. To choose a measurement basis, quarter-wave plates (QWPs) and half-wave plates (HWPs) rotate the polarizations of the photons on each arm prior to two polarizing beam splitters (PBSs). The outputs of the PBSs direct to two SNSPDs of the INQUIRE instrument for singles and coincidences measurements. The measurement data will allow students to derive the violation of the CHSH inequality [Clauser1969] and thus observe the "nonlocality" predicted by quantum mechanics. *Hong-Ou-Mandel interferometer experiment*: Signal and idler photons from EPS1 interfere on a 50/50 beam splitter after being imparted polarization rotations to completely match their profiles. By scanning the delay of the idler photons, students measure a Hong-Ou-Mandel dip using the SNSPDs and derive its visibility [Hong1987]. This experiment will enable students to grasp the concept of "indistinguishability" in quantum mechanics. *Nonlocal dispersion cancellation experiment*: A WDM filter separates TEE photons from EPS2 into two bands. In the absence of dispersion-compensating modules (DCMs), the photons in the two arms should exhibit sharp temporal correlation. Such tight correlation vanishes when strong dispersion is applied on photons in one arm via a DCM. By applying anomalous dispersion of the same magnitude onto the photons in the other arm, the sharp temporal correlation recovers—a quantum phenomenon known as nonlocal dispersion compensation [Franson1992]. In this experiment, students will grasp the concept of monochromatic dispersion that is frequently used in optical communications. They will also receive hands-on experience of using conventional optical devices such as polarization controllers (PC) and DCMs, as well as quantum devices such as SNSPDs. They will understand that entanglement exists in different forms.

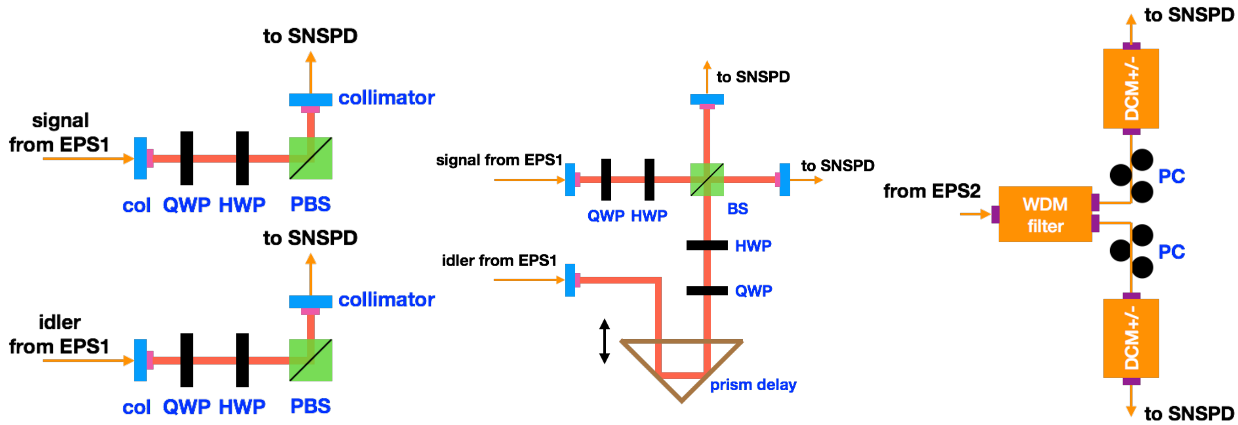

Figure 14. Planned experiments for the QIS teaching laboratory. (*left*) violation of CHSH inequality; (*middle*) Hong-Ou-Mandel interferometer; (*right*) Nonlocal compensation of dispersion.
QWP: quarter-wave plate; HWP: half-wave plate; PBS: polarizing beam splitter; BS: beam splitter; DCM: dispersion compensating module; PC: polarization controller.

IV.2 Student and Postdoctoral Researcher Mentoring: Our PI/co-PI team strongly commits to educating the next-generation of students and postdoctoral researchers (PD), as evidenced by our track record. PI Zhang and co-PI Djordjevic will jointly mentor a Graduate Research Assistant (GRA) and PD during the development of the INQUIRE instrument. The GRA and PD will participate in the component-level design and the implementation of the EPSs, the routing scheme, and the control hardware. They will characterize the performance of the EPSs and interface them with the fiber-link network. In addition, we will collaborate with the well-established Arizona's Science, Engineering, and Mathematics Scholars (ASEMS) competitive mentoring program at UA to host two underrepresented undergraduate STEM students each project year for their involvement in building the INQUIRE instrument.

IV.3 Outreach: Our outreach efforts will involve three linked and sustainable activities that build off the successful outreach of CIAN, extending the impact of this program to introduce under-served populations to this complex and exciting new area of science, consistent with the UA goal of greatly increasing the number of underserved and first-in-family to college students in STEM disciplines: 1) we will regularly invite middle and high-school students and their teachers, from the local community (Tucson High Magnet School and Sunnyside High School, both with ~80% minority student populations and be in the AVID and MESA programs for first-in-family, low-income, and historically underserved populations) to participate in QIS-based teaching experiments and to tour the INQUIRE central facility. We have robust contacts at both schools, including Ms. Marquez and Ms. Quan Nahar, who have routinely and enthusiastically linked our photonics programs to their student populations. Since QIS is a new area particularly relevant to the educational mission of public schools, we will focus equally on educating the faculty on the principles of QIS as for their students; 2) we will engage Native American high-school students in QIS summer camps through the Expect Academic Success in STEM and the Native American Science & Engineering Programs. These are robust and sustainable programs initiated at UA that designed to increase access to STEM pathways and encourage college readiness for underserved, underrepresented, first-generation college bound students and to provide a vision of a career in STEM fields; and 3) we will leverage CIAN's IOU-

NA REU and O-RETINAS RET Programs by hosting Native American undergraduates and teachers in the labs to engage them in building the INQUIRE instrument and receiving QIS educational training.

IV.4 Technological and Societal Impacts: QIS leads to unconditional security [Zhang2017] and opens a window for ultrasensitive metrology for gravitational-wave detection [Abadie2011, Aasi2013], bio-sensing [Taylor2013, Mauranyapin2017], radar detection [Zhang2015], and microscopy [Ono2013]. In addition, prototype quantum-computing cloud has been launched [IBM2016] to seek new paradigms for artificial intelligence and big data. The INQUIRE instrument provides networked quantum resources to enable advanced research and research training in the US and pursue QIS-enabled science and technologies to benefit society. The infrastructure will also support other research activities such as entangling quantum emitters, testing novel quantum networking theory, and a heterogeneous quantum-communication network.

V- Management Plan

V.1 Description of the Space Housing the INQUIRE Instrument: Room ECE 111 is 66 m^2 to be equipped with chilled water to cool the SNSPD array and compressed air to float the optical tables. Air filters and temperature control maintain the optimum operational condition for the instrument. In addition, the room will have a separate area with two optical tables for visiting and UA users to build their experimental setups required to readily access the INQUIRE instrument. Racks and cabinets will be available for equipment storage.

V.2 User Training Plan: All users of the INQUIRE instrument will complete a mandatory Facility Training Course (FTC) given by the PD in Year 3 and a technician thereafter. The user records will be maintained by a part-time technician supervised by the PI in a software database. The FTC will ensure the robustness of the INQUIRE instrument and facilitate users' safe access to the QIS resources. The FTC will comprise a 2-hour hardware training session, a 2-hour software training session, and two optional 2-hour technical training sessions, as follows. *Hardware training*: 1) proper labeling of downlink and uplink fibers to prevent improper operations; 2) fiber cleaning and maintenance; 3) accessing the EPSs and SPSNDs; 4) pump filtering; and 5) safety considerations. *Software training*: 1) remote login and desktop; 2) system configurations and monitoring; and 3) data acquisition and readout. *Technical training*: 1) fiber splicing; 2) dispersion compensation; 3) free-space to fiber coupling; and 4) polarization management. After completing the FTC, each user will need to successfully complete a certification test that grants an access code to the INQUIRE instrument. First-, second-, and third-time violators of the documented operating procedures will be banned 1-week, 1-month, and ultimately permanently from access to the instrument.

V.3 Project Organization: PI Zhang will direct the project and report to the NSF Program Director. The PI is also responsible for supervising one GRA and one PD. Co-PI Djordjevic will work with University Information and Technology Services (UITS) to execute MTT-II and characterize the loss and dispersion of each fiber link. Djordjevic will also co-supervise the GRA and PD to develop the control hardware. Co-PI Peyghambarian will oversee installation in the Meinel Building and co-supervise (with the PI) one technician in Year 3. Co-PI Barton will oversee the installation in the Keating Building. Co-PI Romanowski will be responsible for supervising the installation in the Physics and Mines Buildings. The PI/co-PI team will meet on a weekly basis to discuss the project and future plans. An INQUIRE Advisory Committee (IAC) comprising Pierre Deymier (Dept. Head, Mat. Sci. Eng.), Leo Enfield (IT Manager, Eng.), Brian Ten Eyck (Ass. Dean, Eng.), and Justin Walker (Ass. Dean, Opt. Sci.) will review the progress of the instrument build. The PI will supervise a part-time technician to serve as the administrator of the completed instrument. Long term, the PI will direct the INQUIRE instrument during its lifetime. A steering committee formed by the PI/co-PIs and the IAC will manage ongoing concerns, operation, and maintenance.

V.4 Project Management Plan: Figure 15 depicts the project timeframe for the MTTs and their associated key components. We will execute MTT-I and MTT-II in parallel.

Pre MTT – System Design & Component Procurement (Zhang): The PI, GRA, and PD will complete component-level designs for the pump lasers, the EPSs, and the fiber network. We will base the designs on those presented in Section III and identify all optical and electronic components and their associated providers. We will invite two external quantum-optics experts to review the designed schematics, and address their feedback before lock down of the final designs. Component procurement will then follow. Deliverables include the EPS and fiber network schematics and a purchase list. Anticipated cost $25,749.

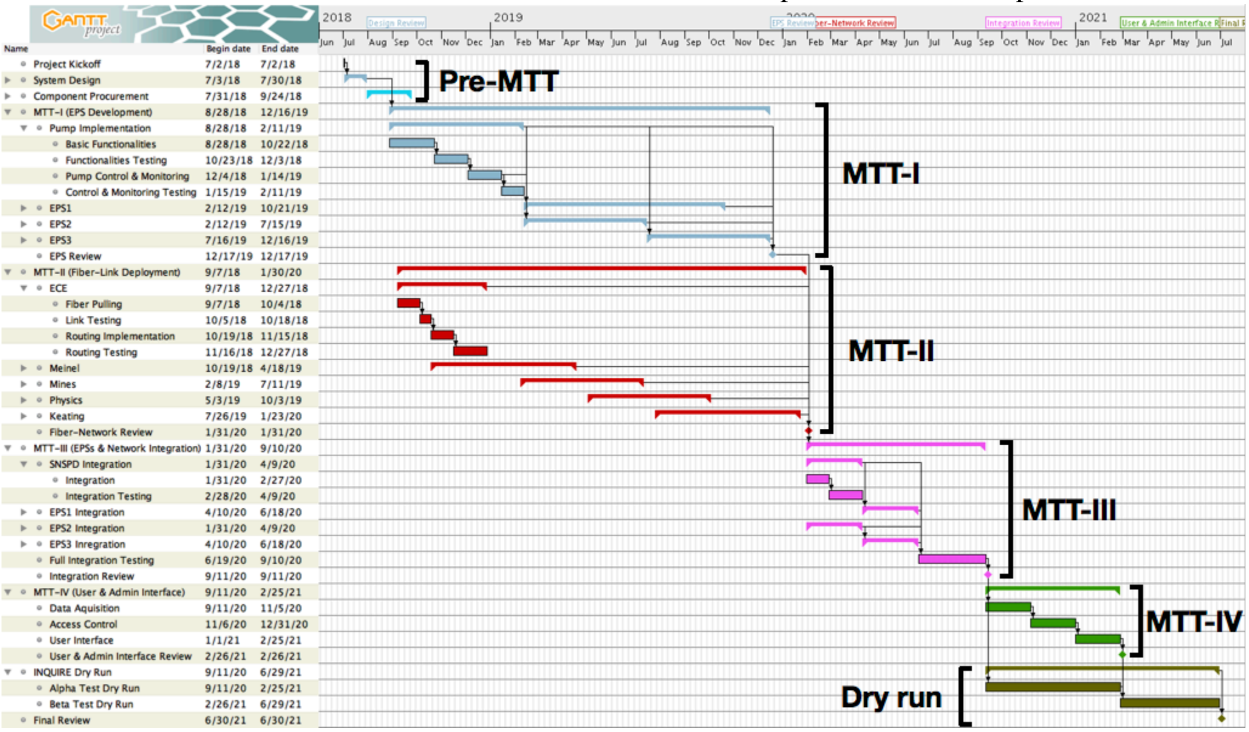

Figure 15. INQUIRE instrument project rolled-up work breakdown structure and schedule.

***MTT-I, EPS Development (Zhang)*:** Following the arrival of the pump lasers and nonlinear crystals, the PI, GRA, and PD will initiate development of the shared pump lasers and three EPSs. For each module, we will first develop and test basic functionalities, and then implement the control and monitoring hardware. An EPS review by the IAC will complete MTT-I. Anticipated cost $734,274.

***MTT-II, Fiber-Network Establishment (Djordjevic)*:** Co-PI Djordjevic will supervise UA's UITS to deploy optical fibers in serial to the four buildings that house the initial users' laboratories. Each Co-PI will oversee the installation at one of the four buildings. After we establish and successfully test each link, the GRA and PD will route photons from the central facility as the first performance test. A 'Fiber-Network' review by the IAC will complete MTT-II. Anticipated cost $362,082.

***MTT-III, EPSs & Network Integration (Zhang & Djordjevic)*:** Upon the successful completion of MTT-I and MTT-II, we will initiate the integrated system build that allows users to receive entangled photons and access the SNSPDs. The PI and PD will integrate and test the SNSPDs and EPS1. The PI and GRA will integrate and test EPS2 and EPS3. We will test the fully integrated system prior to an 'Integration' review by the IAC that concludes MTT-III. Anticipated cost $94,090.

***MTT-IV, User & Administrator Interface (Peyghambarian)*:** Following the completion of the EPSs & Network Integration Task, a technician under the supervision of PI Zhang and co-PI Peyghambarian will start to develop a user & administrator software interface for remote data acquisition, access control, instrument configuration, and system monitoring. The 'User & Administrator Interface' review by the IAC will complete MTT-IV. Anticipated cost $73,692.

***INQUIRE Dry Runs (Zhang)*:** An alpha-test dry run will commence upon the completion of MTT-I through MTT-III. The PI, GRA, and PD will execute the dry run to identify potential instability and weakness of the INQUIRE instrument. A beta-test dry run will follow the completion of the MTT-IV where up to three users will use the INQUIRE instrument in their experiments and report any hardware and software issues for final resolution. A 'Final Review' by the NSF Program Director and IAC will complete the INQUIRE project. Anticipated cost $138,683.

V.5 Risk Assessment: We have modularized the INQUIRE instrument Project and accessed the risks/mitigation in order to build a scientifically capable instrument with high likelihood (Table 4).

Table 4. Key Risks, Likelihood, and Mitigation Analysis

Module	Risk	Likelihood (Severity)	Comment/Mitigation
Pump	Lasing wavelength shift	Moderate (Low)	Compensated by tuning the crystal temperature.
	Output power lower than specified	Moderate (Low)	Tighter pump focus and longer WG can increase the flux of entangled photons.
	Wavelength drift	Moderate (Low)	The Toptica diode laser has a mode-hopping free design. Reinforce wavelength stability by locking to an external cavity.
EPSs	Phase-matching not satisfied	Low (Low)	AdvR & HCP will characterize the EPSs for pump wavelengths and power to ensure phase-matching.
	Inefficient coupling	Low (Low)	The devices will be fully characterized prior to shipping to ensure specified coupling efficiency.
	Leakage of sync signal to channels	Very low (High)	The sync signal is routed by a separate switch. In principle, there is no leakage from the sync channel.
SNSPDs	Cross talk between channels	Low (Low)	All input channels to SNSPDs are at the single-photon level. The 50-dB isolation will suppress cross talks.
Fiber links	Higher loss than modeled	Moderate (Low)	Fiber bending may introduce ~ 0.5 dB loss for an insignificant impact on flux. Overcome connector loss by fiber splicing.
	Polarization drift	Moderate (Low)	Slow/small polarization drift on the fiber links. Training sessions describe active polarization stabilization techniques.
Interface	Unable to control hardware	Very low (High)	All components can be controlled by RS-232, USB, or analog signals with application programming interfaces.

V.6 INQUIRE Instrument Operation and Maintenance: The PI will serve as the director of the INQUIRE instrument during its lifetime. User fees will support the operation and maintenance of the INQUIRE instrument and the fiber-network infrastructure. The administrator management software will configure and monitor users' access to the resources offered by the INQUIRE instrument. Optical switches will automatically grant users access at designated times with users charged on an hourly basis. Planned rates: $10/hour/EPS; $5/hour/SNSPD. An anticipated 25% utility load generates $153k/year. The PI will use $50k to recruit a part-time technician with responsibilities for: 1) training new users; 2) being the administrator for access control and system monitoring; and 3) 1 day/month system maintenance to optimize operation. The user fees will also cover the anticipated maintenance expenses. The PI will then use $30k to organize an annual workshop for students, invited speakers, academic and industrial partners, and current and prospective users. These workshops will promote the capabilities and achievements of the INQUIRE instrument to prospective users, and provide advanced research training for students. The workshops will be the first to focus on and foster interdisciplinary quantum-information research. User fees will also support (in part) fiber-link deployment to new on-campus users and adding new EPSs/SNSPDs.

V.7 Future Expansions: As needed, new detectors can be conveniently added to the SNSPD system. In addition, new EPSs and nonclassical light sources with desired characteristics can be developed to supply new areas of study. Since a major cost on the SNSPD system is its cryostat, sharing the cost of new SNSPDs (~$10k each) is affordable. Also, new EPSs leverage the existing shared pump lasers to significantly reduce their construction cost. The INQUIRE instrument user fees will cover a portion of any expansion cost.

V.8 External Users Management Plan: We will provide laboratory space in ECE 111 at $25/day/optical table for UA users and external users such as from ASU, UNM, and UCR (see 'Statements from Individuals'). External and UA users will pay the same fees to access the EPSs and SNSPDs.

V.9 Design Availability: The INQUIRE instrument design will be published by the PI/co-PIs in peer-reviewed journals and conference presentations.