Photonic Integrated Circuits for Atomic Sensors in Space Observatories/Operations (PICASSO)

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Space telescope programs detecting tiny signals from our solar system to distant galaxies covering nearly all of the electromagnetic spectrum have changed our understanding of the universe. A new frontier in the detection of distant astronomical objects is the observation of gravitational waves. The impressive demonstrations and observations by the terrestrial gravitational wave observatories motivate space-based observatories that should offer increased sensitivity. While today's gravitational wave observatories and most proposed space-based observatories utilize optical interferometers, atom interferometers measuring the gravity gradient offer an alternative sensing modality for gravitational waves [JH11, GB15, JH16, YE20], have demonstrated exceptional sensitivity in the laboratory, and may allow detection of a different-wavelength range of gravitational waves with a shorter baseline compared to optical interferometers. Thus, long-baseline or arrayed gravity gradiometers, using atom interferometer technology, in terrestrial and low earth orbit (LEO) platforms for gravitational wave detection have been proposed, and several programs already have been started. A compelling reason to place an atom-interferometer gradiometer in space is because atoms released into freefall remain relatively stationary, greatly enhancing the interrogation time and thereby the sensitivity of the atom interferometer. In LEO, the Cold-Atom Laboratory has been also realized to perform micro-gravity atomic physics experiments with an atom-chip-generated Bose-Einstein Condensation (BEC). Another critical application of atom interferometry is advanced positioning, navigation, and timing (PNT) systems for spacecraft navigation. Space industry partners, such as Space X, Blue Origin, and Virgin Galactic, have successfully developed a new generation of launch vehicles, and PNT is critical for achieving the correct orbital trajectory. Moving beyond the Earth relies on navigation with the Deep Space Network (DSN), which is a limited resource that will be strained as deep space exploration continues to expand. However, use of high precision inertial navigation systems (INS) can reduce reliance on GPS and other external navigational aiding systems for Earth centric orbits and reduce the frequency of tracking updates with the DSN for deep space missions. Atom interferometer inertial sensors can form the core of a high-precision INS, and in combination with external aiding such as star tracking [JG16], the INS can provide a medium-term navigation solution. Finally, atom-interferometer-based gravity gradiometers can be used to map the gravitational field near planets and moons, and in addition to providing information about the object, the map can be used for navigation through map-matching techniques.

Groundbreaking scientific experiments in space observatories and spacecraft navigation have proposed the use of atom interferometers and motivate further development and technology maturation of atom interferometers. In this white paper, we outline the technologies that need to be developed to improve the robustness and performance and to reduce the cost, size, weight, and power (C-SWAP) of an atom interferometer and its laser systems. In particular, complex and expensive laser systems should be replaced with chip-scale, low-power-consumption, and mass-producible photonic integrated circuits (PICs) (Fig. 1). The development and validation of PIC-based laser

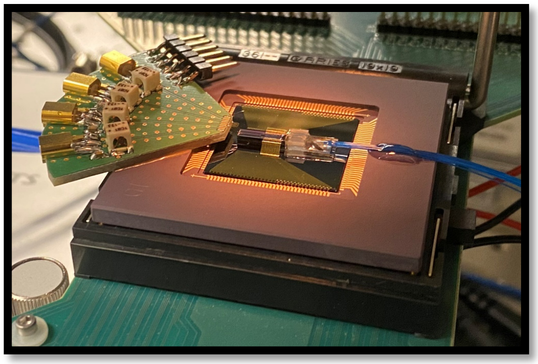

Figure 1. Compact and mass-producible PIC-based chip-scale laser system for atomic and optical sensors.

systems with compact and reliable atom interferometry sensors will be crucial to accelerate space exploration.

Our team at Sandia has worked to fill the gap between laboratory-based light-pulsed atom interferometers (LPAIs) and deployable LPAIs for real-world missions and to reduce C-SWaP of LPAI technology while maintaining high performance. Significant investments over a decade allowed us to research relevant technologies, such as compact LPAI prototypes designed for dynamic environments [JL21], many-atom LPAI simulations and feedforward schemes for an atomic accelerometer in dynamic environments [DBSS20], high data-rate LPAI approaches [HM12, AR14], low-SWaP passively pumped vacuum package technology [BL21], and PIC-based laser system architectures [AK19, JL21]. Among these on-going efforts, we highlight the PIC-based laser system as the critical step toward deployable high-sensitivity LPAI-based sensors, operable as gravimeters, gravity gradiometers, accelerometers, and gyroscopes, in space observatories and spacecraft navigation. The PIC-based laser architecture brings the potential of extreme miniaturization and a low-cost scalable approach and will be impactful across multiple application sectors beyond the needs space applications. The goal of PICASSO is to advance PIC-based laser system using silicon, III-V material, and nonlinear photonic platforms. **Through PICASSO, we will find optimal PIC laser system solutions for compact and low SWaP atomic sensors for space applications** (e.g., current laser systems: ~$200k, 1-2 kW based on the same laser architecture, and 8 Cu ft; advancement with PIC-based laser system: mass-producible, cost per chip < $1k, < 100W, and < 0.01 Cu ft). We also identify the need for **the functional validation of specific PIC sub-components with atomic sensors, and reliability improvements in the packaging of PIC chips.**

Atom Interferometry

The LPAI (Fig.2) is a highly promising, quantum sensing technology for inertial navigation and gravitational wave detection, which has been demonstrated in the laboratory with unprecedented sensitivities in the laboratory [TG97, SD13, PA20, CGA19]. The acceleration measurement of an LPAI can be modeled as laser ranging of cold atoms in free fall (Fig. 2). Imagining that the wavefront of the light pulses is analogous to the tick marks on a ruler, one measures path curvature (acceleration) using three light pulses that interact with the atoms. Intrinsic accuracy is achieved due to the wavelength stability of the laser (exceeding 10^{-9}) and the identical properties of the atoms. The ranging is accomplished with two phase-coherent Raman laser fields that couple two electronic states of the atom. The acceleration value is encoded in the probability of atomic population. During the atom interferometry operation, the LPAI laser system must laser cool and trap roughly a million atoms at a sufficiently low atomic temperature, prepare their atomic state, perform the LPAI light-pulse sequence with the Raman beams, and detect the atomic state, reading out the atomic interference fringe sensitive to inertial forces.

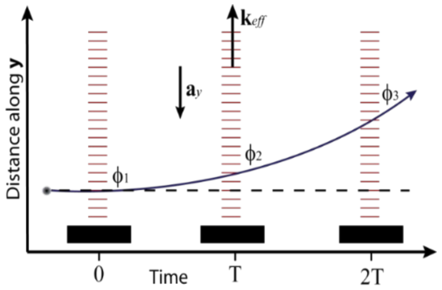

Figure 2. The concept of the LPAI accelerometer. Optical wavefronts (red) act as ruler tick marks to stroboscopically measure the position/phase of a free-falling atom at three points in time when the platform is accelerating, a_y.

Technical Approach

In PICASSO, we will ***advance PIC-based laser architecture*** for space-based atom interferometry by optimally configuring multiple state-of-the-art integrated photonics technologies.

This effort can reduce the C-SWaP of the sensors and achieve the required sensor performance for space missions. Through PICASSO, first, we will perform ***the functional validation of a multi-channel PIC chip for photonic device demonstration and high-sensitivity LPAI operation***. Second, we will pursue ***the reliability improvement of PIC chips*** through low-loss optical packaging and vibration/shock/radiation tests for space applications. These efforts will provide the progress needed to close the gap between the promise of extreme miniaturization with PICs and today's reality and demonstrate LPAIs with high sensitivity using mass-producible PICs suitable for scaling LPAIs. Our general-purpose PICs for atomic sensors will save time and cost through "rapid prototyping" to develop compact laser systems to miniaturize various atomic sensors, e.g., gravimeter, accelerometers, gyroscopes, gravity gradiometer, magnetometers, and clocks, including applications of optical communication and light detection and ranging.

We suggest following three laser system approaches: (1) converting a 1560-nm master laser to multiple 780-nm optical channels, (2) a 780-nm master laser to multiple 780-nm channels, or (3) hybrid optical interconnecting between multiple PIC chips. In a complete PICASSO effort, we would consider laser integration as well.

1560-to-780-nm Approach

This approach is assumed to use ^{87}Rb atoms (780 nm) for the atomic sensors. This frequency-doubling scheme is composed of silicon photonic light modulators at 1560 nm, III-V compound semiconductor optical amplifiers at 1560 nm, and nonlinear photonic frequency doublers to convert 1560 nm to 780 nm, as shown in Fig. 3 (a). Multi-channel, active laser-frequency control components can simultaneously demonstrate laser cooling, state-sensitive detection, and LPAI interferometer function together with optical amplification and frequency doubling. The frequency synthesis mainly happens at 1560 nm because silicon photonics are operable at this wavelength. The mass-producible CMOS fabrication process allows the reliable and mature silicon photonics platform, which covers single sideband and phase modulators, amplitude and phase control with thermal phase shifters, Ge photo detectors to monitor light intensities, and optical filtering. These integrated photonic modules developed at telecom wavelengths would be attractive across a broad market in optical communication and sensor industry. In addition, a commercially available 1560 nm fiber-laser shows the state-of-the-art performance in terms of a laser linewidth, an optical signal-to-noise ratio, and laser frequency drift, and it is a good seed laser, although an integrated laser source is ideal and is a long-term goal.

The first PIC component is a silicon photonic single sideband modulator (SSM) PIC. A single chip has four optical channels, and the SSM in each channel can time-multiplex the optical frequency. Each optical channel works as follows: (1) master laser locking to an atomic transition, (2) Doppler and sub-Doppler laser cooling and initial state preparation, (3) repump, detection, and the first Raman beam, and (4) the second Raman beam. The SSM is made with a dual-parallel Mach-Zehnder interferometer architecture and four silicon photonic phase modulators [CD12], where the optical carrier is suppressed and either the positive or negative first-order sideband is selected

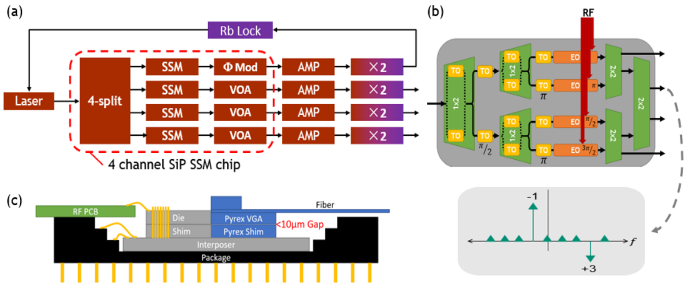

Figure 3. (a) The 1560-to-780-nm approach for LPAIs including a 1560-nm laser, a multi-channel SSM PIC (red dashed box), amplifiers, frequency doublers, and a laser lock module. (b) Diagram of a SSM PIC including thermo-optic (TO) phase shifters and electro-optic (EO) phase modulators. (Inset) Diagram showing the ideal SSM spectrum where all tones are suppressed except the -1 sideband (the desired tone) with an unavoidable residual +3 sideband. (c) Optical packaging of Si SSM PIC with a RF PCB board and a fiber-coupling array.

(Fig. 3 (b)) [AK19]. The frequency of the RF input determines the offset of the first-order sideband, and with the various functions of the LPAI being performed sequentially, the frequency of the RF can be rapidly switched to move to the required optical frequency.

The second PIC component is a III-V compound semiconductor optical amplifier (SOA), i.e., a monolithic, multi-stage InP-based high-power amplifier (> 500mW) to provide enough power for efficient frequency doubling. The third PIC component is a nonlinear photonic frequency doubler made of thin-film lithium niobate. In our most successful frequency doubling approach, our University of California San Diego collaborators implemented an etched thin-film lithium-niobate frequency doubler with world record efficiency [JZ20], which now needs to be heterogeneously integrated with our SSM PICs [PW18, NB20].

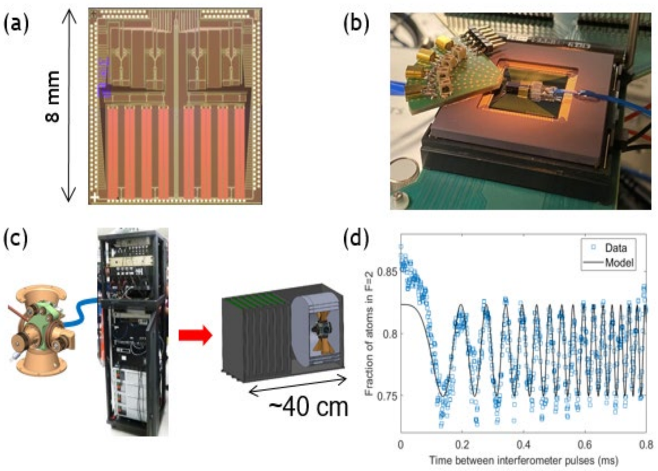

Figure 4. (a) 4-Ch SSM PIC design (silicon photonics, 8 mm x 8mm). (b) Fully packaged SSM PIC. (c) Vision of PIC technology. (Left) A LPAI inertial sensor with the commercial-off-the-shelf (COTS) laser system (19'' rack) to (right) a compact LPAI sensor with PIC technology. (d) First LPAI demonstration with two counter-propagating Raman beams generated from a SSM PIC. The data show the fringes of the LPAI as the atom interrogation time

In LPAI operation, high optical power (> 500 mW) of light at 1560 nm must be supplied to the input of the frequency doubler to generate sufficient 780-nm light (~ 100 mW). In our previous work, a multi-stage SOA was made of monolithic InP-based PICs to facilitate high gain and high saturation power, but the approach is difficult (but possible [JD20]) to integrate with the SSMs and frequency doublers with low loss. An alternative approach is to utilize coherent arrays of lower-power hybrid Si/III-V amplifiers, with phase adjustments to maximize power combining, to achieve high amplified power (up to ~1 W) and integrate this with silicon photonics (e.g., the SSM). This hybrid approach with silicon photonics and III-V photonics is being explored in the DARPA LUMOS HIGHP (Heterogeneously Integrated Gain for High Powers) program at Sandia, which includes a narrow-linewidth hybrid Si/III-V laser at 1560 nm, a hybrid SiN/$LiNbO_3$ modulator at 1560 nm, and coherent arrays of hybrid Si/III-V amplifier at 1560 nm. The work in HIGHP is complementary our previous work, advancing different PIC components of an LPAI laser system.

780-nm Direct Approach

This approach is to directly modulate the 780-nm light with precise frequency and timing controls to manipulate ^{87}Rb atoms to form the LPAI accelerometer. In an Air Force program, the 780-nm direct approach has been attempted using monolithic GaAs/AlGaAs platforms for III-V lasers, III-V quantum-well-based modulators, and III-V SOAs. Without multiple bonding operations, it is possible to integrate all the functions of lasing, modulation, and amplification on the same chip. The fabrication process of III-V material needs more custom and manual procedures compared to silicon photonics' automated CMOS processes. Risk mitigation can be achieved by utilizing a combination of hybrid boding techniques, although the downside will be a slightly larger system. In an internal program, a hybrid SiN/$LiNbO_3$ modulator at 780 nm has been used instead of III-V quantum-well-based modulators, and a SiN waveguide connects a III-V laser with the hybrid modulator.

While our focus has been on Rb, other atoms and other types of quantum sensors require different wavelengths. Lately, there has been work on developing custom integrated optics platforms at wavelengths of interest for quantum applications. Sandia has a second LUMOS program developing integrated photonics from 400 nm - 800 nm, which uses multiple III-V materials according to target wavelengths and epitaxial-layer transfer rather than hybrid bonding. There is also a piezoelectric silicon nitride platform at Sandia [PS19] that demonstrated modulation at 780 nm that may be extended to high frequencies. They may be viable to provide chip-scale solutions with lower power consumption in the future.

Hybrid Optical Interconnecting Approach and PIC Packaging

Heterogeneous integration between multiple integrated photonics technologies is still very challenging. In addition, the monolithic III-V approach also has limitation for mass-production. Alternatively, we can also optically interconnect different types of integrated photonics chips using polymer waveguides 3D-fabricated by direct laser writing. In the near future, sub-micron structures are planned using this technology. In the DARPA PIPES program, Sandia also tested the hybrid optical interconnecting approach between a VCSEL laser and a photonic chip with "optical wire bonds." Another approach is to fill the gap between multiple integrated photonic chips with polymer and perform direct-laser-writing of waveguides within the polymer for an optical interconnect. The successful development of reliable, low-loss optical interconnects would accelerate the development of chip-scale laser systems for atomic sensors with low cost analogous to electrically wired integrated-circuit chips on a PCB board.

Finally, we point out that PIC development has largely focused on developing the PICs themselves without substantial consideration of how to connect the PICs to where the light will be used, i.e. the atomic sensor. While the polymer interconnects are an exciting solution for inter-PIC connections, interfacing the PIC to the rest of the system must be developed and be part of the investment of PICASSO, focusing on low loss, vibration insensitivity, and system compatibility.

Summary

The realization of the PICASSO vision would enable a revolutionary size reduction for atomic sensors and would boost their rapid prototyping for space observatories and PNT applications. Such a chip-scale PIC-based laser system with low-loss and reliable optical packaging can be readily installed in a physical sensing system. We believe future research should focus on both the 1560-to-780-nm approach and the direct 780 nm approach. The technologies associated with the 1560-to-780-nm approach are more mature and should lead to fieldable systems in a shorter timeframe. The downside is the additional complexity and power consumption associated with frequency doubling. The direct 780 nm approach is less mature but is appealing because of the potential reductions in complexity and power consumption. The other critical areas of research are the hybrid integration of different PIC platforms with polymer interconnects being a possible solution for the overall PIC packaging and interface with the atomic sensor system. Finally, the PIC-based laser system must be validated in an LPAI system and studied for radiation hardness for the space environment. Our group has demonstrated the operation of an LPAI with a PIC chip. While the LPAI performance was initially limited, the demonstration shows the potential improvement in LPAI SWaP that is possible in a PICASSO approach for real-world space missions. Also, our initial studies of silicon PICs and III-V materials show promising results in radiation environments [KD19]. As shown in recent investments on PIC technologies for atomic sensors, PICASSO will be extremely compelling to customers concerned with precision inertial navigation applications without GPS aiding and will have application beyond atomic sensors in devices requiring precise control of light in a highly miniaturized package.

Bibliography

[AK19] A. Kodigala, et al., "Silicon Photonic Single-Sideband Generation with Dual-Parallel Mach-Zehnder Modulators," in *Conference on Lasers and Electro-Optics*, OSA Technical Digest (Optical Society of America, 2019), paper STh4N.6.
https://doi.org/10.1364/CLEO_SI.2019.STh4N.6
[AR14] A. V. Rakholia, et al., "Dual-Axis High-Data-Rate Atom Interferometer via Cold Ensemble Exchange," Phys. Rev. Applied **2**, 054012 (2014).
https://doi.org/10.1103/PhysRevApplied.2.054012
[BL21] B. J. Little, et al., "A passively pumped vacuum package sustaining cold atoms for more than 200 days," AVS Quantum Science, Volume 3 035001 (2021).
https://doi.org/10.1116/5.0053885
[CD12] C. T. DeRose, et al., "High Speed Travelling Wave Carrier Depletion Silicon Mach-Zehnder Modulator," SPIE, In Opt. Interconnects Conf., 135–136 (2012).
https://doi.org/10.1109/OIC.2012.6224486
[CGA19] C. L. G. Alzar, et al., "Compact chip-scale guided cold atom gyrometers for inertial navigation: Enabling technologies and design study," AVS Quantum Sci. **1**, 014702 (2019).
https://doi.org/10.1116/1.5120348
[DBSS20] D. B. S. Soh, et al., "Modeling of Atom Interferometer Accelerometer," United States: N. p., 2020. Web.
https://doi.org/10.2172/1670252
[GB15] G. Biedermann, et al., "Testing gravity with cold-atom interferometers," Phys. Rev. A, **91**, 033629 (2015).
https://doi.org/10.1103/PhysRevA.91.033629
[HM12] H. McGuinness, et al., "High data-rate atom interferometer for measuring acceleration, " Appl. Phys. Lett., **100**, 011106 (2012).
https://doi.org/10.1063/1.3673845
[JD20] J. A. Davis, et al., "III/V silicon hybrid laser based on a resonant Bragg structure," Appl. Opt. **59**, 4158-4164 (2020).
https://doi.org/10.1364/AO.390522
[JG16] J. R. Guinn et al., "The Deep-space Positioning System Concept: Automating Complex Navigation Operations Beyond the Earth," AIAA Space Forum 2016-5409.
https://doi.org/10.2514/6.2016-5409.
[JH11] J. M. Hogan, et al., "An atomic gravitational wave interferometric sensor in low earth orbit (AGIS-LEO)," General Relativity and Gravitation volume 43, 1953–2009 (2011).
https://doi.org/10.1007/s10714-011-1182-x
[JH16] J. M. Hogan and M. A. Kasevich, "Atom-interferometric gravitational-wave detection using heterodyne laser links," Phys. Rev. A 94, 033632 (2016).
https://doi.org/10.1103/PhysRevA.94.033632
[JL21] J. Lee, et al., "A Cold-Atom Interferometer with Microfabricated Gratings and a Single Seed Laser," (under review in Nature Communication in 2021).
https://arxiv.org/abs/2107.04792
[JZ20] J. Zhao, et al., "Shallow-etched thin-film lithium niobate waveguides for highly-efficient second-harmonic generation," Opt. Express **28**, 19669-19682 (2020).
https://doi.org/10.1364/OE.395545
[KD19] K. Dean, et al., "", conference: GOMACTECH (2019).
https://www.osti.gov/servlets/purl/1592290
[NB20] N. Boynton, et al., "A heterogeneously integrated silicon photonic/lithium niobate travelling wave electro-optic modulator," Opt. Express **28**, 1868-1884 (2020).
https://doi.org/10.1364/OE.28.001868

[PA20] P. Asenbaum, et al., “Atom-interferometric test of the equivalence principle at the 10^{-12} level,” Phys. Rev. Lett. 125, 191101 (2020).
https://doi.org/10.1103/PhysRevLett.125.191101
[PS19] P. R. Stanfield, et al., “CMOS-compatible, piezo-optomechanically tunable photonics for visible wavelengths and cryogenic temperatures,” Optics Express Vol. 27, Issue 20, pp. 28588-28605 (2019).
https://doi.org/10.1364/OE.27.028588
[PW18] P. O. Weigel, et al., "Bonded thin film lithium niobate modulator on a silicon photonics platform exceeding 100 GHz 3-dB electrical modulation bandwidth," Opt. Express **26**, 23728-23739 (2018).
https://doi.org/10.1364/OE.26.023728
[SD13] S. M. Dickerson, et al., “Multiaxis Inertial Sensing with Long-Time Point Source Atom Interferometry,” Phys. Rev. Lett. **111**, 083001 (2013).
https://doi.org/10.1103/PhysRevLett.111.083001
[TG97] T. L. Gustavson, et al., “Precision Rotation Measurements with an Atom Interferometer Gyroscope,” Phys. Rev. Lett. **78**, 2046 (1997).
https://doi.org/10.1103/PhysRevLett.78.2046
[YE20] Y.A. El-Neaj, et al., "AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration in Space," EPJ Quantum Technol. 7, 6 (2020).
https://doi.org/10.1140/epjqt/s40507-020-0080-0