Sub-mm Scale Fiber Guided Deep/Vacuum Ultra-Violet Optical Source for Trapped Mercury Ion Clocks

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BIOGRAPHIES

Lin Yi received the Bachelor degree in Electronics (2003) and Doctorate degree in radio physics (2009) with honors from Peking University, Beijing, P. R. China, where he worked on ultra-cold atoms, vapor-cell atom and molecule spectroscopy and femtosecond optical frequency comb. 2009-2011, he worked as a postdoctoral researcher on mercury optical lattice clock at Observatoire de Paris (French national metrology laboratory). Dr. Yi and his colleagues, for the first time, determined the "magic" wavelength and carried out the first precision spectroscopy in the Lamb-Dicke regime of mercury lattice clock. In 2011, he briefly worked as a visiting scholar on In+/Yb+ trapped ion(s) clock at Physikalisch-Technische Bundesanstalt (German national metrology laboratory). Dr. Yi was involved in the concept formulation and setup of experiment apparatus, which enabled the first observation of symmetry breaking and topological defect formation in ion coulomb crystals. 2011-2013, he worked as a NASA postdoctoral fellow at NASA Jet Propulsion Laboratory/California Institute of Technology, with subjects of Hg+ trapped ion spectroscopy and capillary mercury micro-plasma optical source for trapped ions. Currently he is a member of technical staff at Jet Propulsion Laboratory/California Institute of Technology and his main research is optical system development, spectroscopy experiments, and characterization of the mercury ion clock against other ground-based clock sources. Dr. Yi is a reviewer for OSA, IOP, AIP and IEEE journals.

Eric Burt was born in Berkeley, CA, in 1957. He received a B.S. degree with honors in mathematics from the University of Michigan, Ann Arbor, MI, in 1979, an M.S. degree in physics from the University of Washington, Seattle, WA, in 1990, and a Ph. D. degree in physics from the University of Washington in 1995. His Ph. D. thesis was in experimental atomic physics on the trapping and laser-cooling single indium ions. From 1995 to 1997, he was a postdoctoral fellow at the University of Colorado in Boulder, co, working with Carl Wieman and Eric Cornell on experiments with Bose-Einstein condensates including the first experiment to demonstrate a dual-species condensate and the first experiment to demonstrate higher-order (laser-like) coherence in condensate atoms. From 1997 to 2001, he worked at the U.S. naval observatory in Washington, D.C., developing a laser-cooled cesium fountain atomic clock. From 2001 to the present, he has worked at the Jet Propulsion laboratory (JPL), California Institute of Technology as a senior member of the technical staff. His work at JPL has included development of both ion and laser-cooled neutral atomic clocks and the use of atomic clocks to place limits on fundamental constant variation. Dr. Burt is a member of the American Physical society and the IEEE. He is on the technical program committee for the IEEE Frequency control symposium and on the steering committee for the APS Topical Group on Precision measurement and Fundamental constants.

Shouhua Huang (Senior Member, IEEE) received the M.E. degree from the Wuhan Research Institute of Posts and Telecommunications (WRIPT), China, in 1986 and the Ph.D. degree from Beijing University of Posts and Telecommunications, China, in 1992, both in electrical engineering. From 1980 to 1983, he was with a laboratory of the Ministry of Aeronautics and Space of China for microwave research. From 1986 to 1988, he performed high-speed coherent optical transmission research at WRIPT. From 1992 to 1995, he was with Tsinghua University, China, and the University of Southern California (USC), performing research focused on ultra-long-haul (9000 km) DWDM optical communication technology and systems. After developing several product families for two optical communication pioneer companies, he joined the Jet Propulsion Laboratory as a Senior Member of Engineering Staff in 1999. His current research interests include high-stable photonics transmission systems and ultralow-phase-noise photonic microwave oscillators. He is author or coauthor of more than 90 journal papers, conference proceedings, and invited papers. He is a Technical Reviewer of several journals of the SPIE and OSA. Dr. Huang has held 5 U.S.

patents. He received 3 NASA Space Act Awards and 3 NASA Group Achievement Awards.

Robert L. Tjoelker was born in Bellingham, WA. He received degrees in architecture, physics, and mathematics from the University of Washington in Seattle and the Ph. D degree in physics from Harvard University, Cambridge, MA, for a precision comparison of the proton and antiproton mass. From 1985 to 1990, he was an inaugural member of the Trapped antiproton collaboration (TRAP). From 1988 to 1990, he resided at the European laboratory for Particle Physics (CERN), where he performed a series of confinement, cooling, and precision measurements with antiprotons in an ion trap. In 1990, he joined the Frequency Standards Laboratory, NASA Jet Propulsion laboratory, California Institute of Technology, Pasadena. He currently is a principal member of the technical staff and technical group supervisor of the Frequency and Timing Advanced Instrument Development Group. He is involved in numerous time and frequency research and development activities with interests in the development of practical high-stability mercury trapped ion frequency standards, state-of-the-art clocks and timing, and reference distribution systems. His group leads and is responsible for the JPL Frequency Standards Test Laboratory, the NASA Deep Space Network Frequency and Timing System, and frequency and timing technology development, implementation, and characterization for the Deep Space Network and spaceflight. He has published more than 100 journal papers, conference proceedings, and invited papers in the areas of fundamental constants and atomic physics, precision trapped ion mass spectrometry, atomic frequency standards, and frequency and timing systems. Dr. Tjoelker is a senior member of the IEEE Ultrasonics, Ferroelectrics, and Frequency control society, a member of the American Physics society (DAMOP, FIAP, and GPMFC), the International Telecommunication Union UsWP-7a, the ION Precise Time and Time Interval systems and applications meeting (PTTI) committee, and the Technical Program committee of the IEEE Frequency control symposium.

ABSTRACT

We demonstrate the functionality of a mercury capillary lamp with a diameter in the sub-mm range and deep ultra-violet (DUV)/ vacuum ultraviolet (VUV) radiation delivery via an optical fiber integrated with the capillary. DUV spectrum control is observed by varying the fabrication parameters such as buffer gas type and pressure, capillary diameter, electrical resonator design, and temperature. We also show spectroscopic data of the 199Hg+ hyper-fine transition at 40.5GHz when applying the above fiber optical design. We present efforts toward micro-plasma generation in hollow-core photonic crystal fiber with related optical design and theoretical estimations. This new approach towards a more practical DUV optical interface could benefit trapped ion clock developments for future ultra-stable frequency reference and time-keeping applications.

INTRODUCTION

The mercury linear ion trap frequency standards (LITS) at NASA Jet Propulsion Laboratory have been demonstrated with applications in NASA deep space missions [1]. In particular, the long-term stability and practicality of the ground-based clock LITS9 [2] have attracted significant interests for ground-based time-keeping and metrology. However, the mercury RF discharge lamp and the associated optical design used in these clocks for optical pumping and detection may limit the short-term stability of the clock [3,4], which consequently constrains broader applications [5].

An increase of the VUV light output from the plasma discharge lamp light source used in trapped ion clock atomic state preparation and detection would improve the clock signal-to-noise ratio (SNR) and decrease optical pumping times. Both lead to an improvement in clock short-term stability and/or enable the use of a local oscillator having lower cost and performance.

In this paper, we demonstrate the functionality of sub-mm scale capillary mercury discharge lamps which are compatible with fiber integration for the LITS imaging system. DUV and VUV spectrum control effect is observed in these capillary lamps and physics explanation is provided. In addition, we present the effort of mercury discharge generation in hollow-core photonic crystal fiber (HCPCF), which may greatly enhance the DUV intensity than the traditional mercury lamps and the capillary lamps above. We propose to use these HCPCF lamps in future LITS systems and other lamp-based atomic frequency standards.

CAPILLARY HG LAMPS FIBER INTEGRATION

194nm VUV discharge lamps in LITS systems require bulky imaging optics systems to filter/reject the unwanted light emanating from the lamp. Reliable, smaller and longer life 194 nm light sources would benefit broad ion clock applications. Simpler light delivery mechanisms from the lamp to the trapped ions that do not compromise signal-to-noise ratio (SNR) would reduce size, complexity, and cost.

We present a novel approach to simplify the 194 nm light source and optical guidance in mercury LITS: Mercury plasma is generated in a capillary tube with a diameter of a few hundred microns (in contrast to current lamp bulbs with a diameter of 10 mm). The DUV/VUV light from the plasma is guided directly to the clock ions held in an ion trap in a vacuum system via a piece of DUV/VUV fiber fused at the end of the capillary tube.

Argon and mercury are prepared and sealed in a capillary tube with a diameter of a few hundred microns. The mercury plasma can be generated inside the tube with externally applied RF or microwave power. Inductive coils or surface strip electrodes can be used as a RF or microwave inductive/capacitive resonator to sustain the plasma. One end of the tube is sealed and the other end is fused with a piece of large-core DUV/VUV step-index fiber, where the DUV/VUV radiation from the plasma is collected. A gradient-index lens can be manufactured at the output tip of the fiber to deliver the condensed and quasi-collimated light to the ions. The fiber output can be brought close to the ion trap assembly and coupled via a DUV/VUV window or fiber feed-through. Alternatively the micro-plasma and delivery assembly could be placed entirely in the ion trap vacuum.

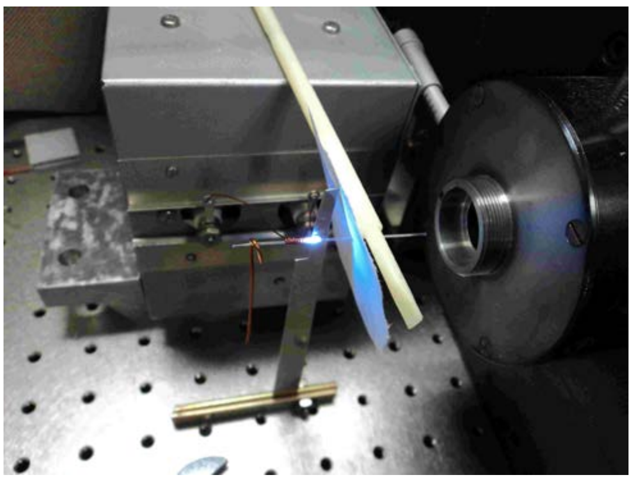

Fig.1. Sub-mm scale DUV/VUV plasma generation and integrated fiber light guidance. Mercury plasma (the bright blue light in the center of the photograph) is generated in a capillary tube with inner diameter of 250 micron. The capillary is fused with a DUV/VUV fiber to deliver light out to the right.

We use a DUV/VUV grating to separate the 194nm light from the rest of the lamp radiation. A photo-multiplier tube is used to record the DUV/VUV photon counts as a function of time. Our first capillary-fiber manifold is only filled with the saturation pressure of the metallic mercury rather than

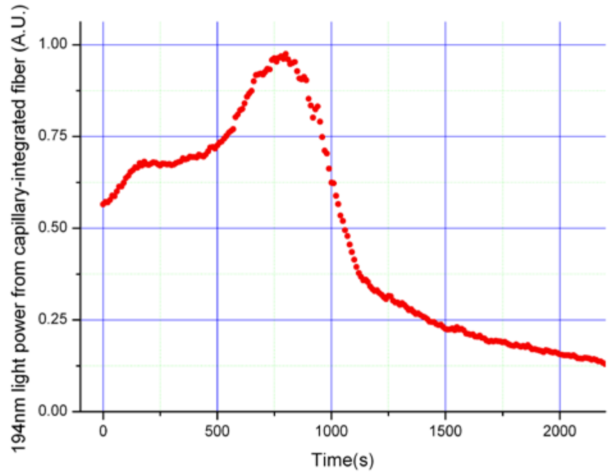

Fig.2. DUV/VUV radiation lifetime from a 250 micron diameter capillary tube integrated with a DUV/VUV fiber. (Lifetimes exceeding three years have already been demonstrated in larger mercury bulbs when fabricated with a macroscopic quantity of mercury.

directly sealing metallic mercury inside. As a result, the DUV capillary lamp has a short lifetime due to insufficient amount of mercury (see Fig.2). This phenomenon is well known in lamp industry and is well documented in the rubidium discharge lamp for rubidium atomic clocks [4]. DUV/VUV degradation of the fiber itself is ruled out by the specifications provided by the fiber provider [6].

DEEP ULTRA-VIOLET SPECTRUM CONTROL IN CAPILLARY LAMPS

The short-term stability of the clock is largely determined by the SNR, which depends on the optical spectrum quality of the 194 nm source. For this application, the spectrum quality is determined by the power ratio of the useful radiation from the Hg ions (194 nm) to the useless radiation from the neutral Hg atoms (254 nm) inside the bulb. Using the current lamp fabrication method at JPL, the 194/254 power ratio is only about 1/50 (Fig.3). To increase the ratio, it is necessary to apply additional spectrum filtering using DUV/VUV coatings, which may increase system complexity and cost. These coatings can also degrade with time when exposed to DUV/VUV limiting the lifetime of the instrument.

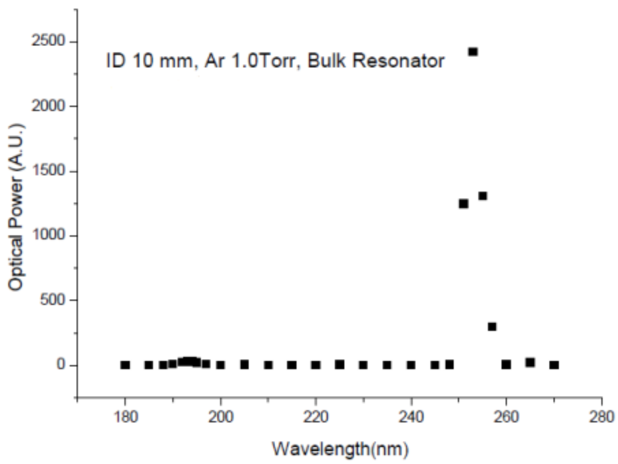

Fig. 3. DUV/VUV spectrum for lamps with 10 mm inner diameter and 1.0Torr argon buffer gas

We discovered that the 194/254 power ratio and the entire DUV/VUV spectrum from the lamp can be controlled by changing the diameter of the cylindrical bulb, the pressure of argon buffer gas and the configuration of related RF electronics. The results (Fig.4, Fig.5) show that we can reduce the need for optical coatings, simplify the optical system, and lower the cost of the clock without losing performance.

We have fabricated several cylindrical mercury lamps with different inner diameters (ID): 0.25 mm and 1 mm. A piece of DUV/VUV fiber is attached to the tube to deliver the light directly from the mercury plasma. The DUV light from the fiber is sent to a grating-based spectrometer to analyze the optical spectrum from 180 nm to 270 nm. The 194/254 power ratio increases dramatically in the capillary lamps compared to the 10mm lamps. We also fabricated several lamps with ID between 0.05mm - 1mm, which show similar results. Other factors such as wall temperature, the pressure of the argon buffer gas in the lamp and RF resonating electronics with different driving frequency and amplitude also affect the spectrum.

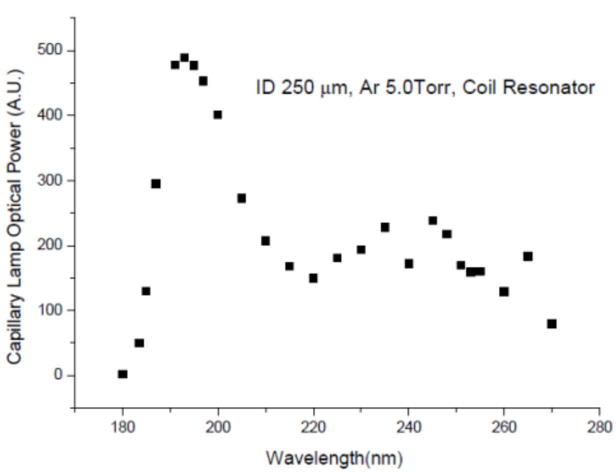

Fig. 4. DUV/VUV spectrum for lamps with 250 micron inner diameter and 5.0Torr argon buffer gas

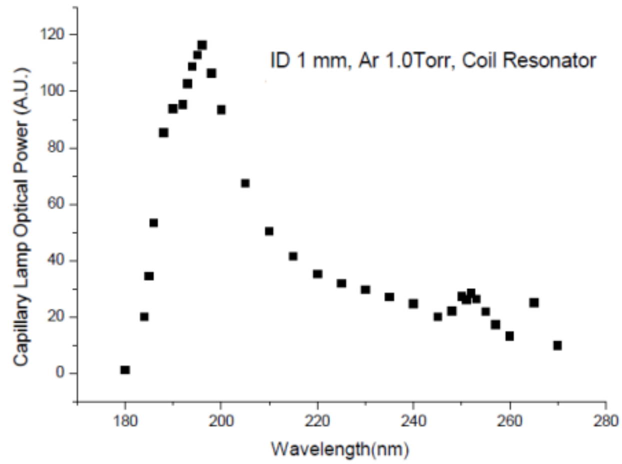

Fig. 5. DUV/VUV spectrum for lamps with 1 mm inner diameter and 1.0Torr argon buffer gas

Due to the complex physics in a multi-species RF discharge lamp, we provide here a simple qualitative explanation: According to well established lamp theory [7], the temperature of the electrons is inversely proportional to the square of ID, when the thermal equilibrium is established. Smaller ID lamps tend to need higher break-down voltage and more electrical power to sustain the plasma. The 194nm and 254nm radiation primarily result from inelastic electron collisions with mercury ions and neutral atoms respectively. As the electron temperature increases, they have a higher probability (than the case of lower electron temperature) to excite the ions to P state, where the ions radiate 194nm decaying to ground S state. In addition, recent study [8] shows that the sub-mm plasma (micro-plasma) may not reach thermal equilibrium during operation. The full quantitative physics picture of the micro-plasma dynamics, especially concerning the ionic and neutral atoms, is under investigation.

LAMP DESIGN IN HOLLOW-CORE FIBER

Argon discharge and ultra-violet light guidance has been successfully demonstrated in HCPCF in several groups [9][10]. Due to the difficulty of generating the 194nm DUV/VUV wavelength for the Hg+ clock, we first theoretically estimate the possible light intensity improvement provided by this new type of lamp.

For the capillary lamps, the effective collecting angle of the fiber decreases quickly as the length of the capillary increases. As a result, the total amount of collected light does not grow in proportional to plasma length increases.

We also designed a cone-based lamp, where a cone shaped waveguide is inserted into the glass capillary tube where the mercury discharge plasma is generated (cross-section shown in Fig.6). In this way, the cone collects light that fulfills the total-internal-reflection condition collecting more light than possible with only a capillary lamp. As the cone capillary length increases, there is additional attenuation for the VUV/DUV light propagating in the cone, depending on the glass material and ray path.

As for the HCPCF discharge lamp, due to the photonic band-gap (PBG) guiding effect provided by the grating-like micro-structure surrounding the hollow-core (Fig.7), light in the core can be collected along the fiber as long as the initial emission angle falls under the fiber numerical aperture (~0.2). The attenuation of light in the fiber is determined by the PBG guiding loss, which we assume a 1.5dB/m for most commercial HCPCF. A comparison of these three discharge lamp approaches is provided in Fig. 8. The HCPCF discharge lamp can provide at least 10 times more intense light than the traditional lamp.

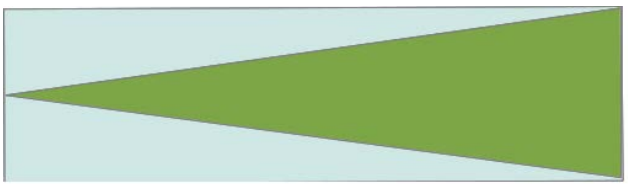

Fig.6. Cone lamp and waveguide cross-section. Light green/blue part is the inner volume of the capillary where the mercury discharge plasma is generated. The green part is the cone shape glass waveguide inserted into the capillary. The light is collected at the surface of the cone which is total-internally reflected and guided by the cone to the output plane on the right.

The HCPCF with low loss at the DUV/VUV wavelength is not currently commercially available. To study the principle, we present here a scheme for the light guidance of light from Hg-Ar discharge in the HCPCF at ~700nm:

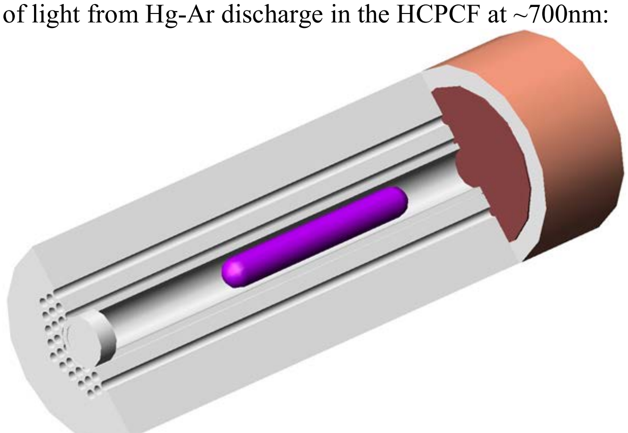

Fig. 7. Cross-section of a HCPCF mercury lamp integrated with a DUV/VUV fiber at one end. The purple part is the mercury micro-plasma. On the left side, the hollow-core is vacuum sealed by high temperature flame. Cross-section of the air-holes structure of the PCF is shown. The dark brown part on the right is the higher index layer of the DUV/VUV fiber, where the light is finally collected for output.

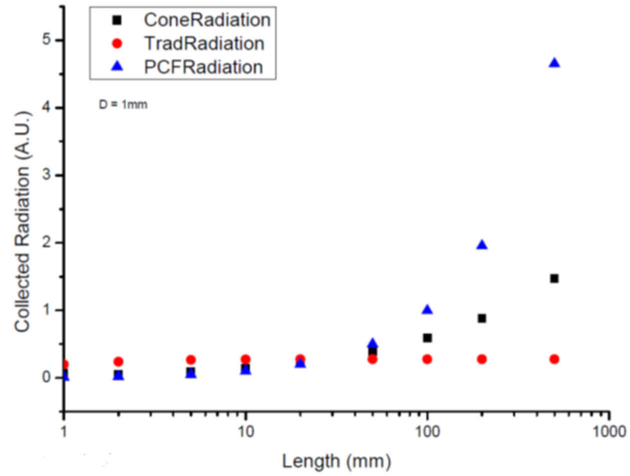

Fig. 8. Light comparison among the three types of lamps. TradRadiation (red solid round) is the capillary lamp, ConeRadiation (black solid square) is the cone based lamp, and PCFRadiation (blue solid triangle) is the HCPCF based lamp. The inner diameter containing the mercury vapor is set to be 1mm for simplicity.

As for the experimental effort, a piece of commercial HCPCF at visible wavelength is fusion-spliced to a broad-band fiber (extends to DUV/VUV) forming a hermetic seal on the output end. The other end of the HCPCF is attached to the UHV system with compatible vacuum glue. Mercury and argon is injected into the hollow core of the fiber, and an inductive resonator (coil) is wound around the HCPCF to generate RF gas discharge. Currently, we are able to generate the plasma at the entrance of the HCPCF, as shown in Fig.9 and visible light guidance is observed.

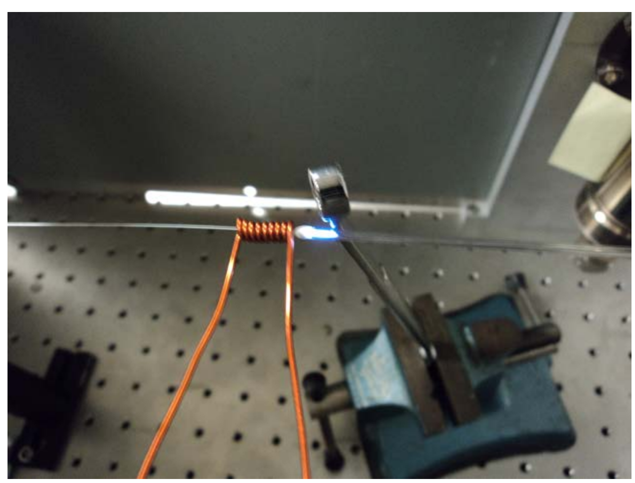

Fig.9. Plasma generation at the entrance of the HCPCF

The diameter of the hollow-core is ~5 micron, which is much smaller than the cases in [9][10]. The gas break-down voltage and the RF power to sustain the plasma are expected to be high. Large-core HCPCF with band-gaps at DUV/VUV wavelength is under investigation. This allows more light at the desired wavelength and requires lower starting voltage and sustaining RF power.

FIBER OPTICS-IONS SPECTROSCOPY

All the above lamps are related to fiber delivery. We present here trapped mercury ion spectroscopy with DUV/VUV fibers [11]. Ten pieces of DUV/VUV fibers with length of 1.5m couple the light from a traditional mercury lamp to the ions in a quadrupole ion trap. The light was imaged onto the group of fibers and then passed to the trap through the existing windows. The flexibility of the fibers allows the lamp to be positioned independent of the ion trap. A mercury ion clock signal using the fiber optic transported 194 nm light for optical pumping and state detection is shown in Fig.10.

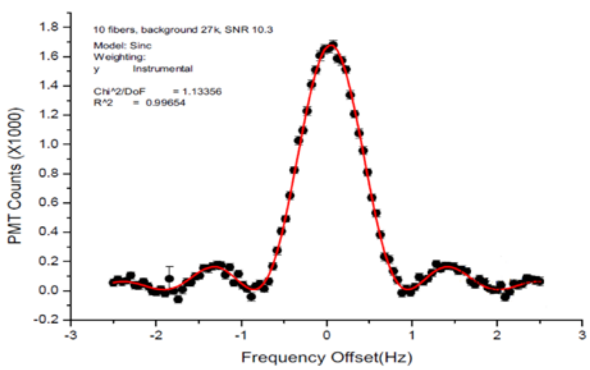

Fig.10. Microwave spectroscopy at 40.5GHz for trapped mercury ions when the 194 nm light is applied through fiber optics.

The SNR is about 10, which can be improved with more fibers. This demonstrates the functionality of the DUV/VUV fiber with existing ion trap system, whereas providing the flexible optical interface. A dedicated ion trapping system has been constructed for the fiber optics and the fiber compatible sub-mm lamps.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the experimental support from W. Diener, J. Gonzalez, R. Hamell, A. Kirk, and B. Tucker. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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