Proposed Ultra-High Sensitivity High-Frequency Gravitational Wave Detector

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(Four peer reviews of the manuscript follow – two for its initial presentation at the 2nd HFGW Workshop in September 2007 and two from different referees for the actual STAIF presentation and AIP Proceedings Volume in February 2008. All reviewers to whom the manuscript was sent were positive. The paper itself follows the peer reviews.)

Space Technology and Applications International Forum (STAIF-2008)

Peer Review Report

(Please Return ASAP – Guidelines Follow this Form)

Title of Paper: Proposed Ultra-High Sensitivity High-Frequency Gravitational Wave Detector

Author: R. M. L. Baker, G. V. Stephenson, F.-Y. Li Log Number: 011__________

Reviewer Name [redacted]________ Date Reviewed: 07/26/2007______

Reviewer's Phone # [redacted]______ Fax # [redacted]_______

Email [redacted]____________________

Review Checklist:

YES_ Is the technical treatment plausible and free of technical errors?

YES_ Have you checked the equations?

NO__ Are you aware of prior publication or presentation of this work?

NO__ Is the paper too long?

YES_ Is the manuscript free of commercialism?

Please give detailed reviewer comments below. Your review must include at least one paragraph of commentary on the technical merits of the paper or else it cannot be used as a qualifying peer review. A separate sheet of paper may be used if more room is necessary.

Review:

I recommend that this paper be accepted.

The authors describe a new concept that could dramatically improve the sensitivity of high-frequency gravitational wave detectors. The detector uses the well known Gertsenshtein Effect to generate photons from the interaction of incoming gravitational waves with a background electromagnetic field. The coupling between the incoming gravitational waves and background EM field generate the mixed-mode oscillating components of the field strength tensors at a resonant frequency which form the stress energy tensor that acts as the source of the outgoing photons. The authors propose to use sensitive microwave, single photon QED detector circuits or Rydberg atom cavity detectors to dramatically improve sensitivity. Also, exterior noise sources can be reduced by using fractal-membrane reflectors to focus the signal at the microwave detector, a mosaic of superconducting tiles or fractal membranes on the interior surface of the detector's cryogenic containment vessel. Internal thermal noise will be reduced by operating the system at < 48 mK. Other techniques will be used to amplify the signal and attenuate noise. It is anticipated that gravitational wave amplitudes ~ 10^{-32} to 10^{-34}, which is 12 to 13 orders of magnitude more sensitive than any of the genre of LIGO type ground detectors now in operation or the pending LISA detector yet to be built or launched into space.

The statement has been modified.

You refer to Figure 1 but it is not shown until two pages later. You do the same on the next page about citing figure 1.

You are quite right and the figure has been moved.

If I read the paper correctly, you are suggesting tracking gravity waves by tracking photons. This should be specified in an unambiguous fashion. Now since light is bent by gravitational fields, how do you prevent unwanted photons from entering the experiment? What if you count photons but the focus point moves and not observed by the photon counting sensor? What is "frequency ore waveform"...

As you have previously suggested we did not want to include even more detail concerning the detector since that was covered in the prior four STAIF papers. However we have attempted to concisely describe the suggested improvements.

What does the last sentence of the second paragraph in the second page mean?

It has been clarified.

Fourth paragraph: detector or receiver is will operate????

We have changed it to: "will be sensitive to"

NOISE SOURCES:

With the high Tesla field, what is the impact of a Faraday cage?

From Fig. 1, it can be seen that the magnet is within the Faraday containment vessel so that there is no impact of the high magnetic field. As you say we already may have too much detail so we have not added this caveat

You mentiuoned that the fractal membrane reflectors are tuned? How are they tuned?.

Tuning is a property of the fractal membranes. That property is described in the prior literature cited in our references and in some of the prior STAIF papers so, again, we did not want to over complicate the paper by describing it again.

In the paragraph after Figure 4, "These two openings.... is one long sentence that has uncertain meaning. Changer to two sentences and clarify what this means

Done.

Top of next page discusses the medium. Where is the medium located?

We have clarified this.

Next page.... tinny should be tiny. The term: "Beyond the scope of this analysis" is repeated many times.

Corrected – thanks.

What does the little paragraph after Figure 7 mean? Mistakes are in it.... At this point too many comments are repetituous especially in the next paraqgraph.

We have edited this.

These are simple fixes. Make these changes and get the paper into STAIF for publication.

REFEREE 2's SUMMARY OF PAPER 011

A design for an ultra-high sensitivity high-frequency gravitational wave detector has been exhibited that depends upon the inverse Gertsenshtein effect. It relies on new-technology, high-sensitivity microwave detectors, a very powerful microwave Gaussian beam and an extremely strong magnetic field. Greatly reduced noise is achieved by keeping the entire apparatus in a cryogenic containment vessel at a low temperature and introducing microwave absorbing structures internal to the apparatus to eliminate internal sources of background-microwave-photon noise. Fractal-membrane reflectors, tuned to the frequency band of interest, focus the detection photons, moving out normal to the axis of the Gaussian beam and the axis of an intense static magnetic field, on to two microwave detectors. The HFRGW detector is expected to be sensitive to relic gravitational waves exhibiting amplitudes, *A*, of the time-varying spacetime strains on the order of 10^{-30} to 10^{-32}. The development of the detector will also enable the study of HFGW signals produced artificially for a possible first HFGW communication test and subsequent applications. Data collected will be useful to assess the possible use of HFGW for space travel, by probing the possible existence of HFRGWs and determining their spectral energy density.

REFEREE 3

ABSTRACT:

The third sentence is too long. What does it mean?

Good point. The sentence has been broken down into three sentences and clarified.

INTRODUCTION:

This should tell the reader what the paper is all about. You missed the boat. For example, why pursue relic HFGWs vice regular HFGWs?

We have added material to more completely tell the reader what the paper is all about.

This section is extremely complex and some of the details is unnecessary; concepts being described would have been of more value.

The authors greatly sympathize with the reader (referee) who is not familiar with the literature relevant to the detector discussed in our paper. The relevant literature is, of course, given in the list of references. More importantly, however, the reader should become familiar with the four papers describing the detector (or its variations or as it is juxtaposed with different HFGW generators) presented at the three prior STAIF meetings (STAIF2005, 2006 and 2007). We have added this advice to our paper. Much of the of the "repetitions" and "unnecessary details" were added in response to a particular prior referee's being somewhat unfamiliar with the prior papers on the subject. Thus we tended to repeat details that would have been obvious from a reading of prior papers and related literature. Nevertheless, we have attempted to tighten up the paper and remove repetitions and as many details as possible.

You make the comment "especially true" comment about photons. Is that a true statement?

The statement has been modified.

You refer to Figure 1 but it is not shown until two pages later. You do the same on the next page about citing figure 1.

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If I read the paper correctly, you are suggesting tracking gravity waves by tracking photons. This should be specified in an unambiguous fashion. Now since light is bent by gravitational fields, how do you prevent unwanted photons from entering the experiment? What if you count photons but the focus point moves and not observed by the photon counting sensor? What is "frequency ore waveform"...

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REFEREE 4

1. There is a question whether or not the x-directed perturbative photon flux (PPF) really exists. Rough general relativistic calculations seem to indicate that an average over time results in non-zero for the PPF, but an average over space should be accomplished – possibly with another paper that addresses this issue only. Will do.

2. The perturbative photons appear to carry equal amounts of momentum in the +x and –x directions so linear momentum is conserved. It does appear that the torques at the fractal membrane reflectors also cancel out, but at some point this needs to be checked. Agreed

3.

. The perturbative photons also may carry noise from the interaction zone with them. What this means in the ability of the device to sense a graviton is unclear. Only in the most general sense does the detector involve the (inverse) Gertsenshtein effect. It does generate EM photons (PPF) in the presence of a static magnetic field and gravitons, but the concept presented here and in the papers by Li dating back to the early 1990s describes an entirely new theory involving an EM Gaussian beam and fractal-membrane reflectors. The surprising new concept seems sound in that PPF is generated along the x-axis not along the z-axis (assuming a y-directed magnetic field) into a relatively noise-free environment at the ends of the x axis. As I stated, my rough calculations show that the PPF photons are real not phantoms, are relatively noise free (true according to my calculations, but should be rechecked by the authors) and the detector should be quite sensitive, S/N greater than one, in the GHz band. The PPF itself is a pure signal and not noise or background. Since the PPF and the noise have very different physical behavior in some local regions no noise is carried along. Looking at it a different way, if there was a perfect vacuum, then since the intensity of the Gaussian beam (GB) falls off exponentially in the x-y plane, there would be some radial distance out from the GB axis where the background photon flux of BPF or noise would be less than the graviton-created photon or PPF (calculated to be about a meter out). In a realistically high vacuum there would be some intervening molecules or sources of scattering in the GB (BPF), but they would be finite in their extent and independent of the PPF whereas the PPF could be made as large as the intensity of the GB and the static magnetic field could allow and a S/N greater than one achieved..

4. In the actual experiment the noise of the device (detector) must be very carefully calculated so that any signal greater than this noise can be interpreted as due to the relic gravitons. These relic gravitons are theoretically sure to exist with $h = 10^{-30}$ m/m, so the detector must be that sensitive. Yes.

Over all the paper makes a valuable contribution to the field of GW detection and should be accepted.

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Abstract. The paper discusses the proposed improvement of a High-Frequency Relic Gravitational Wave (HFRGW) detector designed by Li, Baker, Fang, Stephenson and Chen in order to greatly improve its sensitivity. The improved detector is inspired by the Laser Interferometer Gravitational Observatory or LIGO, but is sensitive to the high-frequency end of the gravitational-wave spectrum. As described in prior papers it utilizes the Gertsenshtein effect, which introduces the conversion of gravitational waves to electromagnetic (EM) waves in the presence of a static magnetic field. Such a conversion, if it leads to photons moving in a direction perpendicular to the plane of the EM waves and the magnetic field, will allow for ultra-high sensitivity HFRGW detection. The use of sensitive microwave, single photon detectors such as a circuit QED and/or the Rydberg Atom Cavity Detector, or off-the-shelf detectors, could lead to such detection. When the EM-detection photons are focused at the microwave detectors by fractal-membrane reflectors sensitivity is also improved. Noise sources external to the HFRGW detector will be eliminated by placing a tight mosaic of superconducting tiles (e.g., YBCO) and/or fractal membranes on the interior surface of the detector's cryogenic containment vessel in order to provide a perfect Faraday cage. Internal thermal noise will be eliminated by means of a microwave absorbing (or reflecting) interior enclosure shaped to conform to a high-intensity continuous microwave Gaussian beam (GB), will reduce any background photon flux (BPF) noise radiated normal to the GB's axis. Such BPF will be further attenuated by a series of microwave absorbing baffles forming tunnels to the sensitive microwave detectors on each side of the GB and at right angles to the static magnetic field. A HFGW detector of bandwidth of 1 KHz to 10 KHz or less in the GHz band has been selected. It is concluded that the utilization of the new ultra-high-sensitivity microwave detectors, together with the increased microwave power and magnet intensity will allow for a detection of high-frequency gravitational waves (HFGWs) exhibiting amplitudes, A, of the time-varying spacetime strains on the order of 10^{-30} to 10^{-34}.

Keywords: High-frequency gravitational waves; HFGW, gravitational wave detection, relic gravitational waves, microwaves, electromagnetic detection, superconductors, fractal membranes.
PACS: 04.30.Nk, 04.30 Db, 04.80.Nn, 95.55 Ym, 95.85 Sz.

INTRODUCTION

The paper by Li, et al.(2007) and four other papers presented at the Space Technology Applications Forum or STAIF (Baker and Li, 2005; Baker, Li and Li, 2006; Baker, Woods and Li, 2006; Li, Baker and Fang, 2007) show that it may be marginally possible to detect High-Frequency Relic Gravitational Waves (HFRGWs). These waves are in the 5 to 10 GHz band exhibiting amplitudes A of the dimensionless spacetime strains (change in length divided by length) of about 10^{-28} to 10^{-31}. The reader should be familiar with this detector, which was described in detail by the four prior STAIF papers. The purpose of this paper is to suggest a detector design, which builds upon these earlier detector concepts, that provides for ultra-high sensitivity detection of both high-frequency gravitational waves generated in the laboratory and HFRGWs from the cosmos (Baker, 2007). The assumptions as to the detector parameters of the previously discussed four papers were conservative. The 10 W microwave generator (or transmitter) can be increased in intensity to as much as 10,000 W or even 1 MW (Fowkes, et al., 1995) and the 3T magnet intensity could, in principal, be increased to 9T or even 15T. The HFRGW detector utilizes the Gertsenshtein effect (1962), which introduces the conversion of gravitational waves to electromagnetic (EM) waves in the presence of a static magnetic field. Such a conversion, if it leads to photons moving in a direction perpendicular to the plane of the EM waves and the magnetic field, will allow for ultra-high sensitivity HFRGW detection. The use of sensitive microwave, single photon detectors such as a circuit QED developed by Schoelkopf and Girvin at Yale (Schuster, et al., 2006) and/or the Rydberg Atom Cavity Detector (Yamamoto, et al. 2001) or off-the-shelf detectors, could lead to such detection. When the EM-detection photons (created in the interaction or reaction zone and termed the perturbative photon flux or PPF) are focused on the microwave detectors by fractal-membrane reflectors (in the y-z plane of Fig. 1) tuned to the 5 to 10 GHz frequency band of the HFRGWs the sensitivity is greatly improved. The interaction or reaction zone is about 30 cm long (or possibly longer), 6 cm wide roughly cylindrically shaped, but "necked in" at the xyz-origin in conformance to the shape of the Gaussian Beam or GB waist sketched in Fig. 1. This is the zone where the magnetic field (y-directed) crosses the GB (z-directed) along with the z-directed HFGWs. It is the sychro-resonance zone where detection photons are created according to the inverse-Gertsenshtein (1962) effect (the GB microwave photons and the HFGWs have the same frequency or waveform, polarization and speed for synchro resonance). The idea is that the EM detection photons (PPF) are created and propagate both ways in the x-direction according to the analyses of Li, Baker, Fang, Stevenson, and Chen (2007) and are reflected or focused to the microwave detectors by the fractal-membrane "mirrors." The focus at the detectors is blurred by diffraction so the detectors need be no more accurately placed than about one wavelength or 3 to 6 cm.

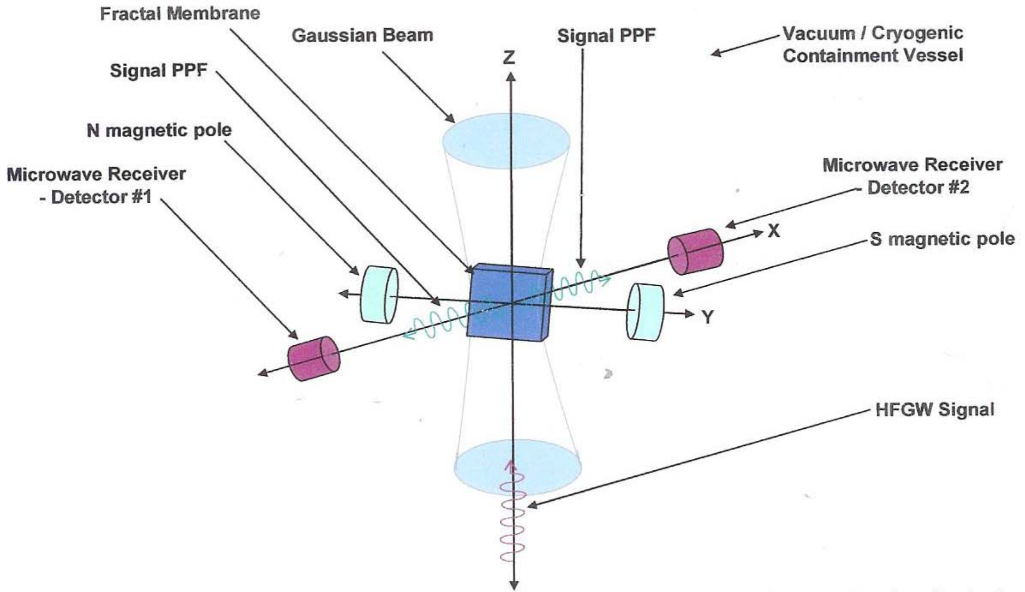


FIGURE 1. Schematic of Containment Vessel, Gaussian Beam or GB, Magnets and Microwave Receiver for the Potential Li, et al. (2007) Detector.

Noise sources external to the HFRGW detector will be eliminated by placing a tight mosaic of superconducting tiles (e.g., YBCO) and/or fractal membranes on the interior surface of the detector's cryogenic containment vessel, shown in Fig. 1, in order to provide a perfect Faraday cage. As discussed by Lee and Wan (2006), suitable geometric structures are required to eliminate background photon flux (BPF) noise. Internal thermal noise (that is, thermal photons, which might reach the microwave detectors) will be eliminated by maintaining the containment vessel at a temperature below 48 mK. A non-microwave-reflecting interior enclosure, shaped to conform to a high-intensity continuous microwave Gaussian beam (GB), will reduce any BPF noise radiated normal to the GB's axis. Such BPF will be further attenuated by a series of non-microwave-reflecting baffles forming tunnels to the sensitive microwave detectors on each side of the GB and at right angles to the static magnetic field. There are issues concerning bandwidth that will be discussed. A HFGW detector of bandwidth of 1 KHz to 10 KHz in the GHz band may be a reasonable choice. The superconductor enclosure could also be configured as a cavity with a standing electromagnetic (EM) wave utilized to reach the required power density with greatly reduced power input. In order to dissipate the microwave power of the GB, sinks or dissipaters or recyclers (rectifiers) could be utilized.

More importantly, very recent new-technology achievements in late 2006 concerning high-sensitivity microwave detectors, could allow for ultra-high sensitive HFRGW detection. One such device, used for radio Astronomy, is a passive microwave antenna array coupled to a HEMT amplifier (high electron mobility transistor amplifier). It is also important to utilize off-the-shelf detection options such as the aforementioned HEMT before moving on to the aforementioned esoteric quantum computing devices. Use of "off-the-shelf" equipment (magnets, cryogenic systems, microwave transmitters and receivers) can be utilized in the detector (and still insure ultra-high sensitivity) in order to increase reliability and simplify fabrication even if the fabricators may not have a tradition of precision assembly.

There are other potentially more sensitive detection means that could be utilized. As already mentioned, the most sensitive microwave detector possible is the cQED Yale detector invented by Schoelkopf and Girvin (Schuster, et al., 2006). This *Yale University* detector can measure one individual microwave photon, which is the theoretical ultimate limit of sensitivity. In practice it is better to have 30 photons in a row to build up resonant energy, but it is sensitive to just one photon. Also this new microwave detector or receiver it will be sensitive to the frequency range we are interested in: 4.9 to 10 GHz. A challenge, however, is the cryogenic-engineering problem of cooling the apparatus to 10 mK to 20 mK for the Yale detector; but Li and Baker have recognized the need for low temperatures of less than 48 mK to reduce background thermal photon noise and empower the superconducting magnet in all of their designs (Li et al., 2007; Li, Baker and Fang, 2007; Baker, Woods and Li, 2006.).

The Yale microwave receiver or detector is a QED (Quantum Electro-Dynamics) circuit. It uses a resonant pair of Cooper Pair Box (CPB) embedded in a co-planar waveguide (CPW). The two sides of the CPB are separated by a pair of Josephson Junctions, and in the middle of those is the inner target cavity. The measurement is made by a photon entering the center inner cavity that is very small (2μm x 2μm). There is the concern of how to focus and align the detector components to concentrate the microwave detection photos (perturbative photon flux or PPF) such a small active cross section. Baker has suggested the utilization of back-to-back parabolic-shaped fractal membrane reflectors (Wen et al., 2002) at the detector's active zone (where synchro-resonant PPF are generated by the HFGWs in a strong static magnetic field – the "inverse Gertsenshtein effect," Gertsenshtein, 1962) to focus the microwave detection photons on the microwave detector(s). The detector is fed with a reference microwave signal, which is transmitted through it, and the transmitted spectrum will have a characteristically shaped loss curve, which looks different for coherent signals (the single photon bouncing back and forth) than it does for thermal noise.

Another microwave-detector possibility is the Rydberg Atom Cavity Detector (Yamamoto, 2001), which uses a cavity filled with so called "Rydberg Atoms" (Hydrogen atoms with excited-state electrons). A cavity of Rydberg atoms could be placed in a strong magnetic field bath and excited by a TEM-mode GB of microwaves, effectively tuning the entire cavity into a Gravitational Wave (GW) conversion medium, and then coupling this to the cQED microwave photon detector. The sensitivity of this detection mechanism to GWs has yet to be calculated and is beyond the scope of this paper. However, such extreme engineering measures may not be necessary. Lee and Wan (2006) report that "... a (satisfactory) signal-to-noise ratio may be achieved ..." for HFRGW detector temperatures less than 600 mK and GB power equal to or greater than 10^5 W using purely off-the-shelf detection components. Furthermore, they did not utilize microwave absorbing components in their detector's structure or fractal membranes to concentrate the detection photons at the microwave receiver, both of which would further improve signal to noise (S/N) ratios.

ANALYSIS

The nominal average microwave power of the GB assumed in the Chinese detectors (Li, et al., 2007; Li, Baker, and Fang, 2007; in the Baker, Woods, and Li, 2006 piezoelectric HFGW generator-detector) is only 10 W. In this 10 W case, $\psi_0 \approx 1.26\text{x}10^3$ Vm^{-1} or the GB having a spot radius at its waist $W_o = 0.061$ m (the length of the 4.9 GHz HFGW utilized in Baker, Woods, and Li), where $\psi_0 =$ the average amplitude of electric (or magnetic) field of the Gaussian beam (Vm^{-1}) and proportional to the square root of the GB power. (For example, if the GB power were raised from 10 W to 100,000 W, then $\psi_0 \approx 1.26\text{x}10^5$ Vm^{-1}.) The number of microwave detection photons (Perturbative Photon Flux or PPF) is roughly proportional to this electrical field. So that the perturbative (detection) photon number propagating along the x-axis of Fig. 1 (notice that the propagating direction of the PPF is perpendicular to both the symmetrical z-axis of the GB and the y-direction of the static magnetic field) will be approximately (Li and Yang, 2004; Li and Baker, 2007) given by:

$$n_x^{(1)} \approx \frac{1}{\mu_0 \hbar \omega_e} A B_y \psi_0 \cdot \tag{1}$$

where $n^{(1)}_x$ is the detection photons per second per square meter. Thus the total number of detection photons passing through the effective receiving surface (the surface area, δs, is approximately the area of the GB's cross-section at GB's waist) having a radius of one GW wavelength of 6.1 cm for the Baker, Woods, and Li (2006) generator and detector system, so that $\delta s = \pi(0.061)^2 \sim 1.13\text{x}10^{-2}\text{m}^2$) will be:

$$N_x^{(1)} \approx n_x^{(1)} \delta s = \frac{1}{\mu_0 \hbar \omega_e} A B_y \psi_0 \delta s \cdot \tag{2}$$

The GB can be either an ultra-high-intensity pulse (i.e., a laser discussed in Baker, Li, and Li, 2006) or a high-intensity continuous microwave beam (discussed in Baker, Woods, and Li, 2006). For the pulse, if the instantaneous power $P=10^{14}$W and the spot radius W_0=0.061 m, then the instantaneous amplitude of electric field of the GB pulse would be $\psi_0 = 3.389\text{x}10^9\text{Vm}^{-1}$ in which, from Baker, Li, and Li, 2006 Table 1, the pulse length (observation interval) is $3.39\text{x}10^{-12}$ s. And for HFGW amplitude, A, of $4\text{x}10^{-25}$, only 21.4 detection photons are produced. On the other hand, for the continuous beam, from Table 2 of (Baker, Woods, and Li, 2006) for an observation interval of 10^3 s, for a $\psi_0 = 1.17\text{x}10^3\ \text{Vm}^{-1}$ and for a HFGW amplitude, A, of $3\text{x}10^{-32}$, as many as 490 detection photons are produced; about 16 times more than the 30 required for microwave-photon detection using the most sensitive Yale microwave detector. This assumes, however, that the microwave detection photons (PPF) reach the small, active microwave detection area. The size of the active detection area is anticipated to drive the alignment requirements of the HFRGW detector components.

BANDWIDTH

There are issues of bandwidth, because different cosmological models give different signal bandwidths (e.g., from much less than 1 GHz to 10 GHz). The HFRGWs energy collected by the detector will be limited in the small frequency region, and then the root-mean-square (rms) value of the HFRGW amplitude will be reduced. The bandwidth detector with wider bandwidth will also encounter increased noise. Thus, a reasonable bandwidth assumption used here will be 1 KHz to 10 KHz. In this case the corresponding rms value of amplitude of the HFRGWs would be $A \sim 10^{-30}$ to 10^{-33} in the GHz band. Moreover, generating a GB exhibiting a bandwidth of 1 kHz to 10 kHz is well within the capability of current technology. As already noted, a GB of wider bandwidth will contain more noise so even a narrower bandwidth could be considered. If the HFRGW signal has a white spectrum, then it would be the S/N ratio versus frequency of the GW to EM conversion that determined the most suitable parameters of the receiver and the required band width. In order to establish that HFRGWs are detected it may be possible to reorient the apparatus and look for repeatable variations in the detection signal. It may well be that the maximum bandwidth is related to the number of wavelengths in the interaction zone. For large bandwidths, the GB generator might require encoding or modulation in order to cover a cosmologically specified bandwidth. By the way, HFGWs are defined by Hawking and Israel as having frequencies of 100 kHz to 100 MHz. Very high-frequency gravitational waves (VHFGWs) have frequencies of 100 MHz to 100 GHz and, presumably, ultra high-frequency gravitational waves (UHFGWs) have frequencies above 100 GHz (theoretically generated by lasers as discussed by Baker, Li, and Li, 2006). The generic term HFGWs describes all three of these bands. (Hawking and Israel, 1979).

NOISE SOURCES

With regard to noise, the external noise can be effectively eliminated through use of a tight mosaic of superconductive chips or tiles (they need not be directly connected or continuous just contiguous and set very closely adjacent – closer than a very small fraction of the GHz wavelength of interest). These tiles would be attached to the inside surface of the detector's cryogenic containment vessel and would represent an almost perfect Faraday

Cage. Additionally, several layers of fractal membrane reflectors, tuned to the HFRGW frequencies in the bandwidth of interest, could also be attached to this surface. Since it is possible that a superconductor could reflect GWs (Baker, Davis, and Woods, 2005) a section of the containment vessel at the negative end of the z-axis should be kept clear of superconductor tiles to allow the HFGWs to enter. Fractal membrane reflectors, tuned to the detection frequency, could be utilized there to keep external microwave photons out. The internal noise sources (thermal, GB, etc.) will be reduced to negligible magnitudes relative to the detection or perturbative photon flux by the design of the HFRGW detector's GB enclosure and baffles. The GB is simply a focused microwave beam as shown in Fig. 2, where the waist of the GB is the focal point of that beam and the beam flares out on either side of the focal point as shown in Figs. 2 and 3. Note that the cross-section of the Gaussian beam exhibits an intensity shown in Fig. 4 that follows the Gaussian formula:

$$n_x^{(1)} \propto \exp\left(-\frac{r^2}{W^2}\right), \tag{3}$$

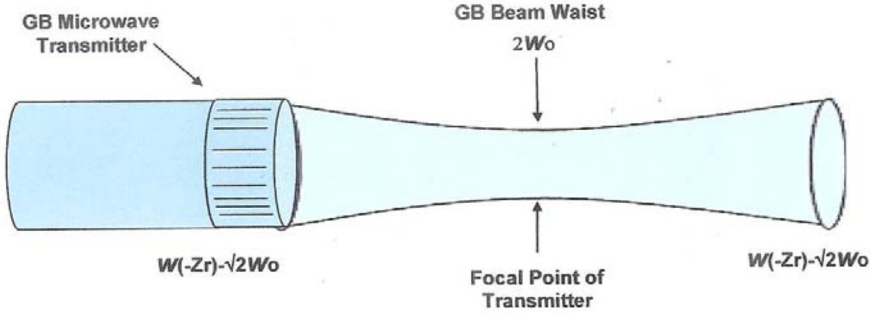
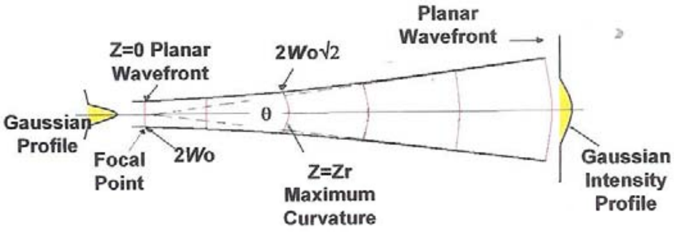


FIGURE 2. Schematic of a GB being Created by Focusing a Microwave Beam.



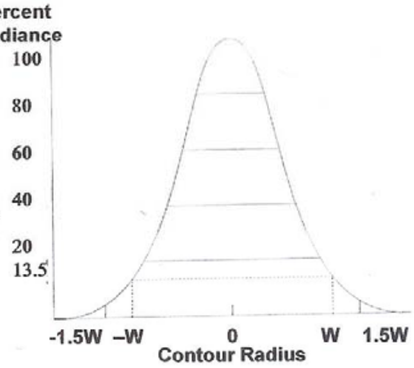


FIGURE 3. GB Propagation and Throat Angle θ.

FIGURE 4. Profile of a GB (TEM_{00} mode).

where *r* is the radial distance out from the central z axis. The microwave photons move in the z direction and there is little BPF radiating in any x-y plane. If one makes an enclosure of superconductor tiles around the GB, then the microwave background flux from the GB will be excluded outside of the enclosure. The concept is to conform the superconductor enclosure to the shape of the GB's most intense flux symmetrically along the z-axis say at the ± 13.5% points shown in Fig. 4. Two openings will be constructed in the enclosure near the GB waist, along the interaction or reaction zone, in order for the detection photons to escape each way along the x-axis and move off toward the two detectors as shown in Fig. 1. These two openings on each side of the GB enclosure would optimally be long ellipses, not circles. This is due to the fact that the reactive area between the poles of the 61 mm gap static magnetic field along the z-axis of the GB might be, for example, 30 cm in length and only a couple of wavelengths in width, roughly 6.1 cm. Fig. 5 is a depiction of the GB enclosure. A possible problem will be that the GB enclosure will change the boundary condition of the GB. Because the GB propagates in the free space, i.e., its wave form satisfies the free boundary condition, one often calls this wave form as standard wave form of the GB. If this boundary condition is changed, then it would influence the wave form of the GB as well as the perturbative effects. Nevertheless, it should not greatly affect the sensitivity of the HFGW detector and will be studied in more detail in future.

The presence of masses will influence the coherence quality and dramatically attenuate the GB's EM field's interaction with the space-time HFGW, i.e., the Gertsenshtein effect (Logi and Mickelson, 1977; Zel'dovich, 1974). This is due to the fact that a mass will slow the EM photons below the light-speed of the HFGWs. However, such a situation should not generate any serious problems for our HFGW detector, because the coherent-resonant interaction of the masses and EM fields in the detector is a local effect, i.e., it affects only on inside region (or effective interaction zone or region) of the detector, and it is independent at the propagation process of the HFGWs outside region of the detectors (outside the containment vessel of Fig. 1). In other words, we must insure that the inside region (or effective interaction or reaction zone) of the detector will have a good vacuum (e.g., $7.5\text{x}10^{-7}$ Torr) so that the mean-free path of a GB photon (before colliding with an atom in the interaction zone) is greater than the length of the interaction zone. The photon mean free path, *l*, for hydrogen gas molecules at a pressure of 10^{-7} Torr and a temperature of 10mK is given by:(diameter d of a H_2 molecule is $2.74\text{x}10^{-8}$ cm and for He it is $2.18\text{x}10^{-8}$ cm) (Tipler, 1978):

$$l = 1/(n\sigma) = 1/([\,N_A P_l/T][\pi d^2/4]) = 1/([9.7\text{x}10^{12}][5.9\text{x}10^{-16}]) = 175 \text{ cm.} \quad (4)$$

Because of very high reflectivity of superconducting GB enclosure walls to the perturbative EM fields inside the enclosure, and the space accumulation effect of multi-reflections by the enclosure walls, the enclosure will exhibit a somewhat higher EM inte y

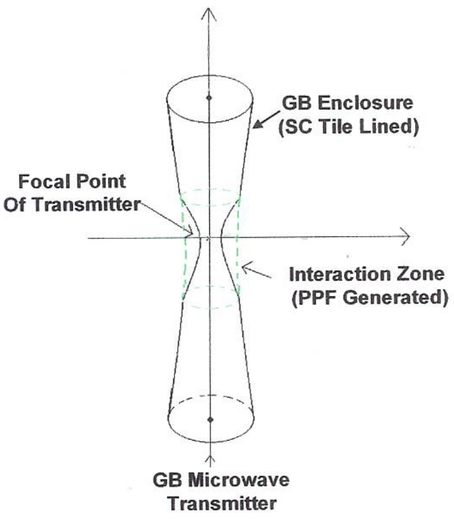


FIGURE 5. Schematic of GB Enclosure and the Interaction Zone or Region.

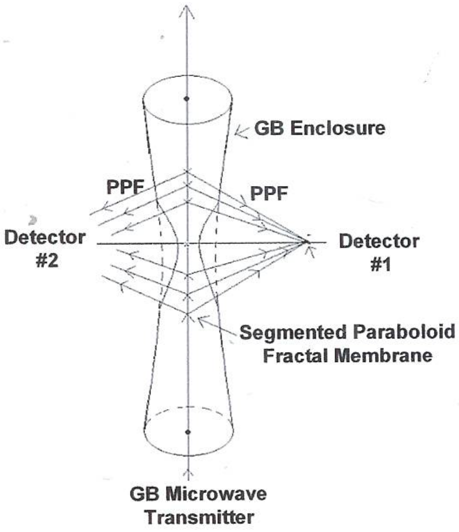


FIGURE 6. Schematic of Fractal Membrane Reflectors Focusing the Detection Photons on the Microwave Detectors

There will be some diffraction through the two side openings of the enclosure near the waist of the GB and perhaps some scattering of the background photons (background photon flux or BPF) from the GB out to the detectors. However, the high vacuum of $7.5\text{x}10^{-7}$ Torr in the detector's containment vessel will remove all or almost all of the suspended particulate and molecular matter. Thus scattering and the adverse effect of intervening mass is essentially eliminated as long as the GB photon mean free path in the interaction or reaction zone does not greatly exceed the zone's length. Diffracted photons from the GB will be minimal since the direction of the microwave photons in the GB is primarily parallel to the z-axis. We can compute the BPF at the detectors by assuming that a fraction *F* of the GB's photon flux at any point along the reactive zone on the z axis moves out in the radial direction in the x-y plane.

F has a value close to zero and its actual value will be studied in future. In our example the openings will exhibit an elliptical shape, whose major axis is 30 cm and whose minor axis is 6 cm. The diffracted BPF will spread out from this opening on to a hemisphere of the area $2\pi R^2$ where R is the distance from the GB opening out to both of the two detectors on each end of the x-axis. If the fraction of this area where the BPF reach the detectors is the detector's area is designated S, then the BPF at the detector will be:

$$F(\text{BPF from elliptical opening in the GB enclosure}) = S/2\pi R^2. \tag{5}$$

For the detection photons, that is for the perturbative photon flux or PPF, the situation is different, since they move out along the x-axis (in both directions) and are focused by fractal membrane reflectors in the interactive or reactive zone. The fractal membranes are long elliptical shaped segmented reflectors – like a Fresnel lenses, but composed of small fractal-membrane reflectors or mini mirrors – contoured into paraboloid-shaped reflectors facing both directions out along the x-axis. They are directed to the HFGW detector's microwave detection area or zone as shown in Fig. 6 and are a few μm to mm distant from the y-z plane. If the detection area, S, is very small, for example, micrometers (such as the Yale detector), then the chance of a detection photon having a diffraction pattern on the order of centimeters reaching that tiny area may be rather small. Of course, for the BPF noise that chance is much smaller considering the foregoing analysis of the BPF diffraction pattern. In any event, the signal-to-noise ratio is large due to the use of the superconductor (e.g., a mosaic of YBCO tiles) baffles and the fact that the GB photons and the detection photons move in perpendicular directions (z and x directions, respectively). Since background photons and signal photons are orthogonal in this detector design, rather than being background limited, this detector will be photon noise limited (the so called "shot noise" or "quantum noise"). Such photon noise could be reduced or eliminated by various techniques called "noise squeezing" (Yurke, et al.; Movshovich, et al., 1990). For these reasons the use of a very powerful microwave transmitter to generate the GB is indicated and the observation interval of 10^3 s could also be increased (or reduced). The YBCO tunnel (one on each side of the GB along the x-axis to reduce stray background photons) is shown in Fig. 7 and can involve an anti-reflecting coating of a quarter wavelength thickness, about 3/4th of a cm for a 10 GHz system, on top of the superconducting tiles, a few cm in dimension, or standard microwave absorbing materials (e.g., ARC Technologies, 2004).

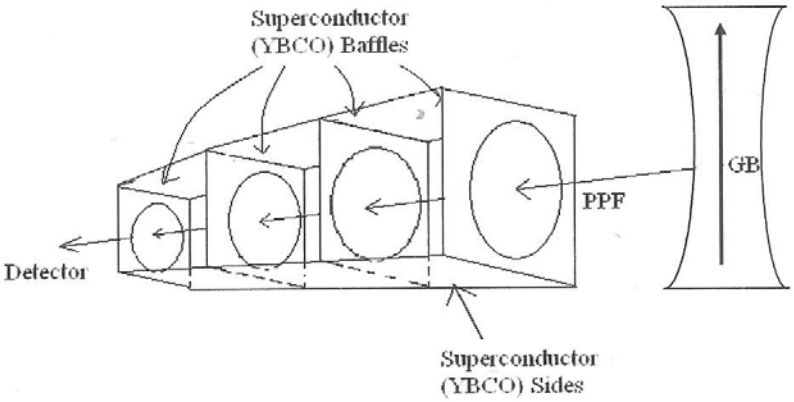


FIGURE 7. Schematic of Non-Microwave-Reflecting Baffles Comprising YBCO Tunnels to each Detector on each Side of the Gaussian Beam or GB.

These superconductors need not be continuous. They can be simply contiguous, that is, they can be a tight mosaic of individual superconductor tiles such as YBCO (having dimensions of only a centimeter or two). Thus they would be inexpensive, easy to fabricate and operable in the low temperature of the cryogenic detection containment vessel.

DETECTION SENSITIVITY

Given the goal of the detection of HFRGWs with the predicted typical parameters (Li, et al., 2007) $\nu_g \sim 10^{10}$ Hz (5 to 10 GHz) and a relic HFGW amplitude $A \sim 10^{-30} - 10^{-31}$, our objective sensitivity is $A = 10^{-32}$. There is about a factor of two difference in the frequency of the proposed HFGW generation and detection experiment (Baker, Woods, and Li, 2007) of 4.9 GHz and the relic (HFRGW) detection experiment (Li, et al., 2007) of 5 to 10 GHz so, assuming a $\sqrt{Hz}$ decrease in detector sensitivity, about 346 detection photons will be produced by the relic HFGWs, an order of magnitude more detection photons than are needed for detection according to the analyses of Schuster et al., 2006. It is also possible to increase the length of the magnetic-field reaction zone from 30 cm to 6 m, but this may be cost prohibitive and exceed the photon's mean free path. If the photon's mean free path of about 175 cm is greatly exceeded, then not only will many of the GB's EM photons be slowed (and synchro resonance reduced), but there will be the possibility of greater scattering of the BPF into the microwave detectors. An easier advance over the Li, Baker, Fang, Stephenson, and Chen detector is the placement of detectors on either end of the x-axis since detection photons produced by relic HFGWs go both ways – actually in all directions, and use that redundancy to improve the reliability of the device (for example, please see, Giovannini, 1999). Taken together the sensitivity of this Li, Baker, Fang, Stephenson, and Chen detector could be theoretically raised by a factor of 10^2 to 10^5. Thus the detection sensitivity for HFGW amplitudes, either relic HFRGW or from a laboratory HFGW generator, could be in the range of $A \sim 10^{-32}$ to 10^{-34}. Such ultra-high sensitivities would not only allow for a robust detector of relic HFGWs; but also could allow for the detection of laboratory generated HFGWs, especially since the artificially generated HFGWs have a definite propagating direction, frequency, phase, waveform, polarization and bandwidth. The relic GWs and usual monochromatic GWs have some important differences. Even if they have the same frequency and amplitude, their minimal detectable amplitudes are often different for the same detector. For a monochromatic GW from a definite celestial point source (such as the very speculative primordial, close-by mini black holes described by Miller ,2002) or a laboratory HFGW generator, the propagating direction of the gravitons in the area of detector are the same or almost same (i.e., plane wave or quasi-plane wave). If the propagating direction of such GWs are parallel to the symmetrical axis z of the GB, then all or almost all gravitons in a cylinder will pass through the spot surface of the GB provided the cylinder has the same size of the spot radius of GB, and its symmetrical axis coincides with to the z-axis. On the other hand, the relic gravitons have every different propagating direction (i.e., isotropy of the propagating direction of the HFRGWs), so that only small fraction of the relic gravitons can pass through the reaction zone depending upon the throat vertex angle (θ of Fig. 3) of the GB and the resulting PPF reaching the detectors depends upon YBOC tunnel geometry. A preliminary estimation shows that the minimal detectable amplitude of the HFRGW may be two orders of magnitude larger than the point-source generated HFGWs. For example, if our detector has a sensitivity of 10^{-32}-10^{-34} for the point-source constant amplitude plane HFGWs, then its sensitivity to the HFRGWs with the same frequency will be only ~10^{-30}-10^{-32}.

CONCLUSIONS

A design for an ultra-high sensitivity high-frequency gravitational wave detector has been exhibited that depends upon the inverse Gertsenshtein effect. It relies on new-technology, high-sensitivity microwave detectors, a very powerful microwave Gaussian beam and an extremely strong magnetic field. Greatly reduced noise is achieved by keeping the entire apparatus at in a cryogenic containment vessel at a low temperature and introducing microwave absorbing structures internal to the apparatus to eliminate internal sources of background-microwave-photon noise. Fractal-membrane reflectors, tuned to the frequency band of interest, focus the detection photons, moving out normal to the axis of the Gaussian beam and the axis of an intense static magnetic field, on to two microwave detectors. The HFRGW detector is expected to be sensitive to relic gravitational waves exhibiting amplitudes, A, of the time-varying spacetime strains on the order of 10^{-30} to 10^{-32}.

NOMENCLATURE

A ($A_{\oplus}$, $A_{\otimes}$) = dimensionless amplitude of the periodic, time-variable GW

B_y = background static magnetic field (T)

d = diameter of a molecule (cm)

F = fraction of the GB's microwave flux that moves out normal to the axis of the GB

$h_{\oplus}$, $h_{\otimes}$ = dimensionless metric perturbations or periodic, time-variable strain in the spacetime fabric caused by the passage of a gravitational wave

L = mean free path of a photon before striking a molecule in the interaction zone (cm)

N_m = number of molecules in a cm^3 at standard temperature and pressure (STP) = 2.7×10^{18}

$N_x^{(1)}$ = total perturbative photon flux in the x-direction (s^{-1})

$n_x^{(1)}$ = perturbative photon flux density in the x-direction ($s^{-1}m^{-2}$)

n_m = number of molecules of gas in the detector's interactive zone per cm^3.

P = power (W)

P = pressure in atmospheres

r = radial distance out from the axis of the Gaussian beam (m)

R = distance from the GB enclosure's openings to the detectors (m)

S = microwave receiver's detection area (m^2)

T = temperature in degrees Kelvin or the ratio of the temperature at STP to that in the detector

σ = area of a molecule in the interaction zone (cm^2)

ω_e = angular rate associated with EM field (radians per second)

ω_g = angular rate associated with HFGWs (radians per second)

δs = area of GB's cross section at the GB's waist (m^2)

W = spot radius of the Gaussian beam (m)

$w(z_R)$ = radius of GB as a function as the distance along the z-axis from the GB's waist (m)

μ_0 = vacuum permeability = $4\pi \times 10^{-7}$ x(NA^{-2})

ψ_0' = amplitude of the electrical field of the Gaussian beam (Vm^{-1})

$\hbar$ = Planck's constant = 6.626068×10^{-34} m^2 kg / s

θ = GB's vertex angle (radians)

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