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Adegbite Inioluwa Precious *

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Prospects of Quantum-Dots for Photo-Detection in LIGO and Other Interferometric Gravitational Experiments

Adegbite Inioluwa Precious

Affiliation; preciousadegbite44@gmail.com

ABSTRACT: Quantum dots are semiconductor Nano-structures with Optical or photoelectric properties and Quantum mechanical properties such as Quantum confinement due to the Nano-scale size of the molecular structure where Quantum mechanical effects are dominant. Because of its Optical properties Quantum dots have found applications in the development of future Solar cells and Photovoltaic detectors. The developments of these Solar cells and detectors are made possible through the use of Spray-coated layering of colloidal solutions containing the quantum dots forming what can be regard as thin quantum dot films, of which the compound thickness of all the layers is in nanometers. These quantum dots are capable of detecting a very wide range of electromagnetic frequencies and even single photon sources with very fast response time overall promising enhanced sensitivity. The features of quantum dots films gives them desirable advantages for detecting minute phase changes in Laser interferometric observatories such as LIGO which was designed and developed to detect gravitational waves coming from distant astrophysical sources. However the detection of low frequency gravitational waves with longer wavelength and those of much lower amplitudes have been rather elusive even with the high sensitivity of LIGO, as its usual Photodetector may not be sensitive to the interferometric phase changes due to gravitational waves of longer wavelengths and low amplitudes. As a potential means of improving phase change detection in LIGO, the use of quantum dots as photodetectors is conceptually proposed exploiting the fast reaction times and its sensitivity to wider range of frequencies. Whether it detects the interferometric phase changes induced by subtle amplitude or low frequency gravitational waves or not, it still promises an improvement to the detection capabilities of LIGO. Other interferometric gravitational experiments can also be performed, such as interferometric detection of Phase difference due to gravitational time dilation or gravitational redshift of light, using two laboratory interferometers one of which is positioned at sea level and the other at much higher altitude leading to a difference in gravitational potential. Together with the use of Quantum dot films as Photo-detectors one can detect the small interferometric phase difference between both interferometers due to Gravitational time dilation at different altitudes.

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Introduction

Gravitational waves [1–6] have long been hypothesized as ripples in spacetime according to Einstein's general theory of relativity. Their direct detection would provide significant addition to our understanding of the universe as a whole including some of the most energetic events in the universe such as mergers of black-holes and neutron stars. However detecting very subtle gravitational waves propagating at the speed of light is not a trivial feat.

The Laser interferometer Gravitational wave observatory (LIGO) broke new ground on the first successful detection of gravitational waves through very advanced Laser interferometry techniques, specifically the Michelson interferometer. It functions by splitting laser beams to perpendicular paths and then recombine them in a manner in that would produce a fringe at its Screen or detector, this

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allows any minute change in path length or phase changes to be detectable. Applying this to gravitational waves LIGO is then developed as a very large interferometer where each beams is at an arm of 4 kilometers in length, such that the passing of a gravitational wave would induce tiny contractions on the arms leading to minute phase change that is then detected using Photodetectors. While LIGO have made successful detections in recent years LIGO, it is however unable to detect gravitational waves of much lower frequency and amplitude as they only lead to interferometric phase changes that are below what current photodetectors may detect.

This shows that there is a need for Photo detection with greater sensitivity and faster response times for LIGO to overcome its limitations, allowing more unique gravitational waves signatures to be detectable.

There is also a possibility of performing the popular gravitational time dilation or gravitational redshift experiment using Michelson interferometer, which would also benefit from a more sensitive photo detection.

The prospective proposition of applying quantum dot films for photo detection presents a possibility of meeting the need for more sensitivity. Quantum dots possesses desirable Optoelectronic properties such as ultrafast response times and can be optimized to detect a wide range of electromagnetic frequencies, including single photon detection also LIGO currently uses an RF photodetector, but Quantum dots promises IR photo detection.

The tunable electromagnetic absorption spectrum property makes them appropriate for detection performing more efficiently at lower cost. The cost advantage comes from the cheaper manufacturing requirement based on the use of colloidal solutions of quantum dots.

LIGO: Background and Overview

The development of the very large scale laser interferometric gravitational wave observatory is motivated by the apparent goal of observing gravitational waves, a fundamental prediction of general relativity. As early as the 1968 Kip thorne initiated primary efforts on gravitational wave detection, later on at some time around the late 1960s Robert. L. Forward and some other scientists at Hughes Research laboratory built a prototype of an interferometer which could serve as a gravitational wave detector, this first prototype had mirrors mounted on a plate isolated from external sources of vibrations. However latter versions of this prototype were also developed in the 1970s this time the mirrors were not mounted on isolated plate but suspended, and isolated from vibrations. Works on latter prototypes are attributed to various scientists in various institutions, some of which includes Weiss (MIT), Heinz billing (Garching, Germany), Roland drevers & James Hough (Glasgow Scotland). In 1980s collaborations were made between MIT, Garching, and Caltech with many of the participating researchers who developed early prototypes involved. Continuous research and development were then made all through years that followed.

Between 2002 and 2010 LIGO [7–11] began initial operations, however no detections were made during these times. However by mid-September 2015 the Advanced LIGO began formal observation with quadrupled level of sensitivity of the initial LIGO interferometer.

Then came 11th February 2016, a paper was published announcing the detection of gravitational waves from a signal detected on 14th September 2015 of a black hole merger at about 1.3b billion light years from earth. Another signal was again picked up on 26th December 2015. A third detection was also announced on June 2017 of a detection on the 4th January 2017, the fourth detection was observed on 14th August 2017. All four detections were of black hole mergers.

LIGO can be described artlessly as a large scale Michelson interferometer but with more technical sophistication and a mission to detect gravitational waves. When gravitational waves gets to the interferometer, the geometry of spacetime experiences a very tiny length contraction leading to a minute change in length in the arms and consequently the beams of the interferometer causing the beams of light to become slightly out of phase which would reflect in the interference pattern that would be picked up by photodetector. To account for background noise the inner cavity of the arm is evacuated and the walls are made of noise cancelling material that should filter out noise from external vibrations, there are also other noise cancelling measures taken to ensure signals or data acquired from the photo detection have at least minimal errors.

Photodetectors

Photodetectors are of various forms, as long as they efficiently transduce electromagnetic energy and radiations to electrical energy. Classifications of photodetectors include;

- MSM photodetectors: a metal semiconductor metal sandwich, where the semiconductor layer is in-between the two metal layers.
- Photodiodes: this is the most common type of photodetector made with a PN junction, such that incident photons generates electron-hole pair in the depletion region of the junction thereby producing a current.
- Phototransistors: this is basically a transistor with a light sensitive base region and these incident light causes a change in the base current serving the purpose of amplification and detection.
- Charge coupled devices: CCDs are composed of tiny arrays of capacitors such that incident light generates electricity in the capacitors.
- CMOS: Complementary metal oxide semiconductor, popular for their low power consumption.
- Photomultiplier tubes: PMT these are photodetectors that uses vacuum tubes consisting of a photosensitive cathode that emit electrons when illuminated they are known to be highly sensitive.

Though there are other sensitive Photodetectors however the ones listed above are the more common ones, which are still used in current technologies requiring photosensitivity such as LIGO.

Quantum Dots for Photo-Detection

Quantum dots [16–19] have been developed for Infrared photo detection [12–15], the earlier developments of quantum dot photodetectors utilized more costly process of molecular beam epitaxy. The lattice mismatch results in accumulation of strain thereby by generating defects that restricts the number of possible layer stacking. However alternative droplets epitaxy growth techniques offered the advantage of strain free quantum dots. Later developments of a cost effective quantum dot production techniques based on wet chemistry and colloidal solution processing were then introduced, in which concentrated colloidal solutions containing nanoparticles are stabilized through the use of long hydrocarbon ligands that keeps the quantum dots being the semiconductor Nanostructures suspended.

For the solution to form a solid film the solution must be casted and crystallized on a substrate which is basically any solid base material onto which the solutions (or generally fluidic substance) is applied or deposited on, most preferably a smooth 2-dimensional surface. One simple method of deposition would be to spray coat the substrate layer by layer this allows a self-assembly of the nanostructures on the substrate, layer by layer. Crystallization then occurs when the solution is dried up such that we have a thin 2 dimensional self-assembled layered crystal structure of quantum dots with thickness being in nanometers. This thin layer of quantum dot crystal can then be considered a photosensitive film suitable for photo detection.

The size of the quantum dot determines the range of electromagnetic frequencies it can detect, and this is of merit because quantum dots are easy to grow to certain sizes of choice which in turn gives us power to tune the range of electromagnetic frequencies which the photodetector is capable of detecting. In addition, its quantum mechanical advantage provides speed up in its level of responsiveness to photon sources making it detect electromagnetic activities and changes that are very ephemeral. Another benefit it provides is its ability to detect even single photon sources.

These advantages are certainly worth considering for the enhancement of LIGO's sensitivity as very slight phase changes in the interference pattern which the quantum dots would pick up would not elude the detectors capability, depending on how we tune the quantum dots. This means that even as the gravitational waves of longer wavelengths and smaller amplitudes would cause very small interferometric phase changes that are not easily detected by regular photodetectors there is still a very good possibility that these phase changes would not elude quantum dot based photo-detectors.

Apart from just for photo detection these quantum dot films are applicable as photocells useful for harvesting energy from solar radiation. And it performs far more efficiently than usual photocells.

Interferometric Detection of Gravitational Redshift

Just as interferometry has been useful in the detection of gravitational waves it can also be useful in detecting gravitational redshifts and gravitational time dilation as phase differences between the interferometric patterns of both interferometers positioned at different altitudes where effect of gravitational potential would vary at each altitude as the gravitational red shifting of the beams of the higher interferometer would affect its phase differently than it would the interferometer at lower altitude. While the phase difference may be very small the use of quantum dot photo-detectors may help in making this difference much more detectable.

Conclusions

LIGO has broken new grounds and has had several improvements from prototypes to an Operational, and then to enhanced LIGO and Advanced LIGO followed by its successful detections from 2015 up to 2017 and was still Operational up to the period of the COVID-19 outbreak. However even with its success, it may also be capable of achieving greater level of sensitivity as more improvements are implemented.

One such improvement to LIGO may be the use of Quantum dots films for photo detection, enabling tunable sensitivity and detection of more subtle phase changes from gravitational waves of spectrums which are currently undetectable and the same applies for an interferometric detection of gravitational redshift. Overall the advantage of quantum dot photodetectors may be beneficial for improvement of LIGO's sensitivity and performance.

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