



The Stimulated Emission and Detection of Gravitational Waves via the use of Dissimilar Superconducting Josephson Junctions

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Presentation Outline



1. 1964 Halpern & Laurent
2. 1982 Ford - Quantum GW
3. 2012 Fontana - spin 2 transitions
4. Fontana - the S-wave to D-wave SC junction
5. Fontana - emission power estimate
6. The curved GASER
7. AC Josephson Effect
8. 150, 200, 300 mm Wafer Scale Emitters / Detector (WSE / WSD) designs
9. GW generation / detection lab setup
10. Output power predictions
11. Detection sensitivity
12. Conclusion / Next Steps
13. Nomenclature
14. References

1. 1964 Halpern & Laurent - the Gravitational Radiation of Microscopic Systems



- 1.1, Gravitational radiation for $J = 2, l = 0$

Angular dependence $\vec{y}_{J,l,M}^{\theta,\varphi}$ of the potentials: $\sqrt{\frac{1}{4\pi}} \vec{\omega}_M$ (1)

Angular dependence of the amplitudes $\vec{y}_{J,l,M}^{\theta,\varphi} \cdot \vec{\omega}_{\mp 2}$:

$$\text{For } M = 2, \mu = +2, (4\pi)^{-\frac{1}{2}} \cdot \cos^4 \frac{\theta}{2} \cdot \exp[2i\varphi] \quad (2)$$

$$\text{For } M = 2, \mu = -2, (4\pi)^{-\frac{1}{2}} \cdot \sin^4 \frac{\theta}{2} \cdot \exp[2i\varphi] \quad (3)$$

$$\text{For } M = 1, \mu = +2, (\pi)^{-\frac{1}{2}} \cdot \cos^3 \frac{\theta}{2} \cdot \sin \frac{\theta}{2} \cdot \exp[2i\varphi] \quad (4)$$

$$\text{For } M = 1, \mu = -2, -(\pi)^{-\frac{1}{2}} \cdot \cos \frac{\theta}{2} \cdot \sin^3 \frac{\theta}{2} \cdot \exp[2i\varphi] \quad (5)$$

$$\text{For } M = 0, \mu = +/ -2, (6)^{-\frac{1}{2}} \cdot \cos^2 \frac{\theta}{2} \cdot \sin^2 \frac{\theta}{2} \quad (6)$$

Angular dependence of the total radiation: $|\vec{y}_{J,l,M}^{\theta,\varphi} \cdot \vec{\omega}_{+2}|^2 + |\vec{y}_{J,l,M}^{\theta,\varphi} \cdot \vec{\omega}_{-2}|^2$:

$$\text{For } M = 2, \cos^8 \frac{\theta}{2} \cdot \sin^8 \frac{\theta}{2} \quad (7)$$

- 1.2, Gravitational radiation for $J = 2, l = 1$

Angular dependence of the potentials:

$$\text{For } M = 2, (2\pi)^{-\frac{1}{2}} \cdot (\cos \theta \cdot \vec{\omega}_2 + \frac{1}{2} \sin \theta \cdot \exp[2i\varphi] \vec{\omega}_1) \quad (8)$$

Angular dependence of the amplitudes:

$$\text{For } M = 2, \mu = +2, (2\pi)^{-\frac{1}{2}} \cdot \cos^4 \frac{\theta}{2} \cdot \exp[2i\varphi] \quad (9)$$

$$\text{For } M = 2, \mu = -2, -(2\pi)^{-\frac{1}{2}} \cdot \sin^4 \frac{\theta}{2} \cdot \exp[2i\varphi] \quad (10)$$

Angular dependence of the total radiation: the same as for $J = 2, l = 0$.

Spinor coupled spherical harmonic tensors were used by Halpern & Laurent to predict the angular distribution of the lowest orders of gravitational radiation from spin 2 transitions



2. 1982 Ford- Gravitational Radiation by Quantum Systems

○ 2.1 Semi-classical metric perturbation

$$\overline{h_{\mu\nu}} = \overline{h_{\mu\nu}^{in}} + 16\pi \int G_r(X, \dot{X}) T_{\mu\nu}(\dot{X}) d^4x' \quad (11)$$

Where:

$\overline{h_{\mu\nu}}$ = metric perturbation

$\overline{h_{\mu\nu}^{in}}$ = in-field metric component

$G_r(X, \dot{X})$ = retarded Green's function

$T_{\mu\nu}(\dot{X})$ = energy momentum tensor

○ 2.2 Setting semi-classical & quantum approaches equal

$$\langle T_{\mu\nu}(\dot{X}) \rangle \langle T_{\alpha\beta}(\dot{X}) \rangle = \langle T_{\mu\nu}(\dot{X}) \cdot T_{\alpha\beta}(\dot{X}) \rangle \quad (12)$$

Where:

$T_{\mu\nu}(\dot{X})$ = energy momentum tensor

$T_{\alpha\beta}(\dot{X})$ = energy momentum tensor perturbation

○ 2.3 Radiated gravitational wave power in semi-classical theory

$$P \approx P_{sc} = [z]^4 \omega^4 (\omega \ell)^{-\alpha} \approx \varepsilon^2 \omega^2 \ell^6 (\omega \ell)^{-\alpha} \quad (13)$$

Where:

$P \approx P_{sc}$ = semi-classical radiated power

$[z]$ = resonant cavity dimension

ω = radiating frequency

ℓ = characteristic cavity dimension

ε = average energy density in the cavity

α = scaling constant, where $(\omega \ell)^{-\alpha}$ is mode function

○ 2.4 Radiated gravitational wave power from quantum theory

$$P_q = n^2 \omega^4 (\omega \ell)^{-\alpha} \quad (14)$$

Where:

P_q = quantum case radiated power

ω = radiating frequency

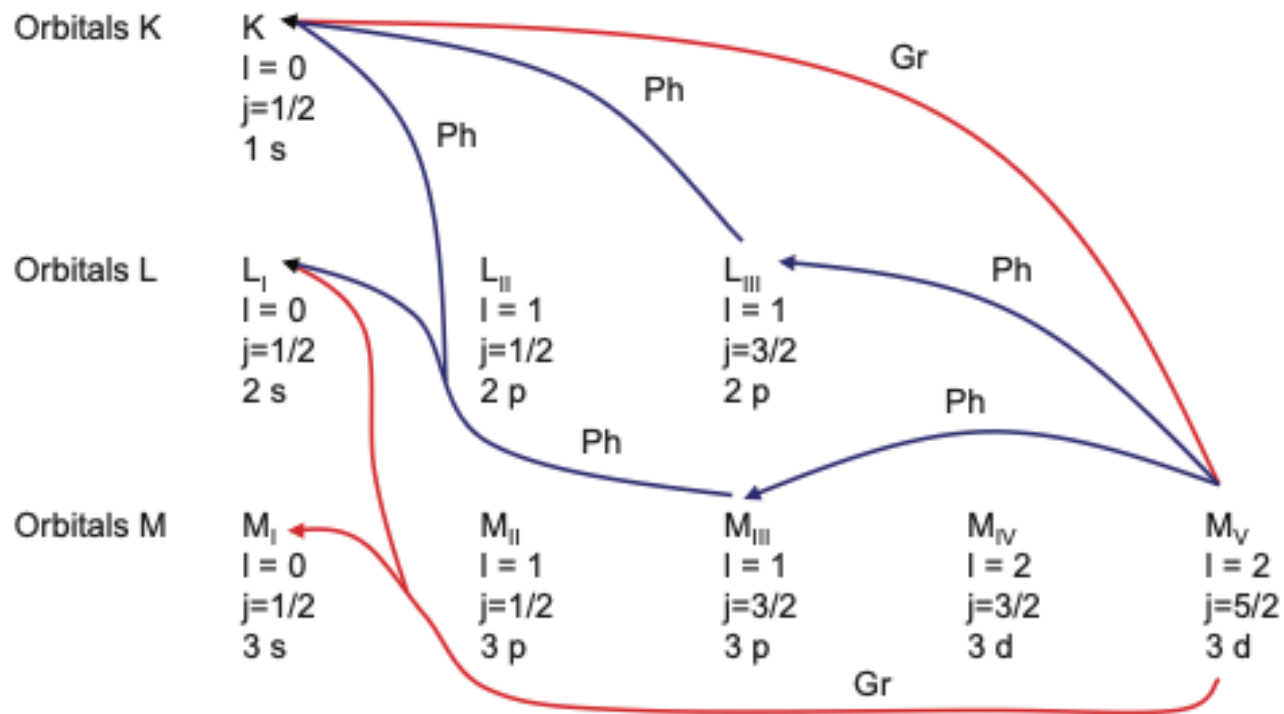
ℓ = characteristic cavity dimension

β = quantum scaling constant

n = number of quantum radiators

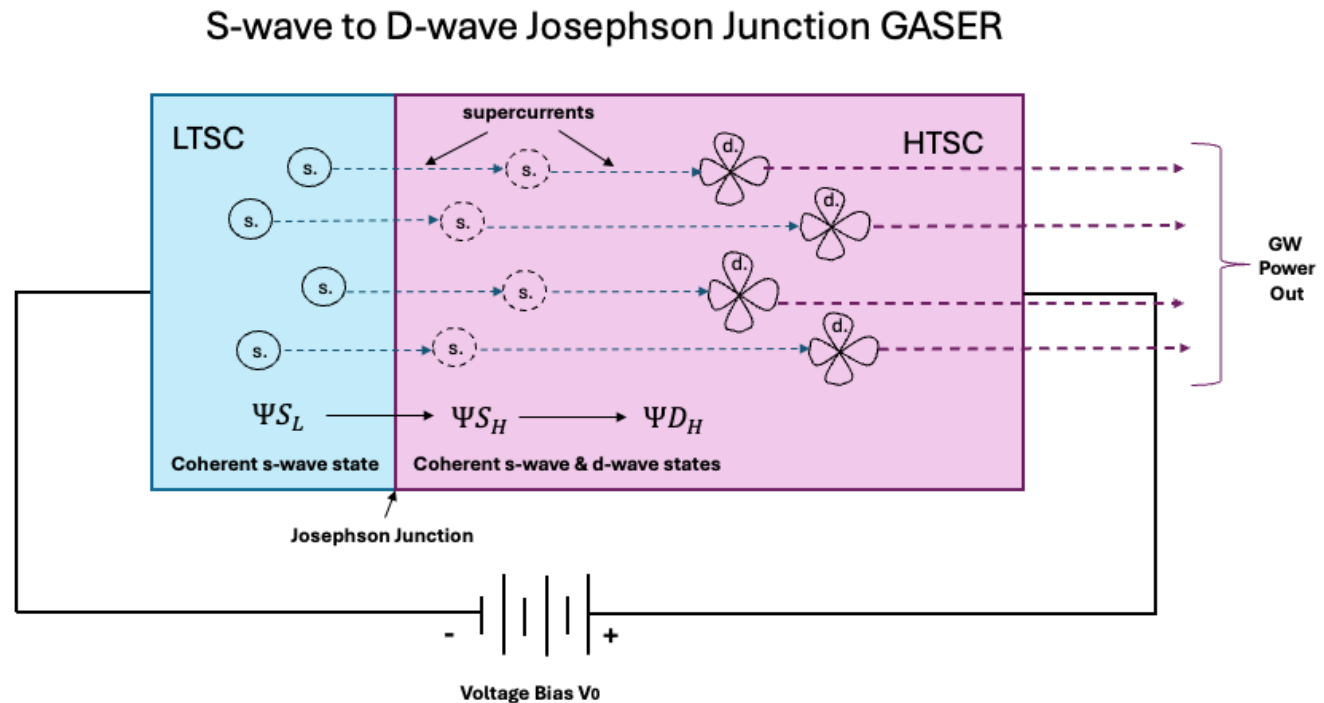


3. 2012 Fontana - spin 2 transitions



- *Examples of photon and graviton transitions [3]
(reprinted with permission)*

4. Fontana - the S-wave to D-wave SC junction



- *Graviton emissions at an s-wave to d-wave junction, adapted from [3]*

(Here the "s-states" and "d-states" refer to orbital angular momentum symmetries in the superconducting order parameter, not the band structure)



5. Fontana - emission power estimate

- 5.1 Spontaneous graviton transitions versus photon transitions

$$\frac{\Gamma_g}{\Gamma_e} \approx 1.28 \times 10^{-47} \quad (15)$$

- 5.2 Macroscopic power versus Planckian scale

$$P/P_p \approx n^2 \left(\omega/\omega_p \right)^4 \quad (16)$$

- 5.3 Where the following nomenclature applies:

Γ_g = graviton transitions

Γ_e = electromagnetic dipole transitions

P = emitted GW power

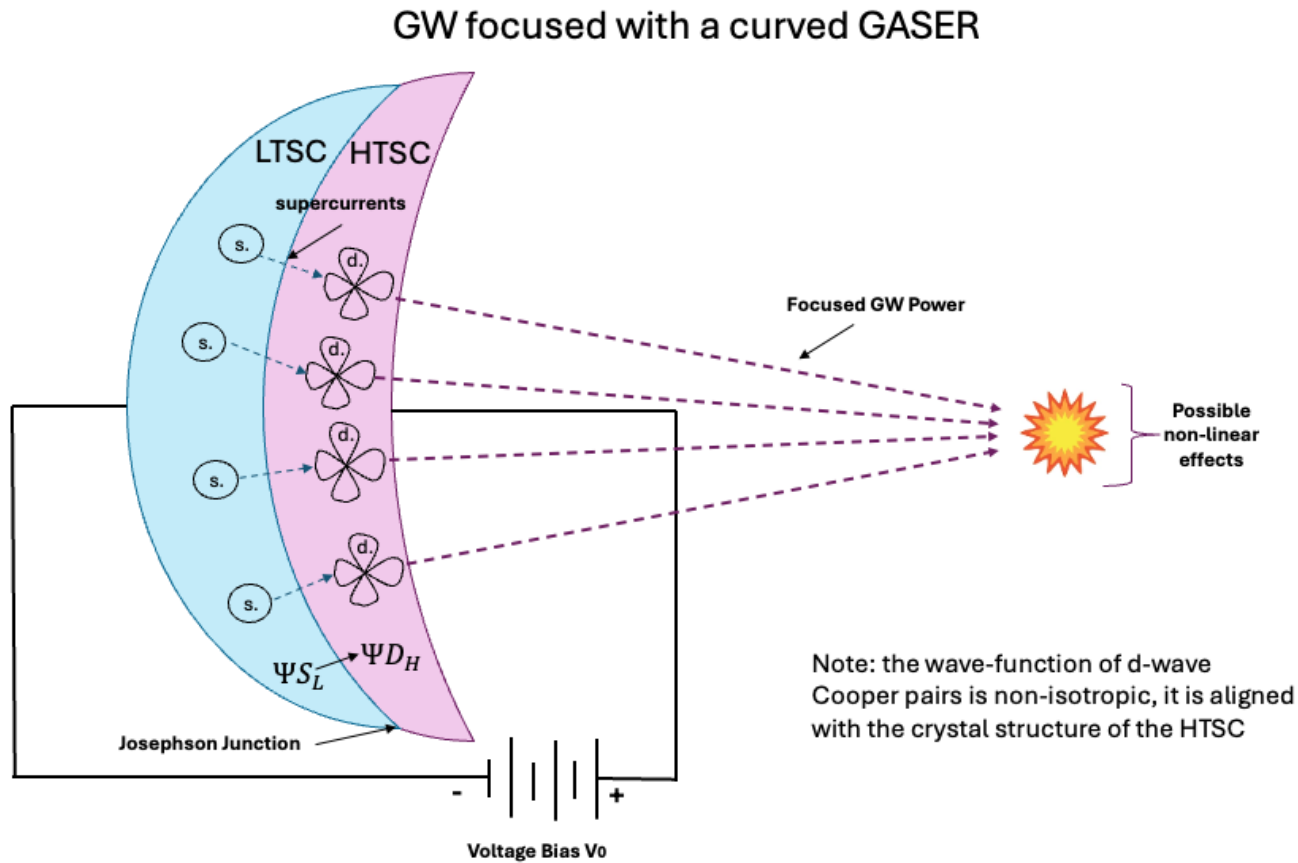
P_p = Planck power $\sim 10^{-5} \text{g}/10^{-44} \text{sec} \sim 10^{60} \text{ ergs/sec}$

ω = emitted frequency

ω_p = Planck frequency $\sim 10^{44}/\text{sec}$

n = number of quantum emitters

6. The curved GASER



- A curved GASER to create an HFGW focal point, adapted from [3], [7]

7. Operating Frequency & Voltage (in concert with the AC Josephson Effect)



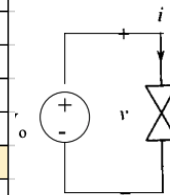
Frequency (GHz)	Wavelength (cm)	Qtr Wave Geom (cm)	JJ Operating Voltage* (uV)
1.296	23.15	5.79	2.68
2.32	12.93	3.23	4.80
3.4	8.82	2.21	7.03
5.76	5.21	1.30	11.91
10.368	2.89	0.72	21.44
24.048	1.25	0.31	49.73
47.088	0.64	0.16	97.37
76.233	0.39	0.10	157.64
120	0.25	0.06	248.14
249	0.12	0.03	514.89
6250	0.0048	0.0012	12923.90

Notes:

(1) Amateur microwave bands selected for examination, except for last far IR band

(2) JJ Operating voltage assumed to be $V_{op} (\mu V) = Op\ Freq / 483600\ GHz^*$

AC Josephson Effect



$$i = I_c \sin \phi$$

$$v = \frac{\Phi_0}{2\pi} \frac{d\phi}{dt}$$

The voltage source is DC with $v = V_0$, so that

$$\phi(t) = \phi(0) + \frac{2\pi}{\Phi_0} V_0 t$$

The resulting current is ac!

$$\begin{aligned} i &= I_c \sin \left(\frac{2\pi}{\Phi_0} V_0 t + \phi(0) \right) \\ &= I_c \sin (2\pi f_J t + \phi(0)) \end{aligned}$$

The Josephson frequency is $f_J = \frac{V_0}{\Phi_0} = \frac{2e}{h} V_0 = 483.6 \times 10^{12} V_0 \text{ (Hz)}$

A dc voltage of 10 μV causes an oscillation frequency of about 5 GHz, a Josephson microwave oscillator. But with a typical I_c of 1 mA, this oscillator delivers a very small power of the order of 10 nW. Therefore need many synchronous oscillators.

Massachusetts Institute of Technology
6.763 2003 Lecture 11

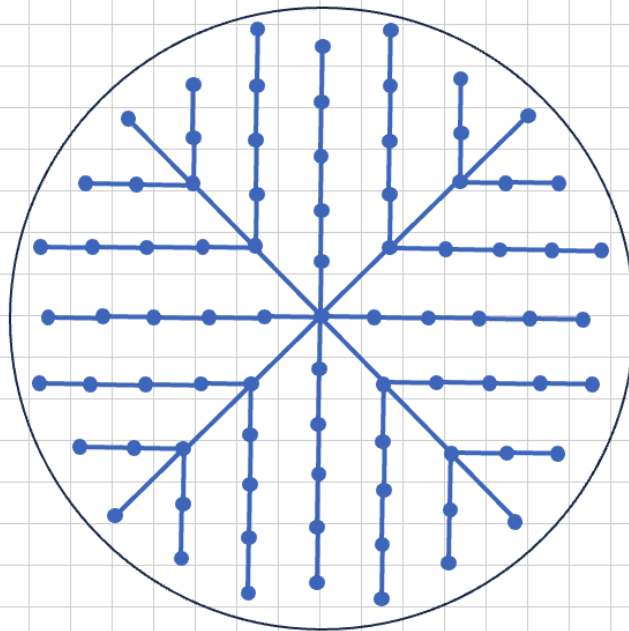


- Operating voltage determines operating frequency in the AC Josephson effect
- Reference slide 14: <https://web.mit.edu/6.763/www/FT03/Lectures/Lecture11.pdf>

8.1 Wafer Scale Emitters & Detectors (WSE & WDE, 150 mm case)



150 mm wafer, 24 GHz case



Notes:

13 diagonal emitters / receivers

20 cross emitters / receivers

12 quad emitters / receivers x 4 quads

81 total emitters / receivers on 150 mm wafer

Diagonal spacing = 2 wavelengths

Cross & Quad spacing = 1 wavelength

Emitter / Receiver pad size = 1/4 wavelength

Geometry for 24 GHz operating frequency:

Diagonal spacing = 25 mm

Cross & Quad spacing = 12.5 mm

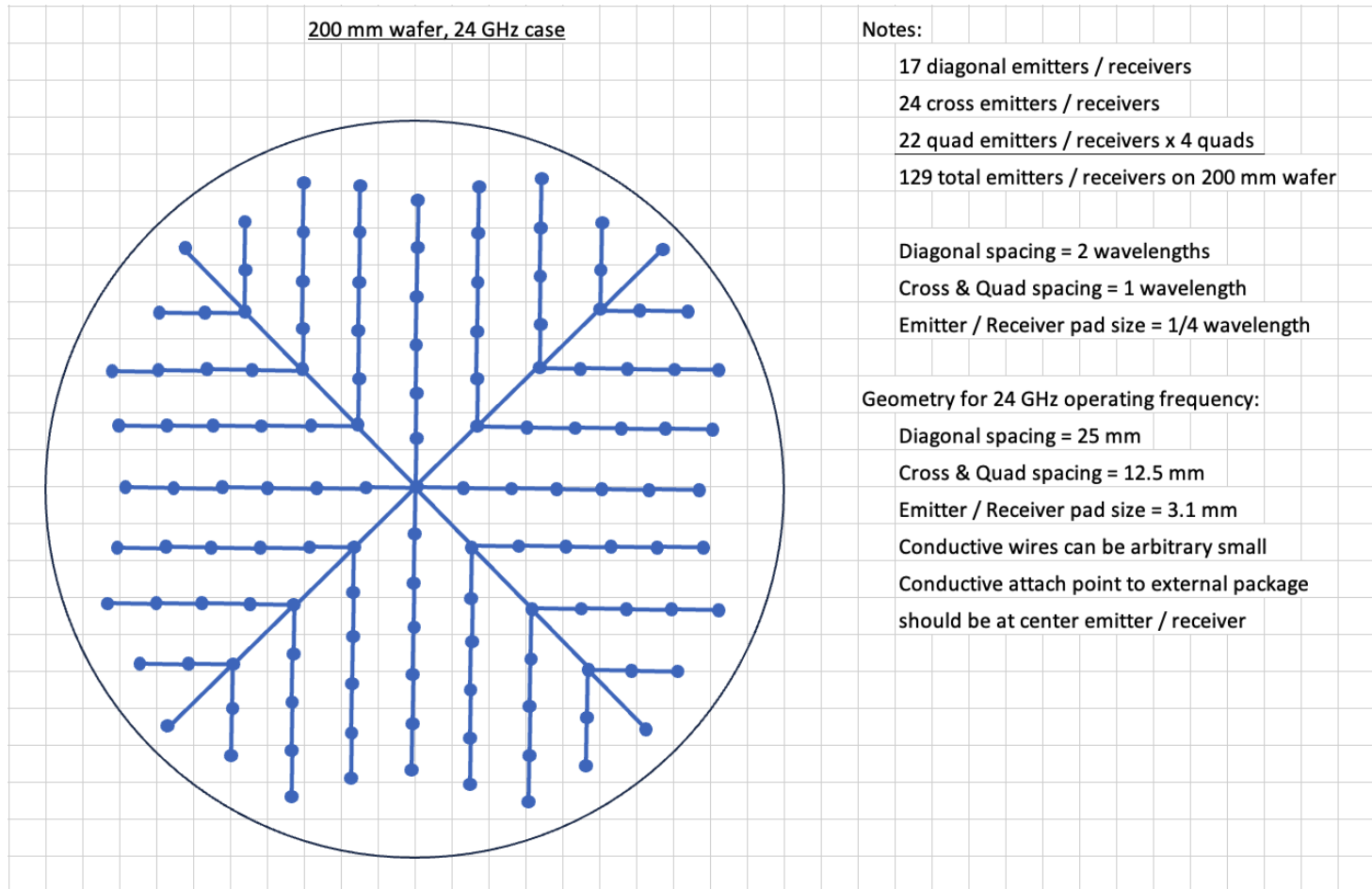
Emitter / Receiver pad size = 3.1 mm

Conductive wires can be arbitrary small

Conductive attach point to external package
should be equidistant for both polarities

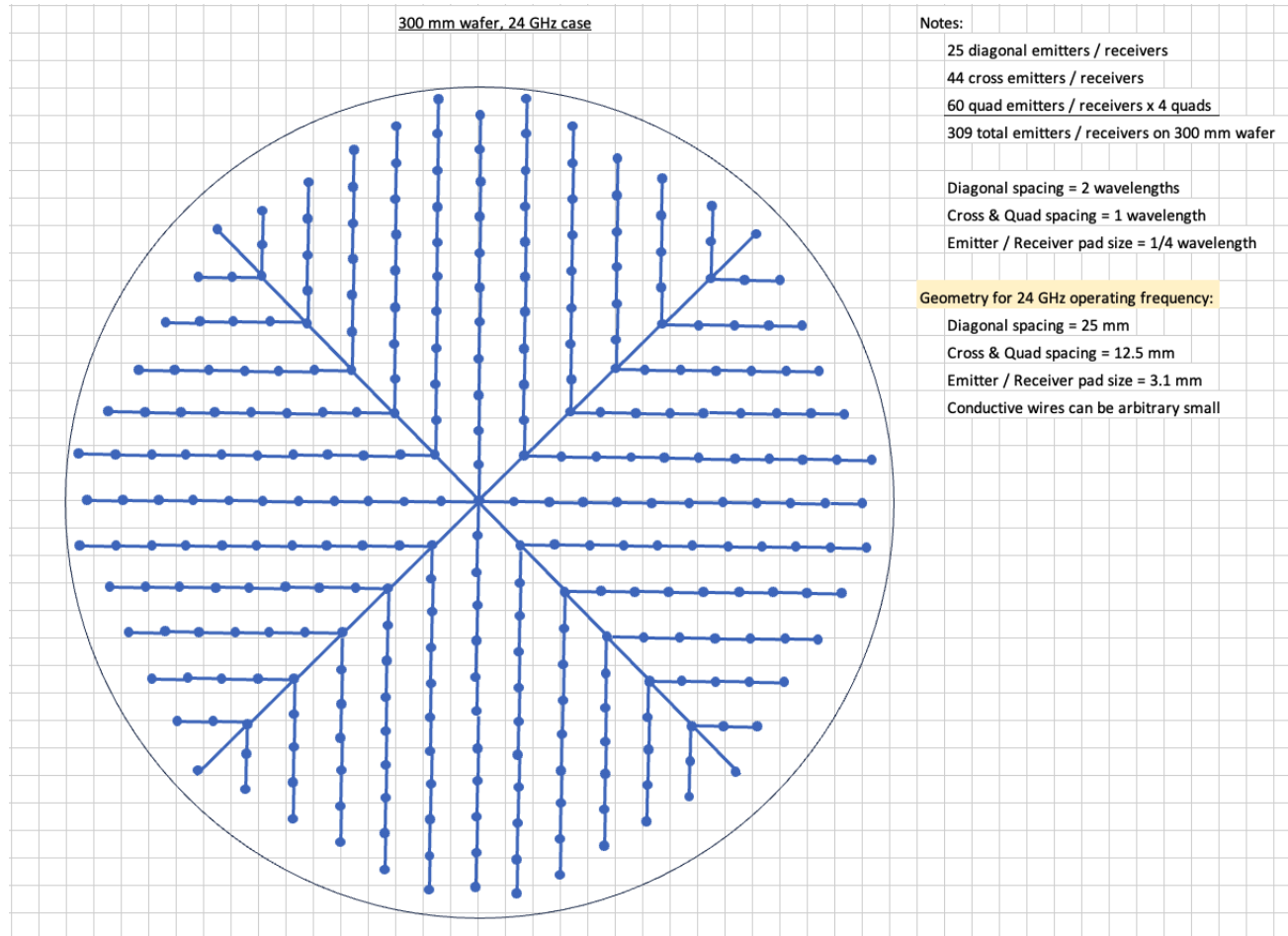
- Phased Array Layout Example for 150 mm (6") Wafer Scale Emitter / Detector

8.2 Wafer Scale Emitters & Detectors (WSE & WDE, 200 mm case)



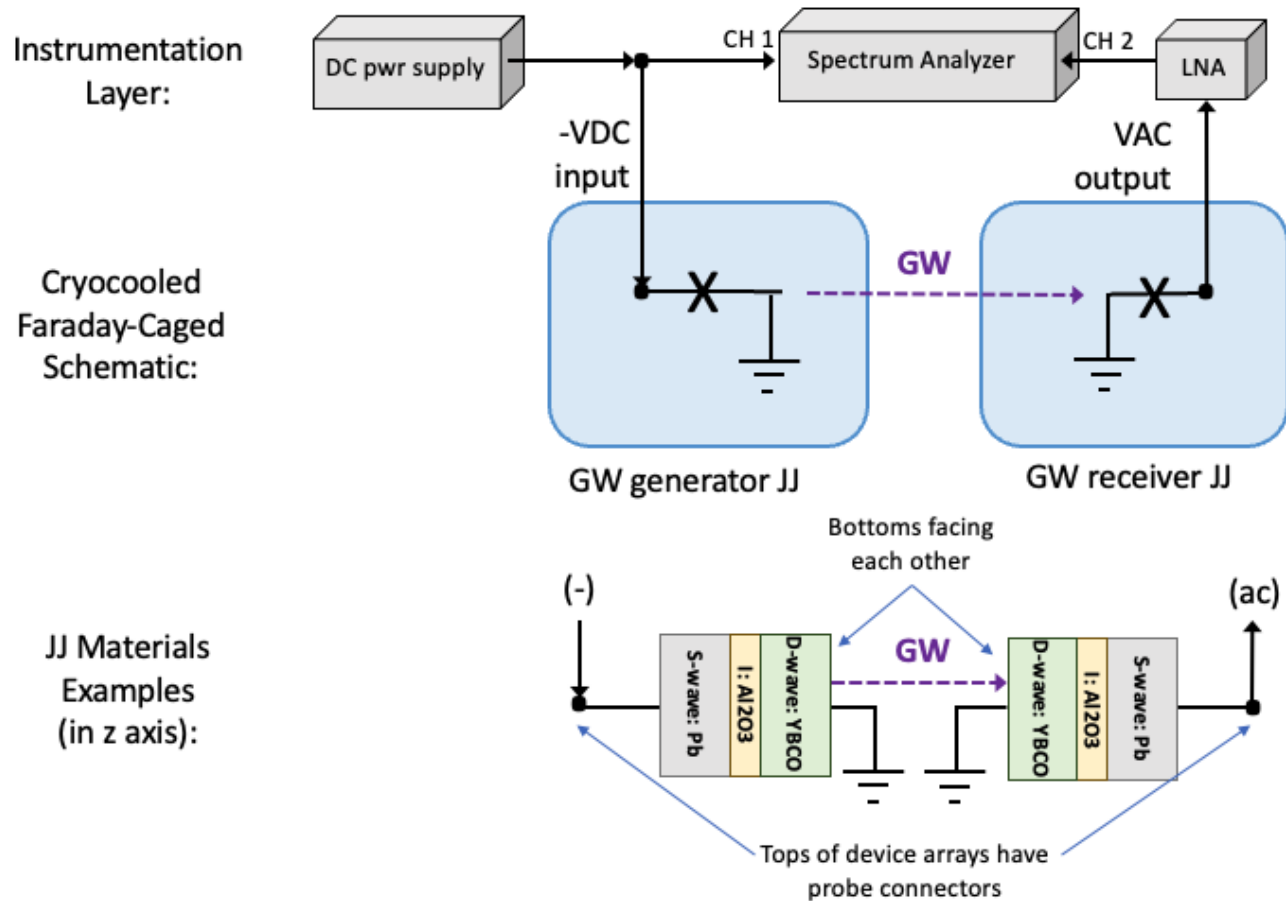
- Phased Array Layout Example for 200 mm (8") Wafer Scale Emitter / Detector

8.3 Wafer Scale Emitters & Detectors (WSE & WDE, 300 mm case)



- Phased Array Layout Example for 300 mm (11.8") Wafer Scale Emitter / Detector

9. GW generation / detection lab setup



- Josephson Junction GW Generation and Detection Lab Setup



10. Output power predictions

- 10.1 Fontana's original estimate for a bulk BSCCO HTSC device

Table 4, Expected performance of bulk BSCCO HTSC GASER [3] (reprinted with permission)

Parameter	Value	Units
Energy of s/d wave gap in BSCCO	~ 1.3	THz
Power output with 10 kA/cm ²	~ 10	W/cm ²
Power output for multilayer	~ 10 ³	W/ cm ²
Volumetric Power Output	~ 10	MW/m ³

- 10.2 Expected performance of thin film YBCO/Pb DJJ arrays

Table 5, Expected performance of thin film YBCO HTSC GASER

Parameter	Value	Units
Power emitted per unit area	~ 5.0	mW/cm ²
Power output of one emitter	~ 1.5	mW
Power output for 150 mm array	~ 121.5	mW
Power output for 200 mm array	~ 193.5	mW

- 10.3 for a per emitter resistance estimate of:

$$R_e = RA/A_e = 10^3 \Omega \mu\text{m}^2 / 30,190,000 \mu\text{m}^2 = 33 \mu\Omega \quad (17)$$

11. Detection sensitivity



NEP of DJJs

In detection applications the sensitivity of a device is limited by its Noise Equivalent Power (NEP). In the context of detection, Dissimilar Josephson Junctions (DJJs) are more commonly known as ‘Superconducting Tunnel Junctions, or STJs. [22] For YBCO NEPs of 10^{-15} to $6 \times 10^{-12} \text{ W}/\sqrt{\text{Hz}}$ have been reported [23], [24]. Holdengreber (2018) [25] goes on to observe that the energy gap of YBCO permits signal detection up into the THz range, therefore our target frequency of 24 GHz as identified in Table 1 should not pose any difficulty in the way of detection. At a bandwidth of 10,000 Hz NEP would be on the order of 600 pW, resulting in a signal to noise power ratio (SNR) of at least $202.5(10)^6$ for the 150 mm array, or better than a power ratio of 83 dB, assuming nearly perfect quantum conversion efficiency per (18):

$$SNR = \frac{\text{Power}}{NEP} = \frac{121.5 \text{ mW}}{600 \text{ pW}} = 202.5(10)^6 \approx 83. \text{ dB} \quad (18)$$

Quantum Efficiency of DJJs

The d-wave to s-wave conversion efficiency needed for a graviton to photon(s) conversion process is not well understood but is likely a function of quantum measurement efficiency [26] and doping profiles [27]. A range of doping regimes is recommended for experimental use to validate the best approach to enabling d-wave to s-wave graviton to photon(s) conversion. Given the small NEP cited in the proceeding analysis, even a small fractional quantum efficiency should result in an easily measurable signal.



12. Conclusions / Next Steps

- Conclusions
 - 12.1 Initial application of GW-JJs would be in GW Com (transmit and receive)
 - 12.2 Receive only GW-JJ detectors could have value in gravitational astronomy
 - 12.3 Receive only GW-JJ detectors may also hold value in SETI (Search for Extraterrestrial Intelligence) efforts
- Next Steps
 - 12.4 Theoretically estimate D-wave to S-wave quantum efficiency
 - 12.5 Explore the Atanasov JJ configuration (versus Fontana's)
 - 12.6 Build and test Fontana configuration as described on chart 9.

13. Nomenclature



○ 13.1 Halpern & Laurent Nomenclature

$\mathcal{Y}_{J,L,M}^{\theta,\varphi}$ = spinor coupling spherical harmonic tensors
 $\vec{\omega}$ = spin eigenvectors
 $\vec{\omega}_M$ = spin potential
 $\vec{\omega}_{\mp 2}$ = spin 2 amplitudes
 J, L, M, μ = quantum indices
 θ, φ = angular indices
 $\vec{q}$ = EM radiation potential

○ 13.2 Ford Nomenclature

$\overline{h_{\mu\nu}}$ = metric perturbation
 $\overline{h_{\mu\nu}^{in}}$ = in-field metric component
 $G_r(X, \dot{X})$ = retarded Green's function
 $T_{\mu\nu}(\dot{X})$ = energy momentum tensor
 $T_{\alpha\beta}(\ddot{X})$ = energy momentum tensor perturbation
 $P = P_{sc}$ = semi-classical radiated power
 P_q = quantum case radiated power
 $[z]$ = resonant cavity dimension
 ε = average energy density in the cavity
 ω = radiating frequency
 ℓ = characteristic cavity dimension
 α = scaling constant, where $(\omega\ell)^{-\alpha}$ is mode function
 β = quantum scaling constant
 n = number of quantum radiators

○ 13.3 Fontana Nomenclature

Γ_g = graviton transitions
 Γ_e = electromagnetic dipole transitions
 P = emitted GW power
 P_p = Planck power $\sim 10^{-5} \text{g}/10^{-44} \text{sec} \sim 10^{60} \text{ ergs/sec}$
 ω = emitted frequency
 ω_p = Planck frequency $\sim 10^{44}/\text{sec}$
 n = number of quantum emitters

○ 13.4 Experiment Design Nomenclature

V_0 = DC supply voltage
 v = AC Josephson effect voltage
 i = AC Josephson effect current
 I_c = DC level of critical current
 f_J = Josephson effect frequency
 Φ_0 = Josephson effect wavelength
 $\phi(t)$ = AC phase
 $\phi(0)$ = initial phase
 Ω = Ohms, units of resistance
 T_c = critical temperature
 J_c = critical current density
 V_c = critical voltage
 I_b = emitter bias current
 V_b = emitter bias voltage
 R_n = normal state resistance
 R_e = emitter resistance
 A_e = emitter area
NEP = noise equivalent power
 $W/\sqrt{\text{Hz}}$ = Watts per root Hertz (units of NEP)
SNR = signal to noise ratio



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