

LED deep UV source for charge management of gravitational reference sensors*

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Abstract

Proof mass electrical charge management is an important functionality for the ST-7-LTP technology demonstration flight and for LISA. Photoemission for charge control is accomplished by using deep ultraviolet (UV) light to excite photoelectron emission from an Au alloy. The conventional UV source is a mercury vapour lamp. We propose and demonstrate charge management using a deep UV light emitting diode (LED) source. We have acquired selected AlGaIn UV LEDs, characterized their performance and successfully used them to realize charge management. The UV LEDs emit at a 257 nm central wavelength with a bandwidth of ~ 12 nm. The UV power for a free-space LED is ~ 120 μ W, and after fibre coupling is ~ 16 μ W, more than sufficient for LISA applications. We have directly observed the LED UV light-induced photocurrent response from an Au photocathode and an Au-coated GRS/ST-7 proof mass. We demonstrated fast switching of UV LEDs and associated fast changes in photocurrent. This allows modulation and continuous discharge to meet stringent LISA disturbance reduction requirements. We propose and demonstrate AC charge management outside the gravitational wave signal band. Further, the megahertz bandwidth for UV LED switching allows for up to six orders of magnitude dynamic power range and a number of novel modes of operations. The UV LED based charge management system offers the advantages of small-size, lightweight, fibre-coupled operation with very low power consumption.

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(Some figures in this article are in colour only in the electronic version)

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1. Introduction

The Laser Interferometric Space Antenna (LISA) and Big Bang Observatory (BBO) are highly sensitive space-borne instruments requiring unprecedented precision. LISA and BBO measure the distances between proof masses up to $10 \text{ pm Hz}^{-1/2}$ from 0.1 mHz to 1 Hz, and $10 \text{ am Hz}^{-1/2}$ from 0.1 to 10 Hz, respectively. The gravitational reference sensor (GRS) is the core of these measurements [1–5, 16, 17]. The charge management system (CMS) is an important part of the ST-7 and LISA GRS [1, 6, 7].

Electrical charges may accumulate on the proof mass in a GRS due to ionization by deep space cosmic rays, electron migration via cold cathode emission and work function difference during proof mass and caging separation. The charged proof mass will be disturbed by the Lorentz force from the interplanetary magnetic field, and by the Coulomb force from the surrounding GRS housing electrodes. The basic function of the CMS is to remove the electrical charges from the proof mass, thereby reducing the acceleration noise due to spurious forces. The CMS is needed in ST-7, LTP, LISA, BBO, STEP, GRACE II and other missions relying on high precision measurement of proof mass position.

The photoelectric effect is the baseline method of altering the charge state of the GRS. To accomplish this effect, the surfaces of the sensor and the sensor housing must be illuminated with light of sufficiently high energy (short wavelength) to free electrons from both surfaces. If those surfaces are coated with a metal such as gold, then the wavelength of the light must reside in the lower end of the deep UV region (approximately 260 nm or shorter). Indeed, as demonstrated by the NASA/Stanford GP-B mission, photoelectron emission induced by deep UV light is an effective method for charge control on the superconducting gyroscopes [8, 9]. Led by this experience, LISA and its test flight LTP will also use UV light as the baseline design for charge management [6, 10–12].

The UV light source is the main component in the charge management system. Mercury lamps, a technology from the early 1900s, have been used in GP-B. These RF excited vapour lamps have several undesirable characteristics such as slow turn-on response, limited dynamic range, high sensitivity to temperature variations and limited lifetime. They are also significant sources of radio frequency interference (RFI) and electromagnetic interference (EMI), and their glass bulbs tend to be fragile.

Recently, we have identified a deep UV LED as the promising light source for charge management. We have acquired custom-made UV LEDs, conducted a series of characterization measurements and charge management experiments. We have directly observed the UV LED induced photocurrent response from an Au photocathode and Au-coated GRS/ST-7 proof mass. We have demonstrated fast switching of UV LEDs and associated fast changes in photocurrent. We have also demonstrated AC charge management, a new technique enabled by the fast switching capability of the UV LED.

Compared with mercury lamps, the UV LED-based charge management system offers the advantages of small size, being lightweight and low power consumption. The power savings created by the UV LED might allow enhancement of the LISA sensitivity by increasing the laser power for the interferometric measurement. The AC charge transfer technique, operating at higher frequencies, allows charge management to be performed outside the gravitational wave signal band, thus reducing the disturbances to the LISA science measurement.

2. Deep UV LED characteristics

LEDs are semiconductor devices emitting light via carrier recombination. LEDs are high efficiency, lightweight and easy to use. Recent developments in III-nitride compound

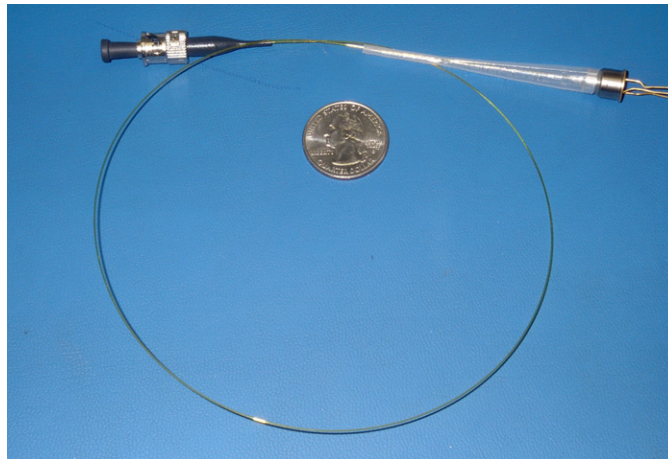


Figure 1. UV LED with fibre output. The UV LED is packaged in a TO-39 metal can. The fibre is terminated with an ST connector. The observed UV power centred at 257.2 nm is $\sim 16 \mu\text{W}$.

semiconductors have provided the material basis for a short wavelength LED. Nakamura realized the efficient blue InGaN LEDs in the mid nineties [13, 14]. Since then significant progress has been made to shorten the wavelength and increase the UV power. In the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ compound, the lower the Ga content and the higher the Al content, the shorter the wavelength. It is postulated that the shortest wavelength for an AlN only compound can reach 230 nm [15]. In 2001, 230–280 nm emission was observed from high-Al-content AlGaIn-based multi-quantum wells. In 2002, Sandia National Lab made an UV LED emitting at 275–290 nm with a power of 0.1 mW at liquid nitrogen temperature. Very recently, more studies have been accomplished in growth techniques in the AlGaIn material and in the geometric structure of UV LEDs. The latest research shows that AlGaIn-based UV LEDs can operate at wavelengths below 260 nm, at room temperature [15].

We worked with a supplier and performed the initial evaluation of the first batch of UV LEDs. The UV LEDs are packaged in both free space packaging in a miniature TO-39 can and in a fibre pigtailed version with an ST connector. A photo of the fibre-connected LED is shown in figure 1.

Similar to the characteristics of semiconductor devices, the lifetime for a visible LED is typically quoted at 100 000 hours by several vendors. Historically, the improvement of the lifetime of a new type of semiconductor device can progress rapidly after the operation demonstration. The initial operation of UV LEDs was limited to a flashing mode at liquid nitrogen temperature. However, the UV LEDs can now be operated as both pulsed and cw devices at room temperature for an extended period of time. The UV LEDs used in our experiment are among the first batches that could operate at room temperature, and there has not been enough lifetime data available for these newly emerged devices. We plan to further investigate the lifetime of the UV LEDs to ensure reliability for space flight.

Figure 2 shows the measured emission spectrum of these LEDs operated in a cw mode. The spectral emission is centred at 257.2 nm and the FWHM of the spectrum is 12.5 nm. The readout current is taken directly from a vacuum diode with the Au photocathode. This is strong evidence that the LED UV will work as a UV source for the charge management of a proof mass coated with Au.

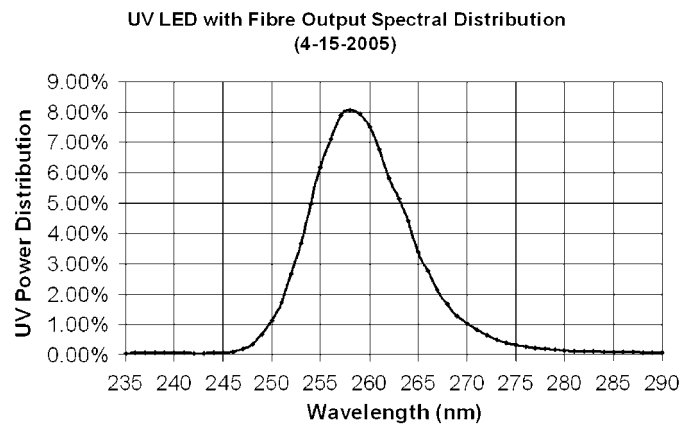


Figure 2. Measured emission spectra of the UV LED. The horizontal axis is wavelength, and the vertical axis is photocurrent reading from a vacuum photoelectric diode with Au as its photocathode. The wavelength is centred at 257.2 nm, and the full width of the half maximum is ~ 12.5 nm.

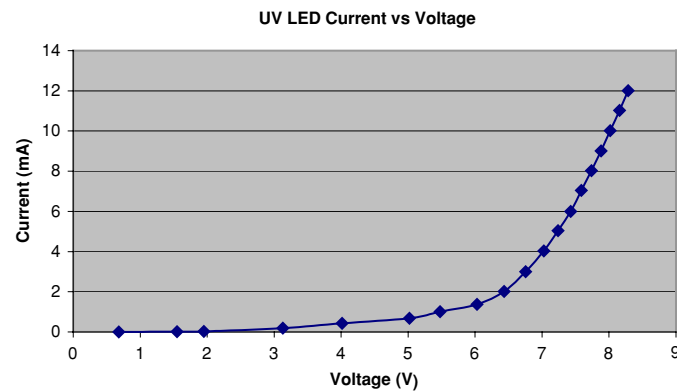


Figure 3. UV LED V - I curve. The horizontal axis is the drive voltage applied across the UV LED, and the vertical axis is the drive current passing through the UV LED. The LED emits sufficient UV light at ~ 5 V and 1 mA. The power consumption for the typical charge management task is 5 mW, and the maximum power consumption on this curve corresponds to ~ 100 mW.

The emission spectral measurement has also been performed by the LED laboratory using a calibrated optical spectrometer. The two measurements showed the same spectral shape, including the peak wavelength, the spectrum width and the spectral extent to shorter and longer wavelength.

We have tested two versions of UV LED: a free space UV LED with a flat window and a fibre-tagged UV LED coupled into an ST connector. The UV spectral shapes of the two detectors are identical. The UV optical power collected from the front window of the UV LED is approximately $\sim 120 \mu\text{W}$. The UV optical power collected at the fibre tip from the fibre-coupled LED is $\sim 16 \mu\text{W}$, which is much larger than the $\sim 0.3 \mu\text{W}$ requirement for ST-7 [10, 11].

Figure 3 shows the measured curve for LED drive voltage versus LED drive current, or the V - I curve of the UV LED. In our recent experiment, the UV LED is capable of handling AC charge management with only 1 mA current and 5 mW power consumption. The fully developed charge management system using a UV LED is estimated to have power

consumption of less than 1 W. Most of the power is required to support the electronics that drives and controls the LEDs. In contrast, the mercury lamp system may consume 12–15 W per unit [11].

The very low power consumption allows UV LEDs to be redundantly deployed, thus improving the reliability without exceeding the power limitation. Further, the lower power consumption on a spacecraft implies much easier thermal management for the 10^{-6} K stability required for LISA. One of the important consequences may be that the power can be redirected into critical applications such as increasing laser power for interferometric measurement. By replacing two mercury lamp systems with UV LED systems, a power reduction of ~ 28 W can be realized. If the satellite system design permits, the saved power can be applied to double the laser power from 1 W to 2 W, enhancing the LISA sensitivity by 41%, and detection volume and event rate by a factor of 283%. This is a significant scientific payoff.

The UV LEDs are packaged into standard TO-39 metal cans, with a maximum dimension of ~ 11 mm. The charge management system based on the UV LED will most likely have a dimension of $10\text{ cm} \times 8\text{ cm} \times 3\text{ cm}$. In contrast, the mercury lamp-based unit has a dimension of $17\text{ cm} \times 13\text{ cm} \times 17\text{ cm}$. The total weight of the UV LED charge management system is estimated to be less than 0.3 kg, compared with 3.5 kg of the mercury lamp CMS.

UV LEDs are intrinsically fast-response semiconductor devices. UV LED modulation is conveniently realized by modulating the drive current. We have tested UV LED modulation up to 10 kHz, limited by the bandwidth of the electronics driver. However, other experiments have shown that megahertz switching is possible for these UV LEDs. LEDs are widely used in short link optical communications with megabits per second data rate. Fast modulation of the UV LED enables many new techniques in charge management. We will describe in more detail an AC charge management experiment below.

The LISA mission will require nominal discharge rates on the order of tens to hundreds of electrons per second during normal operations. However when the proof mass is initially released or comes into contact with a surface, the discharge rate needed is on the order of one to ten million electrons per second. Unfortunately, most RF excited gas lamps are limited to a dynamic range of 10 to 100 falling considerably short of supporting the full range of approximately 100 000. This limitation requires the UV source to have multiple lamps with varying power output ranges to support the mission. The UV LED not only has the ability to vary the intensity, but can also vary the UV pulse width per bias cycle as well as the number of pulses per second. By varying these three parameters, the UV LED easily meets and exceeds the dynamic range requirement. In addition, the quick response of the UV LED allows the charge management system to reject abrupt variations in the incoming radiation flux to the sensor. We will further discuss the dynamic range advantage of the UV LED CMS in the AC charge management below. Table 1 shows the key comparisons of the UV LED versus RF mercury lamp.

3. DC charge management using UV LED

The DC charge management experiment is based on the GP-B and ST-7 charge control designs. The experiment verifies that the UV LED can be a direct replacement of the mercury lamps, given an identical GRS configuration. As we pointed out in previous sections, the simple replacement of mercury lamps with the LED will alone reduce the power consumption, heat generation and mass.

The proof mass in LISA is designed to have gold coating. The work function of Au is measured to be 5.2 eV along the [1 1 1] direction, converting to a wavelength of 238 nm for photoemission. However, the defects in the Au surface allow effective photoelectron emission

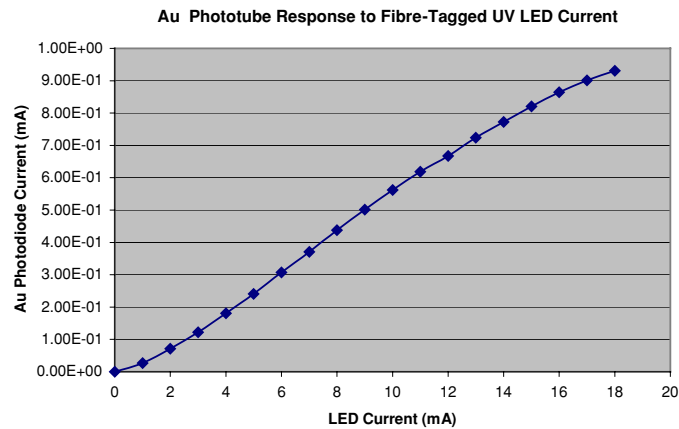


Figure 4. Photocurrent response from an amplified Au diode using the fibre-tagged UV LED as the light source.

Table 1. Comparison of UV LED and mercury lamp charge management systems.

Category	UV LED CMS	RF mercury lamp CMS
Electrical power consumption	1 W	15 W
Electromagnetic interference (EMI)	Minimal	Large due to RF excitation
Weight	0.3 kg	3.5 kg
Dimension of the CMS system	10 cm × 8 cm × 3 cm	17 cm × 13 cm × 17 cm
Volume of the system	240 c.c.	3757 c.c.
UV emission power	~120 μ W	~100 μ W
UV power at the fibre tip	~16 μ W	~11 μ W
UV wavelength, central	257 nm	194 and 254 nm
UV wavelength, spread	12.5 nm	Doppler broadening
Fast modulation capability	Easy implementation by direct current modulation—intensity, pulse train frequency and phase, over large parameter space	Possible but more difficult
Charge management method	AC and DC	DC (AC feasible but need demonstration)
Charge management frequency	Out-of-signal band	In-signal band
Equivalent dynamic range	100 000	100
Charge management resolution	High	Low
Charge management speed	High	Low

for incident light with wavelength at the 254 nm mercury line. We experimentally demonstrate that the continuum spectra of the LED centred at 257 nm are sufficient to excite photocurrent for charge management of Au-coated proof mass.

To directly observe the photoelectron effect from Au surface illuminated by UV LED output, we first measured the photocurrent response from an Au diode to UV LED emission. Figure 4 shows the measurement result. The photocurrent reading is comparable with the result using mercury lamp UV sources. For practical purposes, in the flight hardware design, we have used the UV LED drive current as a parameter for the horizontal axis. The system calibration for UV power input versus output of the pre-amplifier following the Au diode is $\sim 16 \mu\text{W mA}^{-1}$. Figure 4 shows that the light output from the UV LED can indeed effectively excite

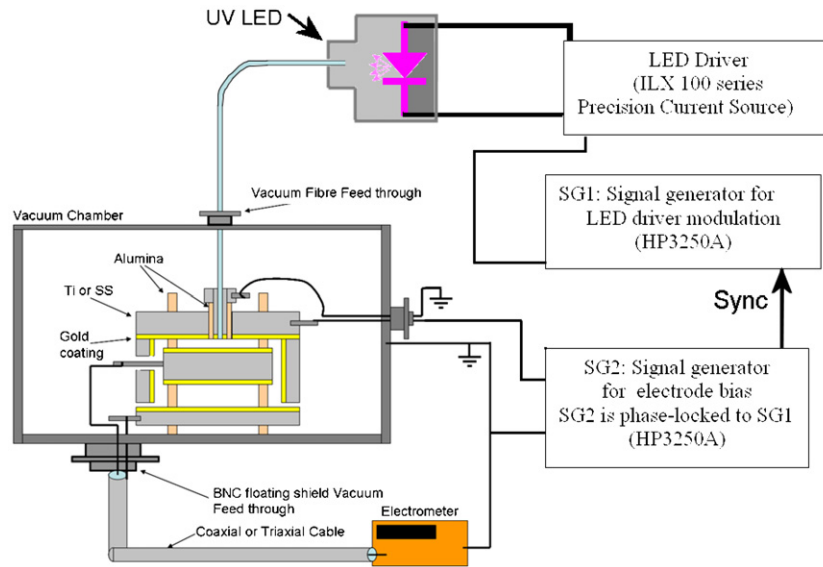


Figure 5. Experimental set-up for the UV LED charge management system experiment.

photocurrent from the Au surface. For a drive current of 10 mA, the UV LED delivers $\sim 3.6 \mu\text{W}$ equivalent power generated by a mercury lamp.

We further measured the photoelectric discharge rate versus the bias potential in the GP-B/ST-7 charge management set-up. As shown in figure 5, the experiment consists of illuminating two gold-coated electrically isolated surfaces. These two surfaces simulate the proof mass (sensor) and the sensor housing wall. The sensor facsimile is electrically connected to an electrometer grade current source, and the sensor housing wall facsimile is connected to a DC voltage bias source. A DC bias is applied while the UV source is turned on, and the current rate of the photoelectric effect is monitored. The measurement shows that the 15 W RF mercury lamp and the 5 mW UV LED produce comparable amounts of discharge current.

4. AC charge management experiments

AC charge management is convenient for implementation in the UV LED-based charge management system, thanks to the availability of direct current modulation of LED. The electro-optical modulation of a widespread spectrum of mercury lamp is not easy with the commercial laser electro-optics products designed for modulation of laser emission with a single wavelength. Further, the power modulation of an RF excited mercury lamp involves modulation of 5–15 W of RF power, which is more difficult than the modulation of several milliamperes of current. The UV LED enables modulating UV light at frequencies higher than the band of gravitational wave measurement. The AC charge management significantly reduces the disturbance to the proof mass, and is more suitable for recently proposed continuous discharge for LISA.

The AC charge transfer experiment consisted of modulating the UV light and the $\pm 0.6 \text{ V}$ electric bias at 10 kHz. The directionality of the charge transfer is controlled when the gold-coated surfaces are pulsed with UV light during a specific portion of the AC electric bias cycle. The total charge level on the proof mass was monitored by measuring the potential of the electrically isolated test mass ($Q = CV$). It was necessary to monitor the slowly varying

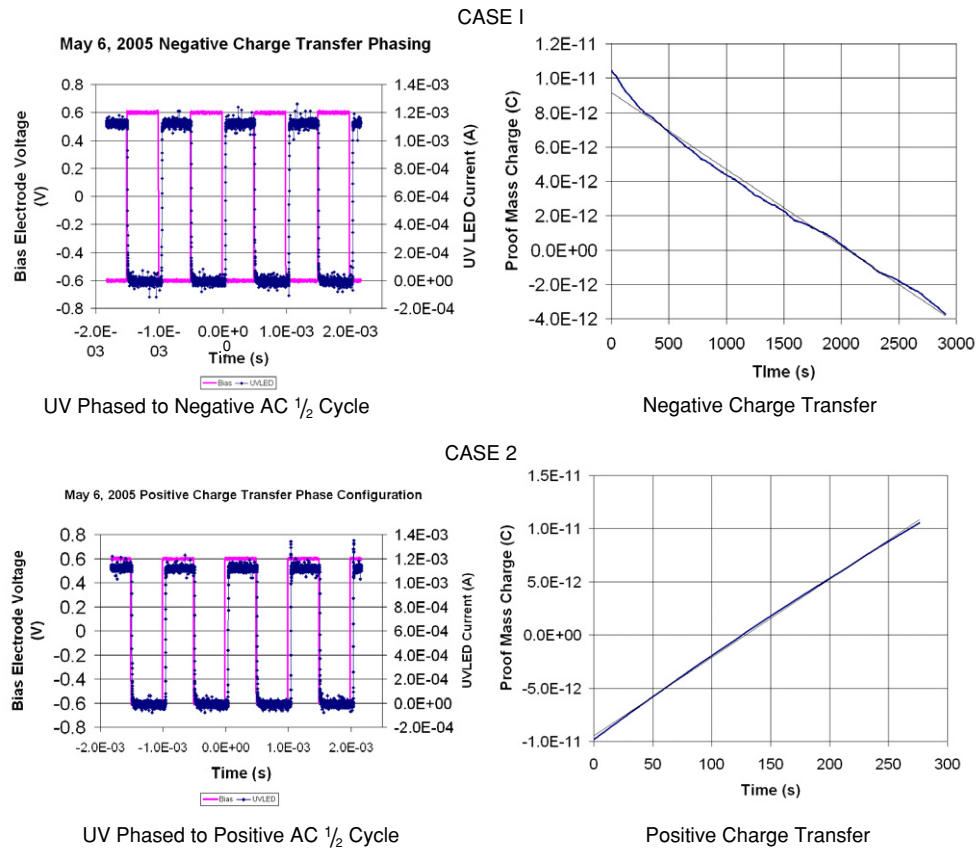


Figure 6. AC charge management experiment. The left-hand side figures illustrate phase control used to control negative and positive charge transfers. The noisier trace and less noisy trace on the left graphs are the driving signal for the UV LED and the electrode, respectively. The right-hand side figures illustrate the charge transfer direction.

total charge level of the proof mass since the electrometer grade equipment did not have the frequency response to directly measure the discharge rate of the 10 kHz pulsing UV light.

Figure 6 shows the AC charge management result. In case 1, the UV light is turned on when the AC electrical bias is in the negative half of the period. As a result, the electrons generated during that short period of time experience a negative bias that repels the electrons towards the proof mass, driving the charge negative. In case 2, the phase of the UV light is shifted 180° resulting in the electrons being attracted away from the proof mass, thus driving the total charge positive.

The successful verification of this technique directly enables two advancements in drag-free charge management. First, the application of any charge transfer bias can now be applied at frequencies that are orders of magnitude away from the frequency band of scientific interest. Second, this AC modulated electric field, when approximately 1 V in magnitude, enables the charge transfer of the proof mass to respond as a simple well-behaved integrative system instead of the long RC exponential decay observed, when low or no electric bias is applied.

The slow turn-on time of RF mercury lamps requires the UV source to operate continuously for tens to thousands of seconds; therefore, any electric bias applied to the system

must also be applied to same period of time. These pseudo DC electric fields unfortunately disturb the sensor in the science frequency band at low frequencies. The fast modulation capability of the UV LED allows the UV source to turn on and off within microsecond pulses. When these UV pulses are phased properly with a high frequency electric field, the charge level of the sensor can be altered with the same discharge rate performance of a DC field, but with the low disturbance effects of a high frequency AC field. Furthermore, modulation of the UV LED at the capacitance bridge frequency, with the phase adjusted as required, will completely remove the need for any charge management bias field.

5. Summary

The deep UV LED-based charge management system has substantial advantages over the more traditional mercury lamp-based system in three key areas: power efficiency, lower weight and flexible functionalities including AC operation out of the science measurement band. We are interested in further research on the UV LED-based charge measurement techniques, and development of a space-qualified system. The research will have significant scientific, technological and economical payoffs in LISA and BBO, and other precision missions such as LTP/ST-7, STEP and GRACE II.

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