ULTRASONIC IONIZATION SPECTROSCOPY

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ABSTRACT

A QED cavity module driven at ultrasonic frequencies is presented having the objective to enable spectroscopy of a chemical sample over a continuous range of electromagnetic (EM) excitation frequencies from the infrared (IR) through the visible (VIS) and ultraviolet (UV) to the vacuum UV (VUV). Here, QED stands for quantum electrodynamics. The QED module comprises an evacuated gap between the face of a moving stainless steel (SS) piston and the inside surface of a stationary transparent glass window. SS is opaque from the IR to the VUV, while the glass is transparent in the VIS, but otherwise opaque in the IR and VUV. Lapping of the sample into the piston face and glass window surface was originally thought possible to achieve the high flatness necessary to produce VUV photons, the assessment of which is presented in this report. In operation, the IR radiation of sample atoms in the QED cavity surfaces for open gaps is freely emitted, but is suppressed as the gap closes. Suppressed IR is EM energy loss that is conserved with an equivalent gain at the resonant frequency of the gap, the process called cavity QED induced EM radiation. The sample is therefore excited continuously from the IR to the VUV, the VIS signature passing through the glass window to be recorded by a photomultiplier and spectrometer. The research is ongoing, and therefore this paper only gives the supporting theory with results that confirm that flatness by lapping of the piston face and glass window surface is not sufficient to produce VIS let alone VUV photons.

KEYWORDS: Spectroscopy, ionization, cavity QED.

INTRODUCTION

Emission spectroscopy from the IR to the UV relies on means to excite the atoms in a sample to Planck energy levels from 1 to 6 eV with emission occurring, the lines of the atoms, ions, or molecules leaving a signature from which the constituents of the sample may be identified.

In contrast, ionization spectroscopy requires excitation [1] to VUV levels from 7 to 11 eV. Typically, VUV levels are provided by subjecting the sample to high temperature and low

pressure, but equilibrium temperatures in excess of 80,000 degrees are required that precludes flame or discharge methods. Moreover, the samples are destroyed in the process, and therefore broadband light sources separated from the sample are favored, e.g., tungsten light bulbs and microwave resonant plasma reactors.

Conversely, cavity QED induced EM radiation [3] offers a simple means to perform VUV spectroscopy of a chemical sample at ambient temperature without the need for high flame temperatures or microwave reactors. The sample is affixed to the surface of a QED cavity made to open and close at ultrasonic frequencies, the sample originally thought to be lapped into the face of the piston and the glass window surface, the assessment of which comprises this report

By opening and closing the QED cavity, work is performed to raise the EM energy of the sample atoms to levels from the IR to the VUV. In effect, the IR radiation from the thermal kT energy of the sample at ambient temperature is used to excite itself to higher EM frequencies. The physics is basic. The IR radiation freely emitted from the sample atoms in the open QED cavity is suppressed as it closes. Suppressed IR is loss of EM energy that must be conserved by an equivalent gain elsewhere in the QED cavity, but the only admissible frequency is its EM resonant frequency which continuously increases, and therefore a continuous source of induced EM radiation at frequencies from the IR to the VUV is available to excite the sample. During QED cavity opening, the thermal kT energy of the surface atoms is rapidly recovered by conductive heat flow from underlying bulk, thereby allowing the IR radiation to once again be suppressed in the subsequent cycle as the QED cavity closes. Each cycle provides a discrete pulse of IR to VUV radiation, but by cycling the QED cavity between opening and closing at ultrasonic frequencies, the sample is effectively subjected to continuous source of cavity QED induced EM radiation to enable steady IR to VUV spectroscopy.

Cavity QED induced EM radiation is applicable to many situations where electrons, photons, or ions are observed at ambient temperature, e.g., static electricity [4], thermophotovoltaics [5], flow electrification [6], and space charge in solid insulators [7].

DESCRIPTION

The QED cavity comprises the gap between the face of the SS piston and a glass window surface as shown in Fig. 1. The piston face is circular with a diameter of 12.7 mm while the glass window is a plano-convex (PCX) lens 23.5 mm diameter x 38 mm focal length. The SS piston is driven by the head of Urawa Minitor Model UC550C/US55 ultrasonic polishing machine. The SS piston mass ~ 10 gm corresponds to that of the supplied Urawa polishing tools. The Minitor operates at 22.6 kHz with amplitude of 45 microns and can be varied in frequency ± 10 kHz about 22.6 kHz. The VIS signature escapes through the glass window to be recorded by a Canberra Industries, Model 2007 photomultiplier.

Unlike the IR to VUV irradiation of a sample by a laser through the light-beam path, cavity QED induced EM radiation is produced directly within the sample located in the QED cavity surfaces, and therefore there is no requirement to evacuate any air in the light-beam path. However, air and in particular nitrogen in the gap that is absorbent in the VUV acts to quench the cavity QED induced EM radiation in the sample located in the QED cavity surfaces, and therefore a vacuum pump Edwards, Type BC2511/12, capable of pumping to 10^{-2} mbar is provided to evacuate the QED module.

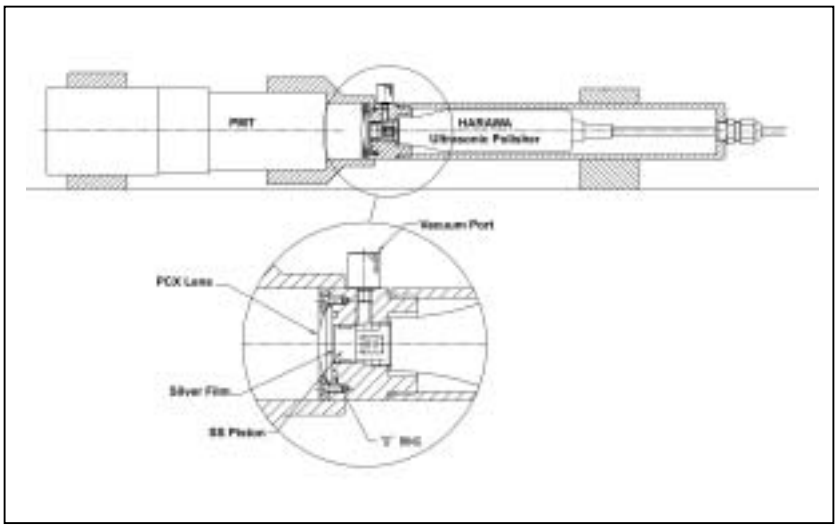

Fig. 1 *QED Cavity Module – Test Setup*

In cavity QED induced EM radiation, contact surfaces between the face of the SS piston and the glass window surface are required to be lapped very flat, say within 10 nm to achieve the VUV levels necessary to ionize the sample. For sodium light having a wavelength of 500 nm, the flatness of each surface must be held to $\lambda / 100$. But the surfaces at best can only be lapped to $\lambda / 10$, and therefore the ionization of the sample is unlikely over the full piston face.

One way to provide contact surfaces at the nano scale comprises applying 3M Silver Conductive Sheet® or Aluminum Conductive Tape® to the face of the SS piston as shown in Fig. 1. Like SS, both silver and aluminum are opaque from the IR to the VUV to avoid loss of suppressed IR radiation, but by being compliant compared to the SS offer the advantage of forming a matched contact surface to that of the glass window. However, the compliant silver or aluminum piston surface was not tested because the preliminary phase reported here sought the best possible lapped SS surface that would produce VIS and VUV photons. It was thought that even though the lapped SS piston surface was not of a high flatness, a limited number of VIS and VUV photons would still be produced adjacent the contact points.

THEORY

The QED cavity comprises the gap δ in the 1-D confined space between the PCX glass window surface and the SS piston face having a dimension $(\delta + 2\varepsilon)$ as illustrated in Fig. 2.

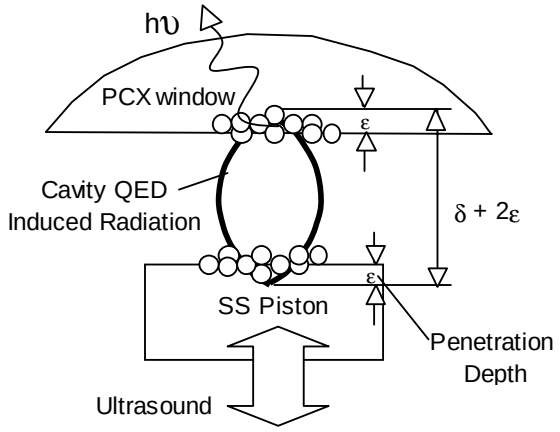

Fig. 2 *QED Cavity under Ultrasound*

The resonant frequency f of the QED cavity is,

$$f = \frac{hc}{2(\delta + 2\varepsilon)} \tag{1}$$

where, h is Planck's constant, c is the speed of light, and ε is the penetration depth of the EM radiation in the piston face and glass window surface.

Whether the frequency f of the QED cavity is sufficiently high to suppress the lower frequency IR radiation depends on the available average Planck energy E_{avg} of the harmonic oscillator [8] with wavelength λ shown in Fig. 3. At ambient temperature, most of the thermal kT energy of the atom resides at wavelengths λ > 100 microns. Thus, QED cavities having dimensions $(\delta + 2\varepsilon) > \lambda / 2 \sim 50$ microns do not suppress IR radiation. But QED cavity collapse, say to dimensions $(\delta + 2\varepsilon) < \lambda / 2 \sim 1$ micron corresponding to the NIR at λ ~ 2 microns, the full thermal kT energy of the atom may be considered suppressed.

Since all atoms in the penetration depth ε are contained within the QED cavity, the total suppressed IR radiation trapped in the atoms,

$$U_{IR} = 3\left(\frac{A\varepsilon}{\Delta^3}\right)kT \tag{2}$$

where, the number of degrees of freedom $N_{dof} = 3$, and the number N_A of atoms is $2A\varepsilon / \Delta^3$. Here, A is the contact area and Δ is the spacing between atoms.

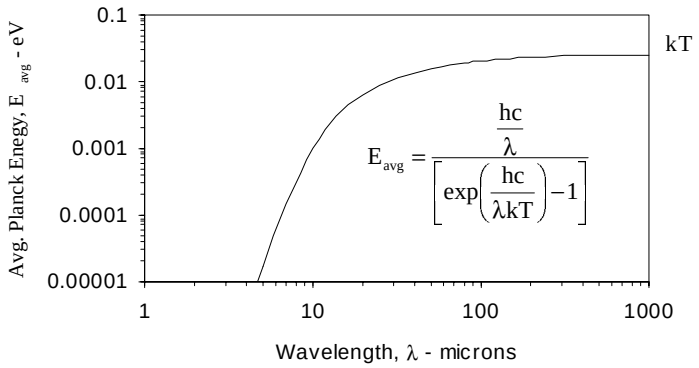

Fig. 3 *Average Planck energy of harmonic oscillator at 300 K.*
In the inset, k is Boltzmann's constant, and T is absolute temperature.

To conserve the EM energy loss by the atoms by suppressing the IR, the necessary equivalent gain occurs by the atoms undergoing frequency up-conversion to the EM resonant frequency of the QEDcavity. Over the area A, the number N of photons produced having Planck energy E is,

$$EN = U_{IR} = 3\left(\frac{A\varepsilon}{\Delta^3}\right)kT \tag{3}$$

The Planck energy E and number density N/A of photons is given by,

$$E = \frac{hc}{2(\delta + 2\varepsilon)} \quad \text{And} \quad \frac{N}{A} = \frac{U_{IR}}{AE} = 6\left(\frac{\varepsilon}{\Delta^3}\right)\left(\frac{\delta + 2\varepsilon}{hc}\right)kT \tag{4}$$

The Planck energy E and density N/A depend on both the gap δ and the penetration depth ε in the sample which for penetration depths of ε = 10 and 30 nm are shown in Fig. 4.

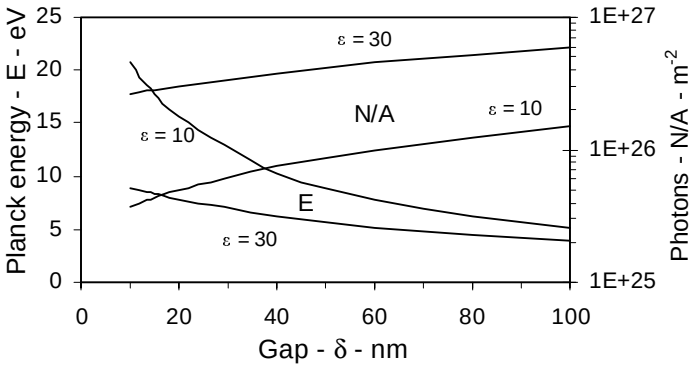

Fig. 4 *Planck Energy and Photon Density*

EXPERIMENTAL RESULTS

The QED module was tested in a darkened room at atmospheric pressure. Observations of the SS piston impacting the glass window for amplitude of 45 microns over a frequency range of 22.6 ± 10 kHz showed no VIS light emission. This is not an unexpected result as explained in the following discussion.

DISCUSSION

Flatness. The flatness of the lapped SS piston face was measured by counting fringes under a sodium lamp. For sodium light having a wavelength of about 500 nm, each fringe observed between an optical flat and the piston face corresponds to ½ λ ~ 250 nm. However, the lapping process could only achieve a flatness of the piston face of about 4 fringes, or about 1 micron. Moreover, the flatness of the glass window is only ¼ λ. Fig. 4 shows that VIS and VUV photons having Planck energies > 5 eV require the gap δ < 100 nm, and therefore the lack of VIS light emission in a dark room is not unexpected.

Transducer amplitude. The Urawa polisher limits the opening and closing amplitude of the QED cavity to amplitude δ ~ 45 microns. Fig. 3 shows the fully open gap every cycle is sufficient at $\lambda \sim 2\delta$ ~ 90 microns to recover the thermal kT energy of the surface atoms in the piston face and the glass windows. The thermal recovery is prompt [4] at about 2.5 GHz. Lack of VIS photons is not caused by unavailable thermal kT energy.

Atmospheric pressure. The presence of any gas or vapor in a QED cavity acts [2] to quench the EM radiation induced in the surface atoms. This would explain the lack of VIS photons. In the QED cavity module, however, there is another problem. Atmospheric air may not be removed at ultrasonic frequencies, and therefore VIS photons were not observed because gap closure was precluded within the required 100 nm as required in Fig.4.

Measurement of gap. Laser interferometer measurements of the gap between the SS piston face and the glass window surface under ultrasonic vibration were not measured, but are necessary to confirm proper operation of the QED cavity module.

EXTENSIONS

For the WESPAC IX meeting, the following results of the QED module as a method for IR to VUV spectroscopy are to be reported.

Compliant sample. For the QED module to produce Planck energies at VIS and VUV levels, the surface irregularities over the contact area are required to be matched at the nanoscale. One way is to apply [9] a compliant 3M Silver Conductive Sheet® or Aluminum Conductive Tape® to the SS piston face, the compliant sheet or tape forming a matched surface at the nanoscale upon repetitive contact of the SS piston face with the glass window surface.

Evacuated QED cavity. Performance of the evacuated QED cavity module.

Laser Interferometer. Verification of gap dimensions during ultrasonic vibration.

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