

The Li-Baker High-Frequency Relic Gravitational Wave Detector

By Robert M L Baker, Jr.
GravWave, LLC and Transportation Sciences Corporation
DrRobertBaker@gravwave.com

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Based In Part on the Following Manuscript

**“A new theoretical technique for the
measurement of high-frequency relic
gravitational waves”**

by

**R. Clive Woods, Robert M L Baker, Jr.,
Fangyu Li, Gary V. Stephenson, Eric W.
Davis and Andrew W. Beckwith**

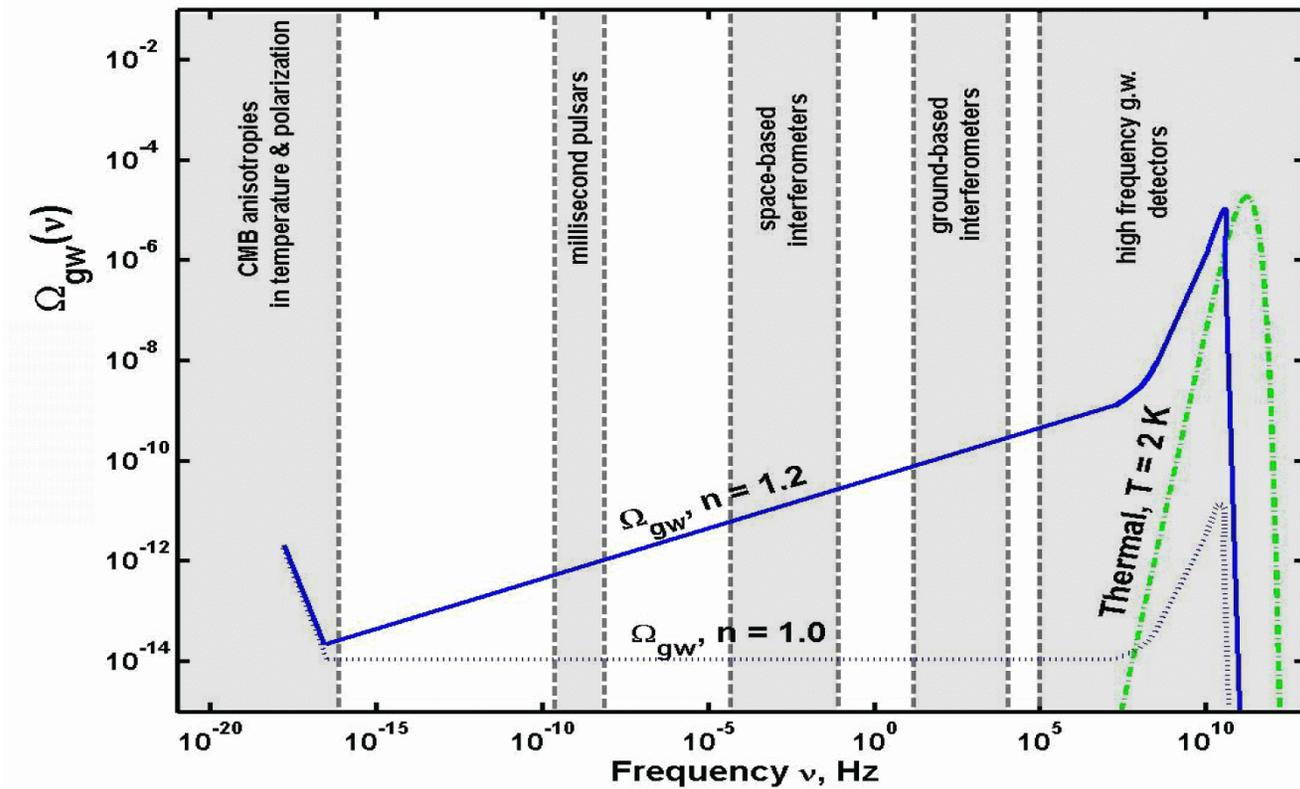
INTRODUCTION

- The measurement of High-Frequency Relic Gravitational Waves or HFRGWs could provide important information on the origin and development of our Universe.
- There have been three instruments built to detect and measure HFRGWs, but so far none of them has the required detection sensitivity.
- This lecture describes another detector, based on a new measurement technique, as referenced in the theoretical-physics literature, called *Li-Baker detector*.
- Sensitivity as well as operational concerns, especially background noise, are discussed.
- The potential for useful HFRGW measurement is theoretically confirmed.

What the Li-Baker Detector is Expected to Measure

- The maximal signal and peak of HFRGWs expected from the beginning of our Universe, the “Big Bang,” by the quintessential inflationary models (Brustein, Gasperini, Giovannini and Veneziano 1995, Buonanno, Maggiore and Ungarelli 1997, de Vega, Mittelbrunn and Sanchez 1999, Giovannini 1999, Grishchuk 1999 and Beckwith 2009) and some string cosmology scenarios (Infante and Sanchez 1999, Mosquera and Gonzalez 2001, Bisnovatyi-Kogan and Rudenko 2004), may be localized in the gigahertz band near 10 GHz.
- Their dimensionless spacetime strain (m/m), h , vary from up to $\sim 10^{-30}$ to $\sim 10^{-34}$. Low-frequency gravitational wave detectors such as LIGO, which are based on interferometers, cannot detect HFRGWs (Shawhan 2004).
- A frequency scan could reveal other HFRGW effects of interest in the early universe at a variety of HFRGW base frequencies other than 10 GHz.

Predicted relic gravitational wave energy density Ω_g was a function of frequency (slide 6, Grishchuk 2007) and Hubble parameter n



HFRGW Detectors Already Built

Three such detectors have been built (Garcia-Cuadrado 2009), utilizing different measurement techniques. And others proposed, for example by the Russians. They are promising for future detection of HFRGWs having frequencies above 100 kHz (the definition of high-frequency gravitational waves or HFGWs by Douglass and Braginsky 1979), but their sensitivities are many orders of magnitude less than that required to detect and measure the HFRGWs so far theorized.

- The following slide shows the Birmingham HFGW detector that measures changes in the polarization state of a microwave beam (indicating the presence of a GW) moving in a waveguide about one meter across. It is expected to be sensitive to HFRGWs having spacetime strains of $h \sim 2 \times 10^{-13}$.

Birmingham (Polarization) HFRGW Detector



Additional Existing HFRGW Detectors

The second of these alternate detectors was built by the INFN Genoa, Italy. It is a resonant HFRGW detector, comprising two coupled, superconducting, spherical, harmonic oscillators a few centimeters in diameter. The oscillators are designed to have (when uncoupled) almost equal resonant frequencies. In theory, the system is expected to have a sensitivity to HFRGWs with intensities of about $h \sim 2 \times 10^{-17}$ with an expectation to reach a sensitivity of $\sim 2 \times 10^{-20}$. Details concerning the present characteristics and future potential of this detector, especially its frequency bands, can be found in Bernard, Gemme and Parodi 2001, Chincarini and Gemme 2003, and Ballantini et al. 2005. As of this date, however, there is no further development of the *INFN Genoa* HFRGW detector.

The third alternate detector is the Kawamura 100 MHz HFRGW detector, which has been built by the Astronomical Observatory of Japan. It comprises two synchronous interferometers exhibiting arms lengths of 75 cm. Its sensitivity is $h \approx 10^{-16}$ and its other characteristics can be found in Nishizawa et al. 2008.

INFN Genoa, Italy HFRGW Detector

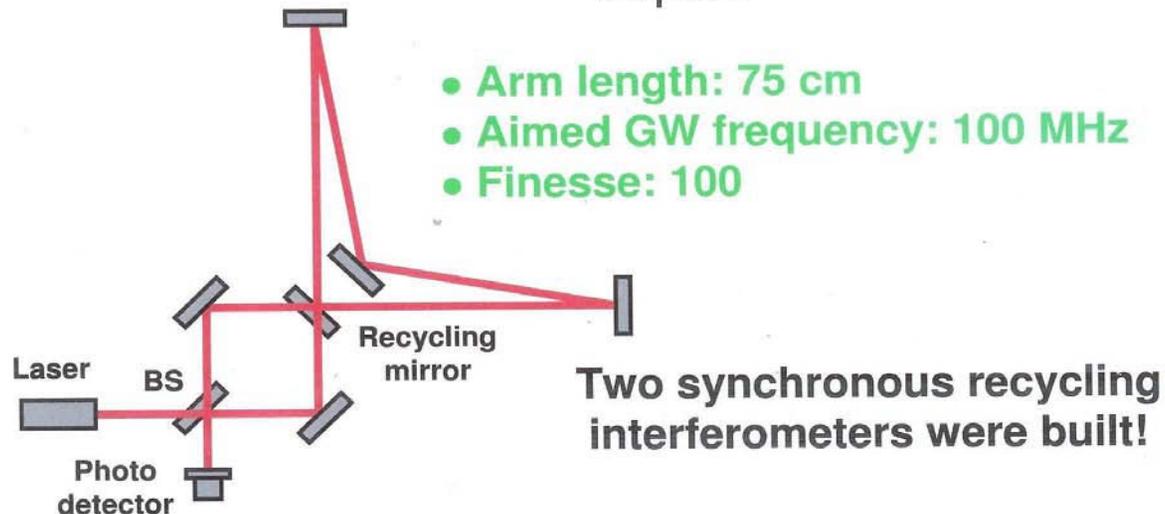


Kawamura 100 MHz HFRGW detector



UNIVERSITY OF
BIRMINGHAM

Development of 100MHz GW detectors
at National Astronomical Observatory of
Japan



Synchronous recycling Interferometer (Concept: Drever 1983)

Other HFRGW Detection Techniques

Another HFRGW detector, under development by the Russians (Mensky 1975; Mensky and Rudenko 2009), involves the detection of gravitational waves by their action on an electromagnetic wave in a closed waveguide or resonator.

Krauss, Scott and Meyer (2010) suggest that: "... primordial (relic) gravitational waves also leave indirect signatures that might show up in CMB (Cosmic Microwave Background) maps." They suggest the use of thousands of new detectors (as many as 50,000) to obtain the required sensitivity.

Publications Presenting the Li- Effect or Li-Theory

Fangyu Li 's new theory, upon which the Li-Baker Detector is based, was first published in 1992 and subsequently aspects of it were published in the following prominent, well-respected and often cited, peer-review journals:

Physical Review D

International Journal of Modern Physics B

The European Physical Journal C

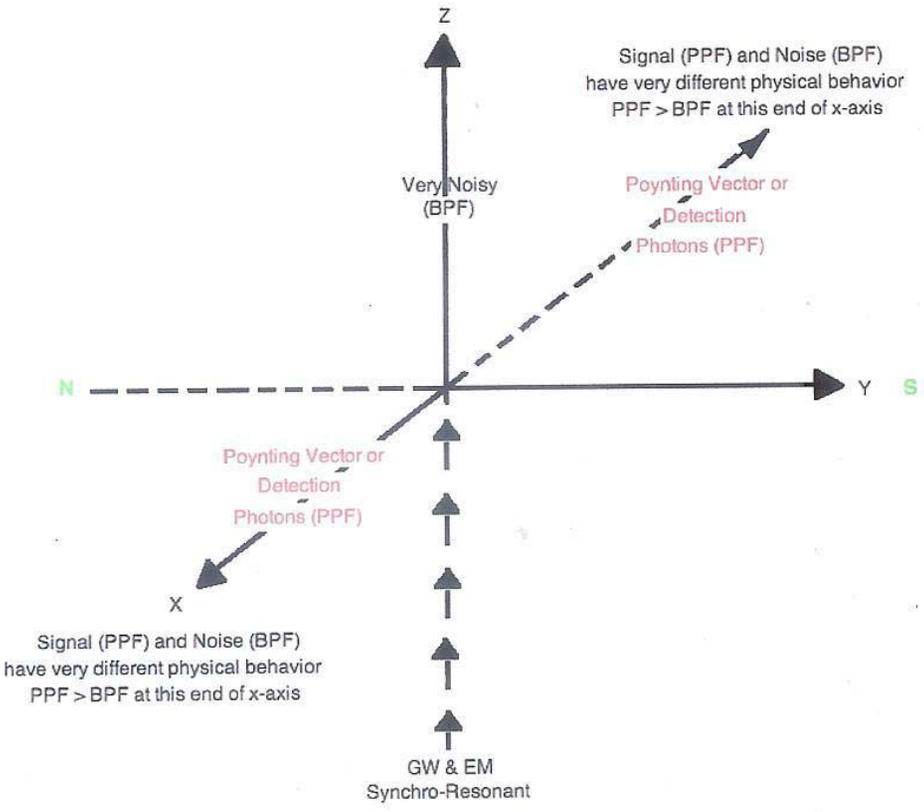
International Journal of Modern Physics D

The Li theory was scrutinized by Valentine Rudenko and Nikolai Kolosnitsyn of the Sternberg Astronomical Institute of Moscow State University in 2010.

Details of the Li Effect

The Li Effect is *very different from* the well-known classical (*inverse*) Gertsenshtein (1962) effect. With the Li effect, a gravitational wave transfers energy to a separately generated electromagnetic (EM) wave in the presence of a static magnetic field. That EM wave, formed as a Gaussian beam (GB), has the same frequency as the GW and moves in the same direction. This is the “*synchro-resonance condition*,” in which the EM and GW waves are synchronized. It is *unlike the* Gertsenshtein effect, where there is no input EM wave that must be synchronized to the incoming gravitational wave. The result of the intersection of the parallel and superimposed EM and GW beams, according to the Li effect, is *new EM photons moving off in a direction (both ways on the x-axis) perpendicular to the directions of the beams (GB and HFRGWs) on the z-axis and of the magnetic field (on the y-axis)*, as exhibited in a following slide. These photons signal the presence of HFGWs and are termed a “perturbative photon flux,” or PPF.

Li-effect detection photons directed to locations at both ends of the x-axis that are less affected by noise



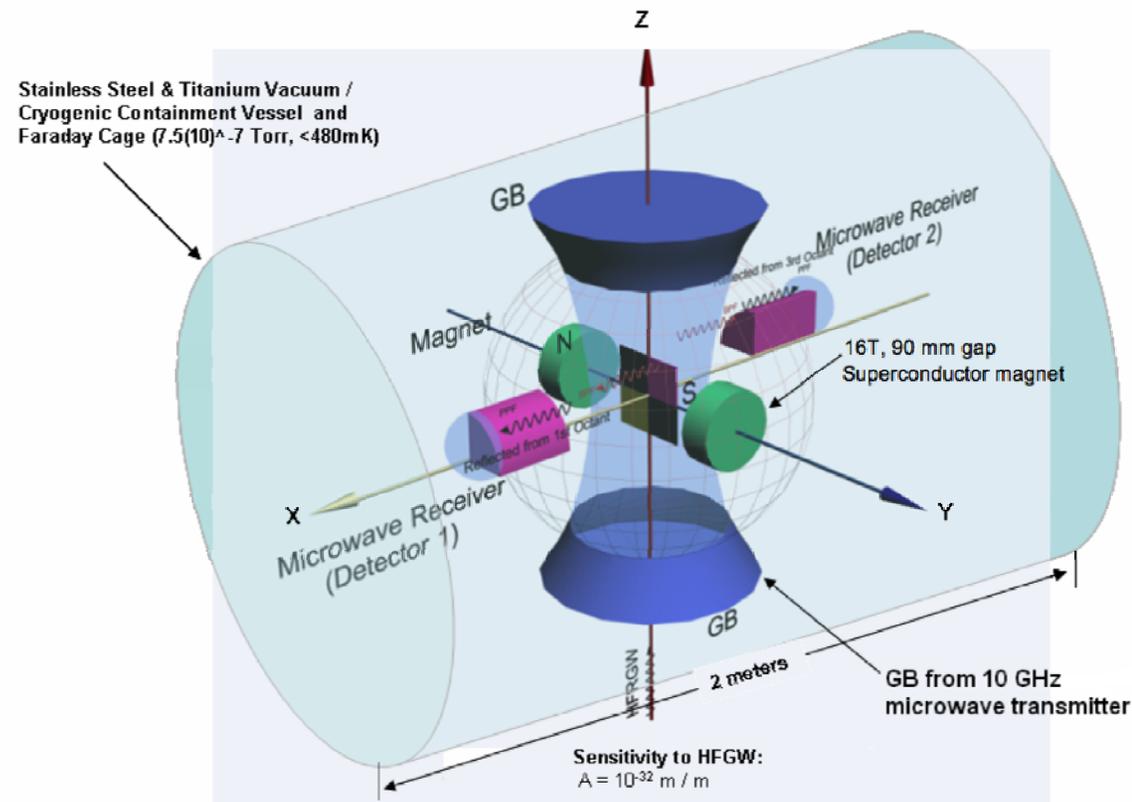
Theory of Operation

- 1. A Gaussian microwave beam or GB (focused, with minimal side lobes) and off-the-shelf microwave absorbers for effectively eliminating diffracted waves at the transmitter horn's edges ("out of sight" of the microwave receivers shown in yellow and blue in slide 21) is aimed along the +z-axis at the same frequency as the intended HFGW signal to be detected .**
- 2. A static magnetic field B (generated typically using superconductor magnets such as those found in a conventional MRI medical body scanner) and installed linearly along the z-axis, is directed (N to S) along the y-axis**
- 3. Semi-paraboloid reflectors are situated back-to-back in the y-z plane to reflect the +x and -x moving PPF detection photons (on both sides of the y-z plane in the interaction volume) to the microwave receivers. Alternatively, microwave lenses could be located outside of GB to focus the detection photons at the microwave receivers (slide 31).**

Theory of Operation Continued

4. High-sensitivity, shielded microwave receivers are located at each end of the x-axis and below the GB entrance aperture to the Interaction Volume. Possible microwave receivers include an off-the-shelf microwave horn plus HEMT (High Electron Mobility Transistor) receiver; Rydberg Atom Cavity Detector (Yamamoto, et al. 2001) and single-photon detectors (Buller and Collins 2010). Of these, the HEMT receiver is recommended because of its off-the-shelf availability.
5. A high-vacuum system able to evacuate the chamber from 10^{-6} to 10^{-11} Torr (nominally about 7.5×10^{-7} Torr) is utilized. This is well within the state of the art, utilizing multi-stage pumping, and is a convenient choice. Utilized to essentially eliminate GB scattering.
6. A cooling system is selected so that the temperature T satisfies $k_B T \ll \hbar\omega$, where k_B is Boltzmann's constant and $T \ll \hbar\omega/k_B \approx 3\text{K}$ for detection at 10 GHz. This condition is satisfied by the target temperature for the detector enclosure $T < 480\text{mK}$, which can be conveniently obtained using a common helium-dilution refrigerator so very few thermal photons will be radiated at 10 GHz in the narrow bandwidth (as narrow as 0.001 Hz).

Schematic of the Li-Baker HFGW detector



Sensitivity

The intersection of the magnetic field and the GB defines the “interaction volume” where the detection photons or PPF are produced. The interaction volume for the present design is roughly cylindrical in shape, about 30 cm in length and 9 cm across. In order to compute the **sensitivity**, that is the number of detection photons (PPF) produced per second for a given amplitude HFGW, we will utilize equation (7) of the analyses in Baker, Woods and Li (2006), which is a simplification of equation (59) in Li, et al. (2008),

$$n_x^{(1)} = (1/\mu_0 \hbar \omega_e) A B_y \psi_0 \delta s \quad (1)$$

where $n_x^{(1)}$ is the number of x-directed detection photons per second produced in the interaction volume (defined by the intersection of the Gaussian beam and the magnetic field), \hbar = Planck’s reduced constant, ω_e = angular frequency of the EM (= $2\pi\nu_e$), ν_e = frequency of the EM, A = the amplitude of the HFGW (dimensionless strain of spacetime variation with time), B_y = y-component of the magnetic field, ψ_0 = electrical field of the EM Gaussian beam or GB and δs is the cross-sectional area of the EM Gaussian beam and magnetic field interaction volume. For a proof-of-concept experiment, the neck of the GB is 20 cm out along the z-axis from the transmitter; the radius of the GB at its waist, W , is $(\lambda_e z/\pi)^{1/2} = (3 \times 20/\pi)^{1/2} = 4.4$ cm.

Standard quantum limit (SQL) -a result of the Heisenberg uncertainty principle

There is another possible concern here: Stephenson (2009) concluded that a HFRGW intensity of $h_{det} = 1.8 \times 10^{-37} \text{m/m}$ (strain in the fabric of space-time whose amplitude is A) represents the lowest possible GW strain variation detectable by each RF receiver in the Li-Baker HFGW detector. This limit is called “quantum back-action” or standard quantum limit (SQL) and is a result of the Heisenberg uncertainty principle. This sensitivity limit might be mitigated, however, by a “quantum-enhanced measurements using machine learning ...” technique as discussed by Hentschel and Sanders (2010) and more specifically applied to optical interferometry as discussed by Steinberg (2010). An additional $(1/\sqrt{2})$ factor increase in maximum sensitivity applies if the separate outputs from the two RF receivers are averaged, rather than used independently for false alarm reduction, resulting in a minimum $h_{det} = 1.2 \times 10^{-37}$. Because the predicted best sensitivity of the Li-Baker detector in its currently proposed configuration is $A = 10^{-30} \text{m/m}$, these results confirm that the Li-Baker detector is photon-signal-limited, not quantum-noise-limited; that is, the SQL is so low that a properly designed Li-Baker detector can have sufficient sensitivity to observe HFRGW of amplitude $A \approx 10^{-30} \text{m/m}$.

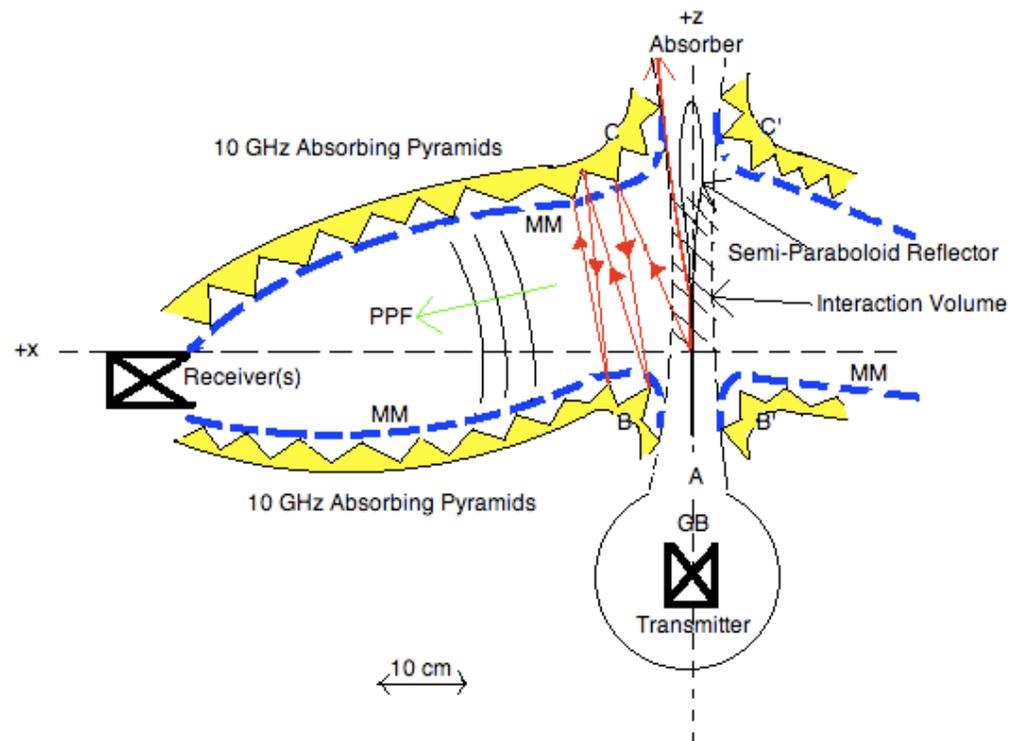
Scattering in the GB interaction volume

We utilize the scattered intensity, I , from a molecule with incident intensity I_0 as given by (Nave 2009)

$$I = I_0 (8\pi^4 \alpha^2 / \lambda^4 R^2) (1 + \cos 2\theta)$$

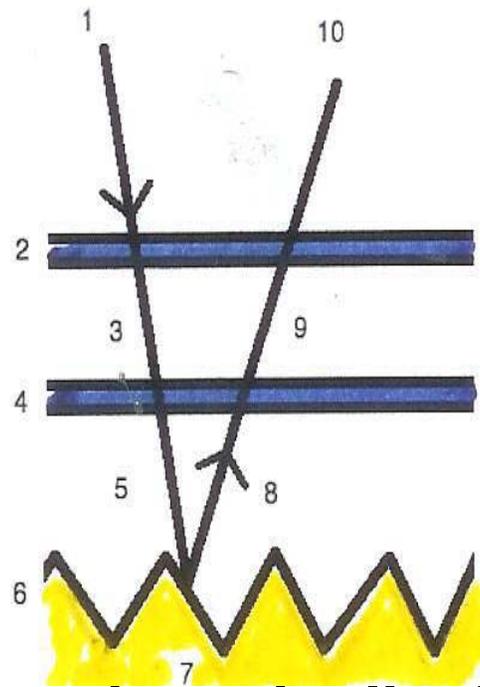
where α is the atomic polarizability expressed as a polarization volume (where the induced electric dipole moment of the molecule is given by $4\pi\epsilon_0\alpha E$), θ is the scattering angle, and R is the distance from particle to detector. Note that the scattering is not isotropic (there is a θ -dependence) but in the present case, $\theta = 90^\circ$ so the ratio of incident to scattered photon intensity is given by . The polarizability is $\alpha \approx 1.1 \times 10^{-30} \text{m}^3$ from Robb (1974) so the scattering intensity ratio is 1.2×10^{-49} for each atom in the chamber. The volume of interaction is about 2000 cm^3 (30 cm long and roughly 8 cm \times 8 cm in area) so at a pressure reduced to its base value of 7.5×10^{-7} Torr at temperature 480 mK, the number of molecules contained is about 3×10^{16} , giving a total scattering intensity ratio of 3.49×10^{-33} . There are 1.51×10^{26} photons produced per second in the 10^3W , 10 GHz GB. Therefore, in 10^3s of observation time, **the number of photons received from Rayleigh scattering in the interaction volume over one-thousand seconds is much less than 1, and again scattering will be negligible.**

Side-view schematic of the Li-Baker HFGW detector, exhibiting microwave-absorbent walls comprising an anechoic chamber



Schematic of the multilayer metamaterial or *MM* absorbers and pyramid absorber/reflector absorbent mat. Pat. Pend.

- 1 Incident
- 2 1st metamaterial (MM) layer
- 3 transmitted
- 4 typical MM layer
- 6 conventional
- microwave absorber
- 8 reflected
- 10 remaining



- **The incident ray can have almost any inclination:
Service (2010)**

Diffraction of GB (from Woods 2011)

$$n_{dif} = k_2 \left((d/2)^2 / (32 L_d^2) \right) \exp(-1/2 k^2 [d/2]^2) (0.01) n_{GB}$$

where $k = 2\pi \nu_e/c$ (nominally, 209 rad/m at 10GHz), c being the speed of light, the diameter of the GB throat is d (~ 0.09 m for the nominal case, essentially 2W) and n_{GB} is the GB photon flux (nominally, 1.51×10^{26} photons per second). We will assume a single bounce or wave reflection of this diffraction-noise wave from the detector walls. The diffraction photon-path distance, prior to reaching the receivers, is L_d (~ 1 m for the nominal case). The number of diffracted photons reaching a receiver per second

$$n_{rdif} = n_{dif} [a_r / \pi L_d] \epsilon_{ab}$$

where ϵ_{ab} is the wall absorption coefficient (e.g., for the nominal case with the absorbent mat, it would be 10^{-22}) and a_r = area of the square receiver horn or receiving surface (nominally, one HFRGW wavelength square or 9×10^{-4} m²).

Summary of Li-Baker detector noise (nominal case)

Noise Contributor	Brief Description of Noise source	Mitigation/Elimination Means	Nominal Computed Value photons s ⁻¹ , NEP W
<i>Dark-background shot noise</i>	GB noise especially diffraction	Wall geometry and absorbing wall materials	$4.2 \times 10^{23} \text{ s}^{-1}, 2.8 \times 10^{-46} \text{ W}$
<i>Signal shot noise</i>	Noise in the signal itself	Part of useful data and not to be eliminated	--
<i>Johnson noise</i>	Thermal agitation in a power amplifier resistance	Refrigeration to low temperature	$5 \times 10^{-5} \text{ s}^{-1}, 3 \times 10^{-28} \text{ W}$
<i>Preamplifier kTC noise</i>	Stray capacitance and load resistance	Reducing bandwidth, load resistance and/or stray capacitance.	$1 \times 10^{-6} \text{ s}^{-1}, 8 \times 10^{-30} \text{ W}$
<i>Quantization noise</i>	Analog to Digital Converter	Increasing the number of bits used	$2 \times 10^{-3} \text{ s}^{-1}, 1 \times 10^{-26} \text{ W}$
<i>Mechanical thermal noise</i>	Brownian motion of sensor components.	Refrigeration to low temperature	$3 \times 10^{-4} \text{ s}^{-1}, 2 \times 10^{-27} \text{ W}$
<i>Phase or Frequency noise</i>	Fluctuations in the frequency of the microwave source for the GB.	Cavity-lock loop or a phase-compensating feedback loop	$5 \times 10^{-15} \text{ s}^{-1}, 3 \times 10^{-38} \text{ W}$

Results

The total Noise Equivalent Power or NEP is 1.02×10^{-26} W and is Quantization and thermal noise limited at roughly 1×10^{-26} to 2×10^{-27} W for a temperature of 0.48K (total noise flux is 1.54×10^{-3} photons per second). If need be the receivers could be further cooled and shielded from noise by baffles in which the spherical BPF wave front if significant, can be reduced by baffle diffraction and the PPF focused by the reflectors passed through the baffle openings with less interaction with baffle edges and less diffraction. Given a signal that exhibits the nominal value of 99.2 s^{-1} photons, one quarter of which is focused on each of the microwave receivers, which is 24.8 s^{-1} photons or 1.6×10^{-22} W, the signal-to-noise ratio for each receiver is better than 1500:1.

CONCLUSIONS

Three HFGW detectors have previously been fabricated, but analyses of their sensitivity and the results provided herein suggest that for meaningful relic gravitational wave (HFRGW) detection, greater sensitivity than those instruments currently provide is necessary.

The theoretical sensitivity of the Li-Baker HFGW detector studied herein, and based upon a different measurement technique than the other detectors, is predicted to be $A = 10^{-30}$ m/m at a frequency of 10 GHz.

This detector design is not quantum-limited and theoretically exhibits sensitivity sufficient for useful relic gravitational wave detection.

Utilization of magnetic-field pulsed modulation allows for reduction in some types of noise. Other noise effects can only be estimated based on the Li-Baker prototype detector tests, and some of the design and adjustments can only be finalized during prototype fabrication and testing.

The detector can be built from off-the-shelf, readily available components and its research results would be **complementary** to the proposed low-frequency gravitational wave (LFGW) detectors, such as the Advanced LIGO, Russian Project OGRAN and the proposed Laser Interferometer Space Antenna or LISA.

Parametric Analyses

Table 1. PPF (photons per second) for various values of B_y and transmitter power for $\delta s = 0.005 \text{ m}^2$.

	Power = 100 W	Power = 1000 W	Power = 10,000 W
$B_y = 9 \text{ T}$	3.4	10.8	34.2
$B_y = 16 \text{ T}$	6.1	19.2	60.8
$B_y = 20 \text{ T}$	7.6	24	76

Table 2. PPF (photons per second) for various values of B_y and transmitter power for $\delta s = 0.0258 \text{ m}^2$. The design or nominal case.

	Power = 100 W	Power = 1000 W	Power = 10,000 W
$B_y = 9 \text{ T}$	17.6	55.8	176.4
$B_y = 16 \text{ T}$	31.4	99.2	313.7
$B_y = 20 \text{ T}$	39.2	124	392

Table 3. PPF (photons per second) for various values of B_y and transmitter power for $\delta s = 1.5 \text{ m}^2$.

	Power = 100 W	Power = 1000 W	Power = 10,000 W
$B_y = 9 \text{ T}$	1.023×10^3	3.2×10^3	1.026×10^4
$B_y = 16 \text{ T}$	1.83×10^3	5.8×10^3	1.82×10^4
$B_y = 20 \text{ T}$	2.3×10^3	7.2×10^3	2.3×10^4

Diffraction Analysis Details

Table 4. Diffraction photons s^{-1} and NEP W for a mat composed of absorber microwave pyramids only, exhibiting an absorption of -40 dB.

GB aperture diameter	$L_d = 0.5 m$	$L_d = 1.0 m$ (nominal)	$L_d = 2.0m$
$d = 6cm$	$3.4 \times 10^6 s^{-1}, 2.3 \times 10^{-17} W$	$4.3 \times 10^5 s^{-1}, 3 \times 10^{-18} W$	$5.3 \times 10^4 s^{-1}, 4 \times 10^{-19} W$
$d = 9 cm$ (nominal)	$3.3 \times 10^{-4} s^{-1}, 2.2 \times 10^{-27} W$	$4.2 \times 10^{-5} s^{-1}, 2.8 \times 10^{-28} W$	$5.2 \times 10^{-6} s^{-1}, 3.5 \times 10^{-29} W$
$d = 12 cm$	$1 \times 10^{-18} s^{-1}, 7 \times 10^{-42} W$	$1.3 \times 10^{-19} s^{-1}, 8.7 \times 10^{-43} W$	$1.6 \times 10^{-20} s^{-1}, 1 \times 10^{-43} W$

Table 5. Diffraction photons s^{-1} and NEP W for absorber microwave pyramids and one MM layer (one layer of two MMs), exhibiting an absorption of -130 dB.

GB aperture diameter	$L_d = 0.5 m$	$L_d = 1.0 m$ (nominal)	$L_d = 2.0m$
$d = 6cm$	$3.4 \times 10^{-3} s^{-1}, 2.3 \times 10^{-26} W$	$4.3 \times 10^{-4} s^{-1}, 3 \times 10^{-27} W$	$5.3 \times 10^{-5} s^{-1}, 4 \times 10^{-28} W$
$d = 9 cm$ (nominal)	$3.3 \times 10^{-13} s^{-1}, 2.2 \times 10^{-36} W$	$4.2 \times 10^{-14} s^{-1}, 2.8 \times 10^{-37} W$	$5.2 \times 10^{-15} s^{-1}, 3.5 \times 10^{-38} W$
$d = 12 cm$	$1 \times 10^{-27} s^{-1}, 7 \times 10^{-51} W$	$1.3 \times 10^{-28} s^{-1}, 8.7 \times 10^{-52} W$	$1.6 \times 10^{-29} s^{-1}, 1 \times 10^{-52} W$

Diffraction Details Continued

Table 6. Diffraction photons s^{-1} and NEP W for absorber microwave pyramids and four (two layers of two) MM layers (*nominal*), exhibiting an absorption of -220 dB.

GB aperture diameter	$L_d = 0.5 m$	$L_d = 1.0 m$ (<i>nominal</i>)	$L_d = 2.0m$
$d = 6cm$	$3.4 \times 10^{-12} s^{-1}, 2.3 \times 10^{-35} W$	$4.3 \times 10^{-13} s^{-1}, 3 \times 10^{-36} W$	$5.3 \times 10^{-14} s^{-1}, 4 \times 10^{-37} W$
$d = 9 cm$ (<i>nominal</i>)	$3.3 \times 10^{-22} s^{-1}, 2.2 \times 10^{-45} W$	$4.2 \times 10^{-23} s^{-1}, 2.8 \times 10^{-46} W$	$5.2 \times 10^{-24} s^{-1}, 3.5 \times 10^{-47} W$
$d = 12 cm$	$1 \times 10^{-36} s^{-1}, 7 \times 10^{-60} W$	$1.3 \times 10^{-37} s^{-1}, 8.7 \times 10^{-61} W$	$1.6 \times 10^{-38} s^{-1}, 1 \times 10^{-61} W$

Note that if during prototype-detector tests it became apparent that diffraction rays reached a microwave receiver without being intercepted by an absorber wall, then one would increase the diameter of the nominal or design GB from 9 cm to 12 cm resulting in diffraction flux at a receiver of $1.31 \times 10^{-15} s^{-1}$, which would be negligible. Such a design change would also increase detector size and cost, so this alternative design would not be pursued unless needed.

Scanning & Bandwidth

The “detected bandwidth” (BW) is determined by two factors:

- random fluctuations in the GB transmitter output causing BW broadening, and
- the bandwidth of the microwave receivers. In general, the narrower the frequency range or bandwidth is the more sensitive is the detector (the noise floor is lowered at smaller BW).

However, frequency scanning allows a wide band of HFRGWs to be analyzed. As an example, in a 1 Hz “bandwidth” and a 1000s observation interval, then over a year of observation about 30kHz HFRGW frequency band could be scanned. Essentially one would sample the detected BW by a number of very narrow actual bandwidths, B_w . If the observation interval is 1000s, then the actual B_w is 0.001Hz. or, for 100s observation interval, then a 300 kHz band of HFRGWs could be scanned. For a 1 kHz BW, then a 0.3 GHz band could be scanned using 100s intervals over a year, and this would be a substantial BW if centered on 10GHz base frequency.

Microwave Lenses Outside of GB

