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WISPFI: Searching for ALPs-Photon conversion on a fiber interferometer

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17th PATRAS WORKSHOP

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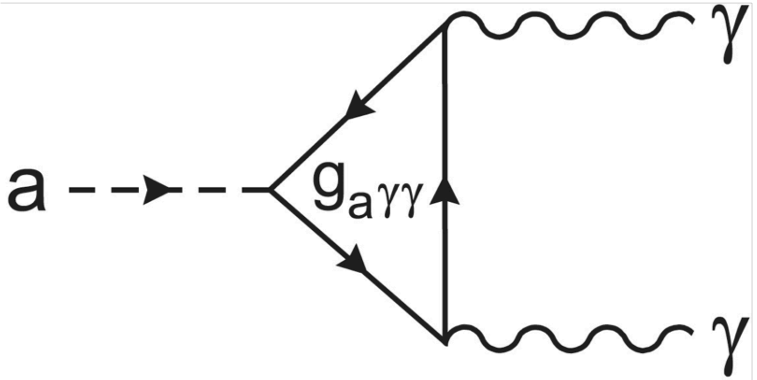
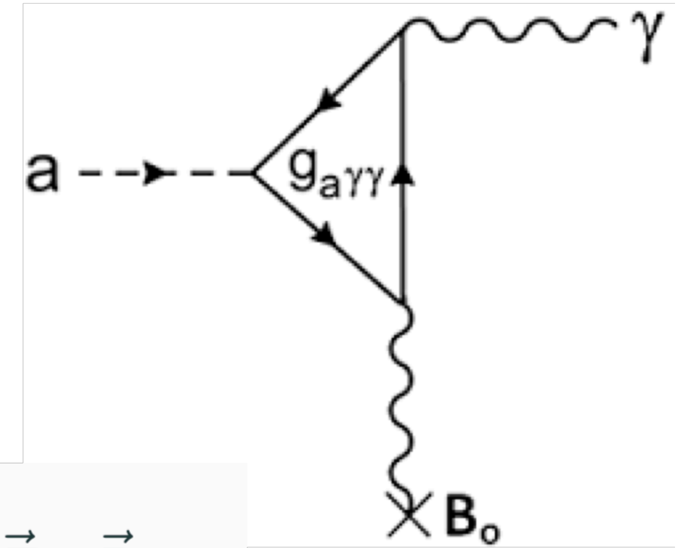
Introduction



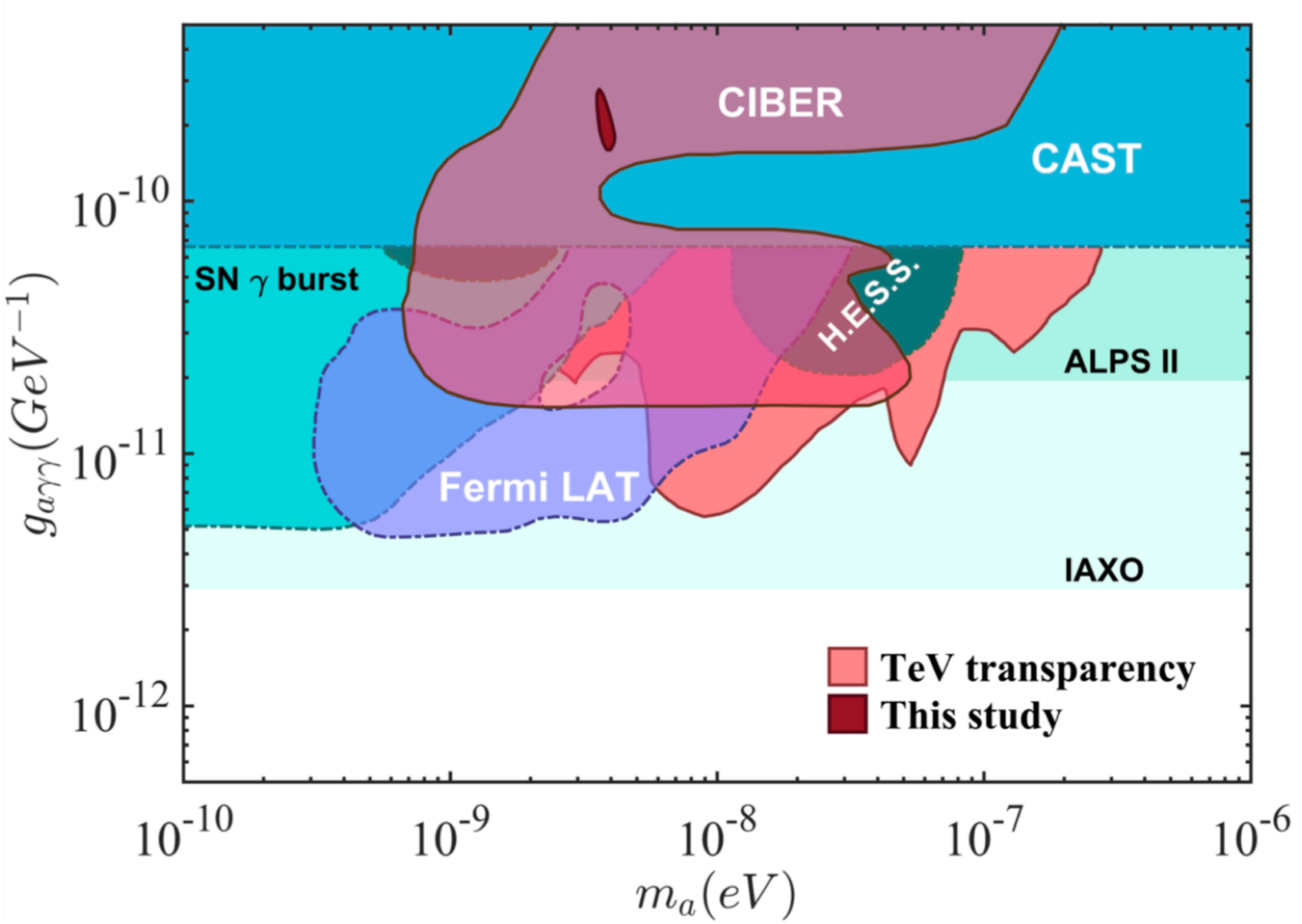


$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma\gamma} \vec{E} \cdot \vec{B} \, a \,,$$

Axion/ALPs oscillate into photons or vice-versa at the presence of magnetic field via Primakoff process.

Introduction

Limits on ALPs parameter space in the $(m_a, g_{a\gamma\gamma})$ plane.



ArXiv: 1801.08813
2008.08100
2208.00079

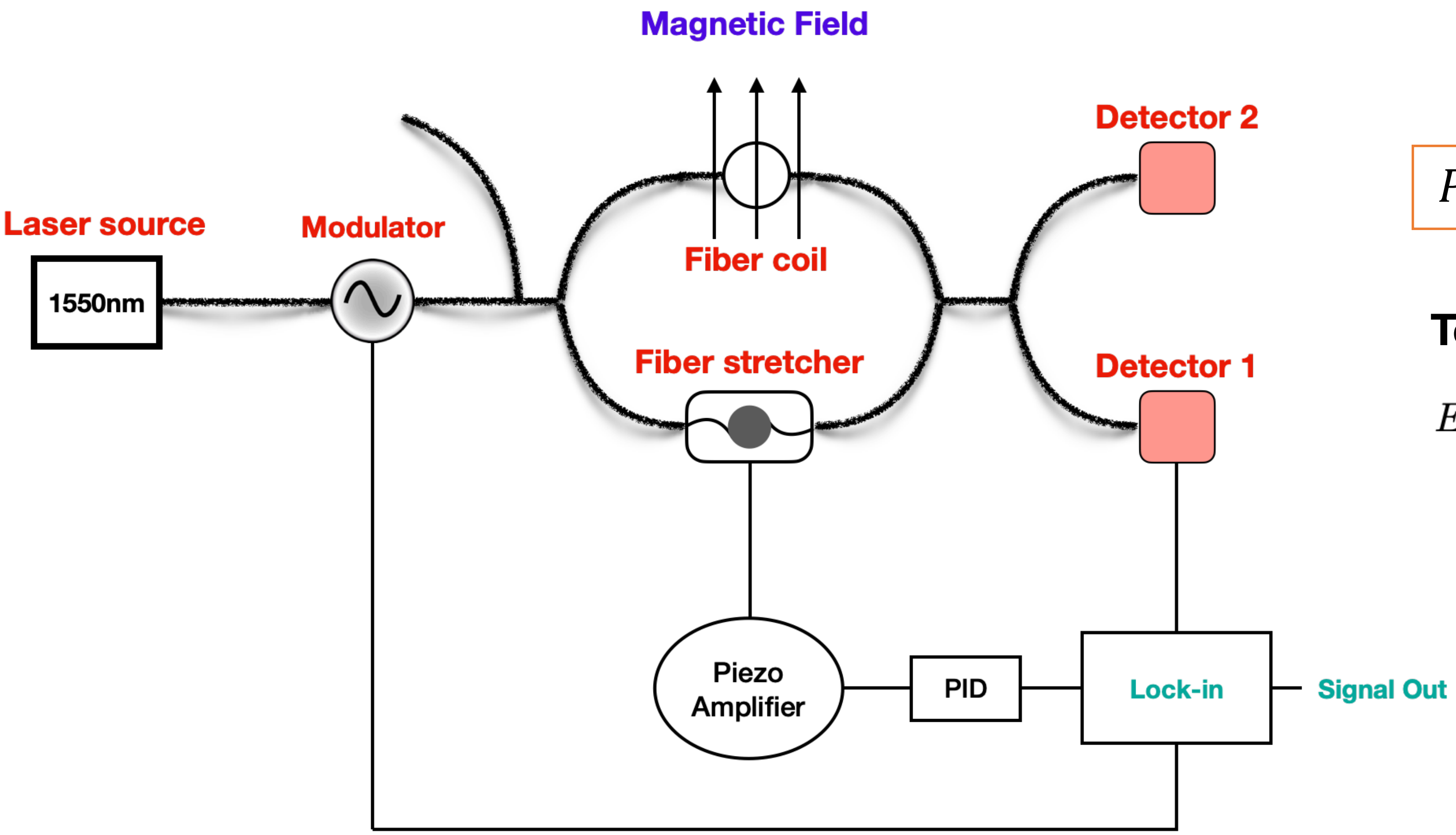
Exclude
Signal
On the way

$$g_{a\gamma\gamma} = (2.3 \pm 0.7) \times 10^{-10} GeV^{-1}$$

$$m_a = 3neV$$

Experiment design

(Tam&Yang) [1]



Basic Mach-Zehnder interferometer for WISPFI

$$P_{\gamma\rightarrow a} \propto g_{a\gamma\gamma}^2 (BL)^2$$

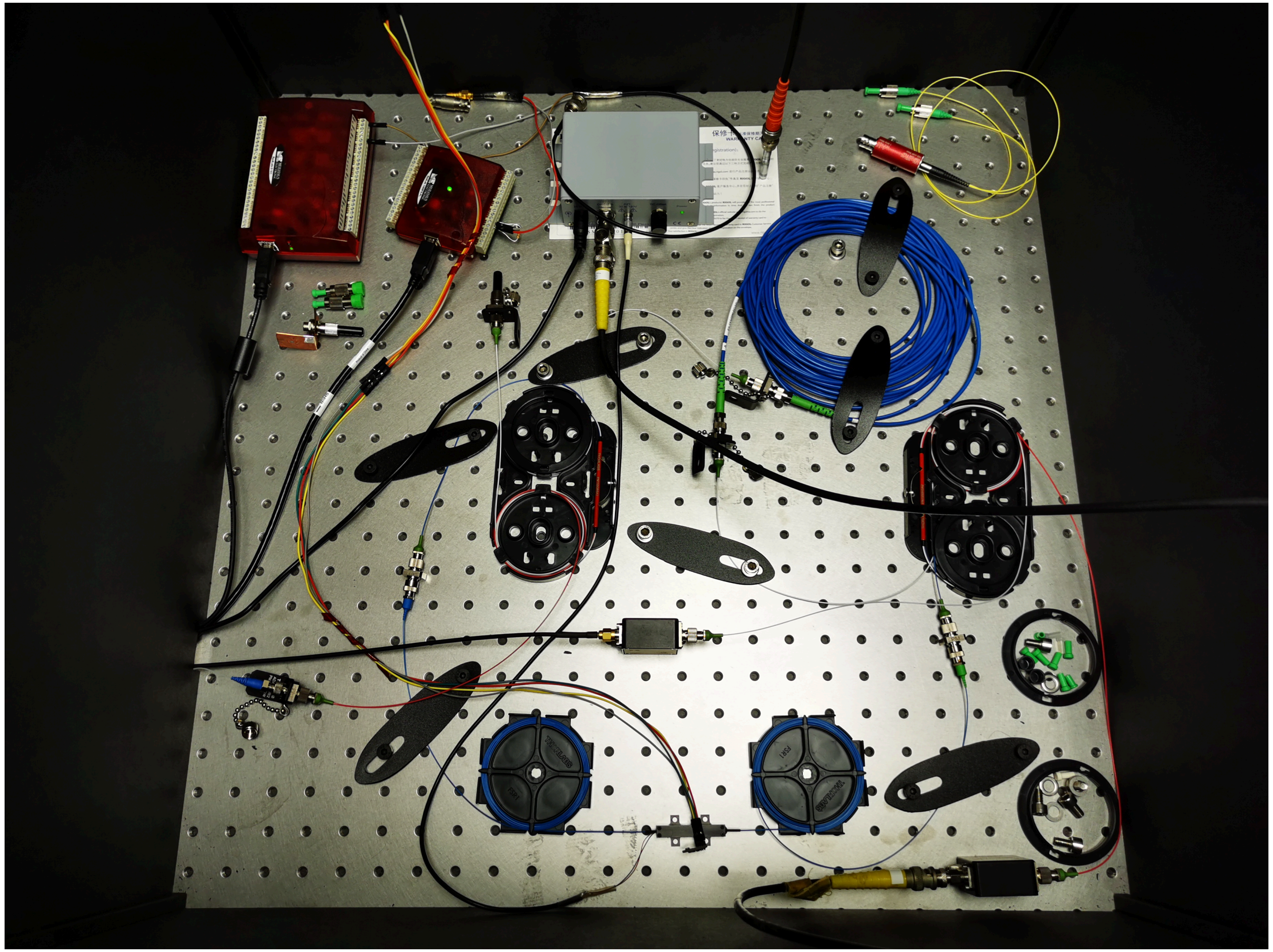
Total output field

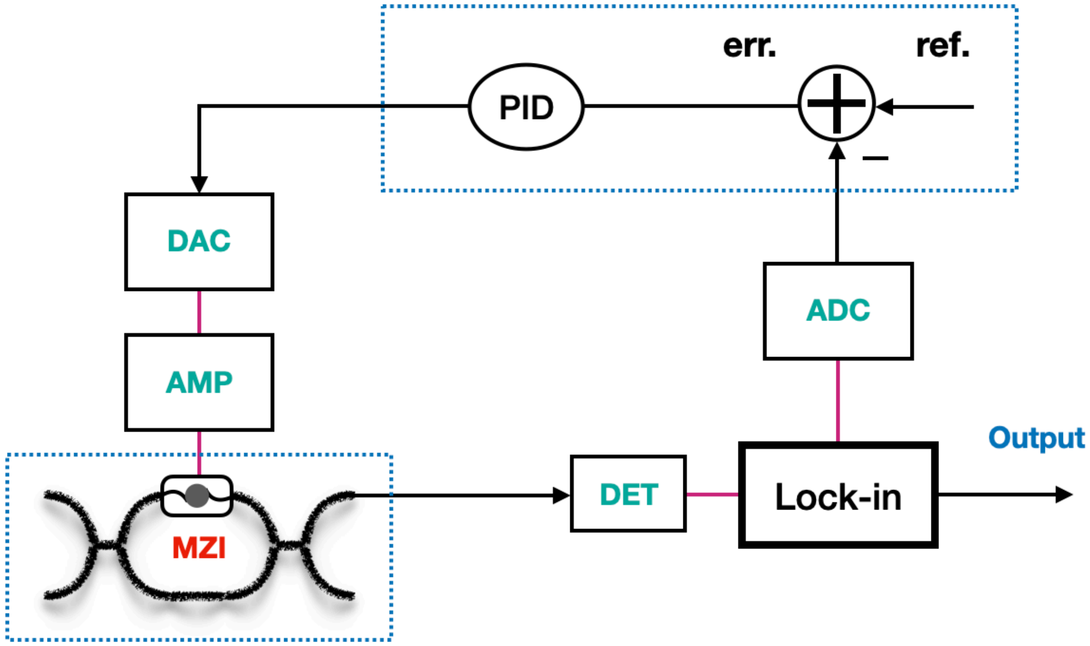
$$E_{\text{tot}} = E_c + E_+ + E_-$$
$$= \frac{E_0}{2} e^{i(\omega t + 2kL)} \Big[2i \sin(k\Delta L) - \alpha e^{-ik\Delta L}$$
$$+ \beta \big(2\cos(k\Delta L) - \alpha e^{-ik\Delta L} \big) \cos(\omega_m t + 2k_m L) \Big].$$

$$\alpha \equiv \frac{\delta A}{A} + i\delta\varphi$$

$$P_m = -4\beta \frac{\delta A}{A} \cos(2k\Delta L) \cos(\omega_m t + 2k_m L).$$

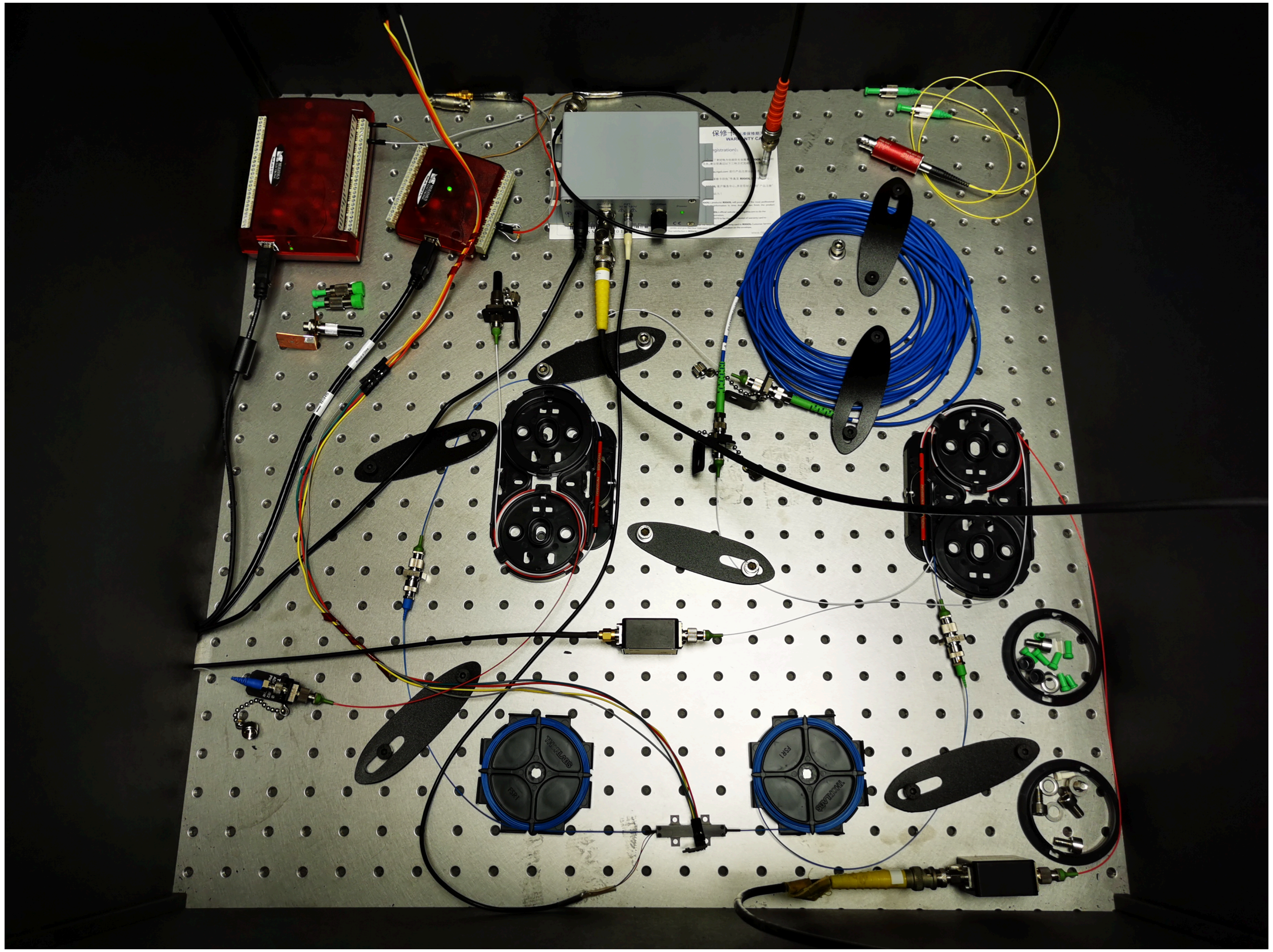
Prototype characterization



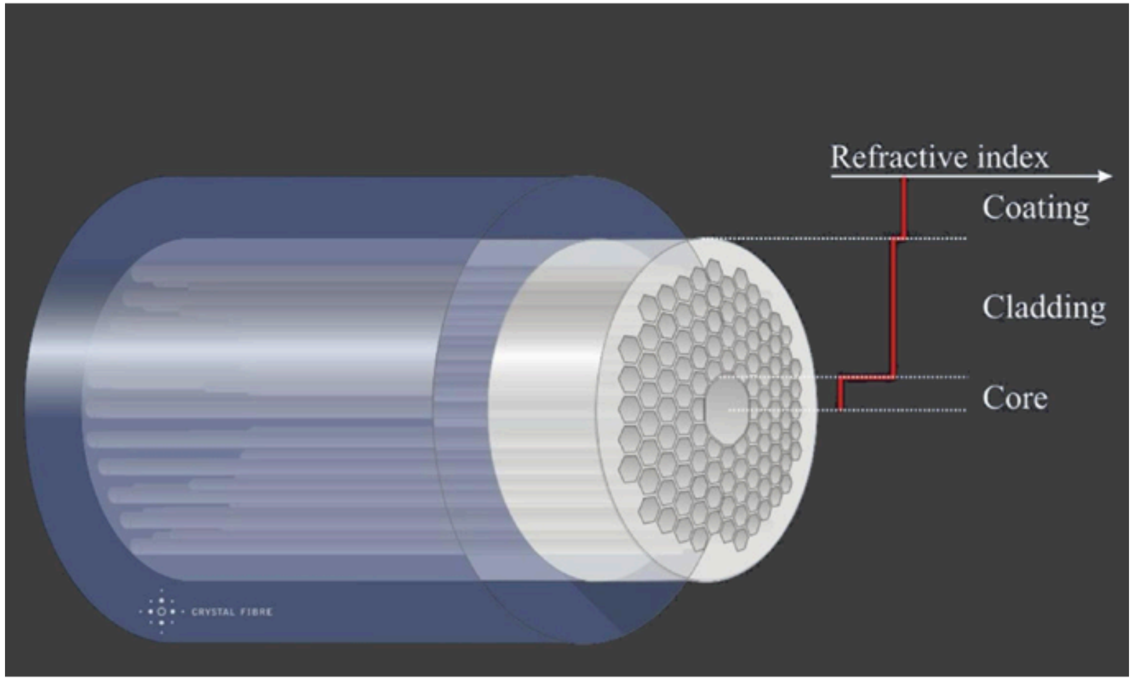


WISPFI prototype and feedback loop

Prototype characterization



NKT Photonics



Hollow-core photonic crystal fiber

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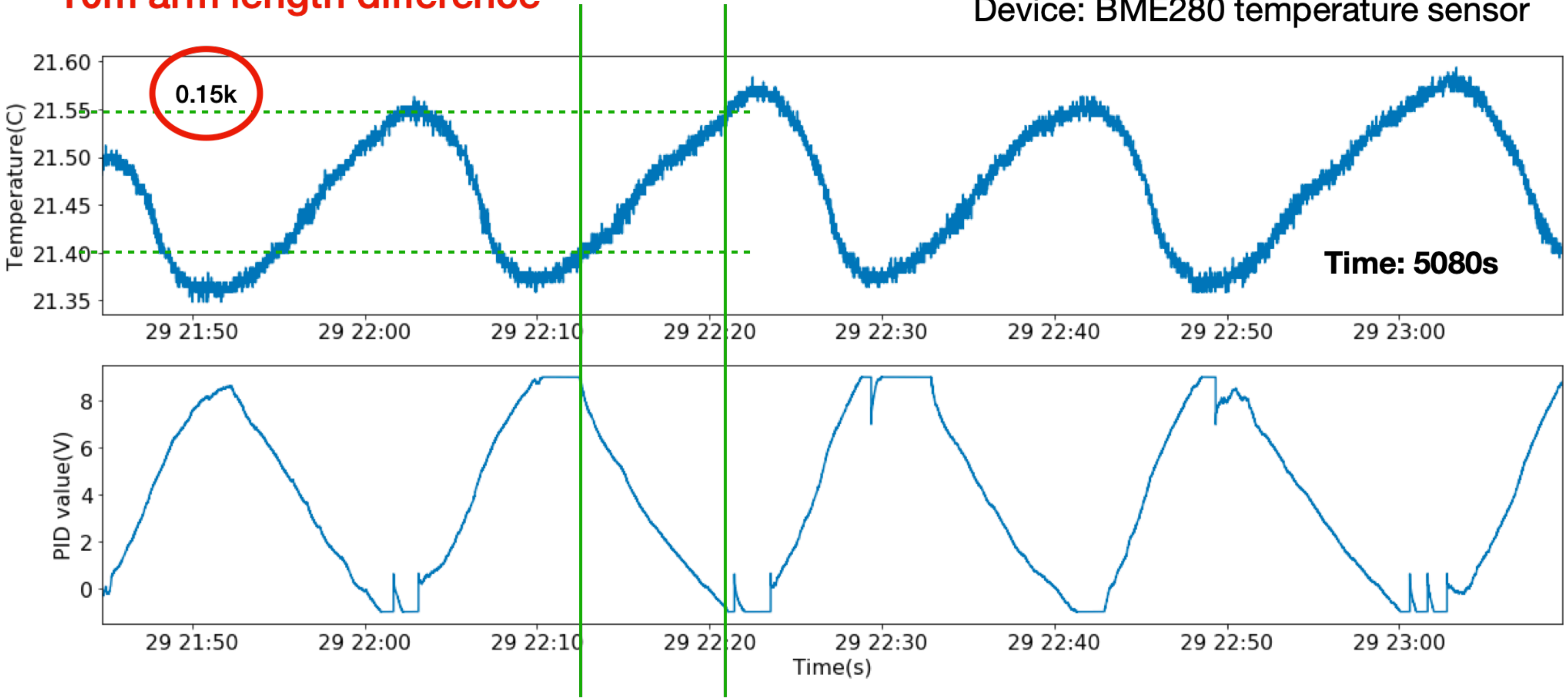
Prototype characterization

10m arm length difference

Device: BME280 temperature sensor



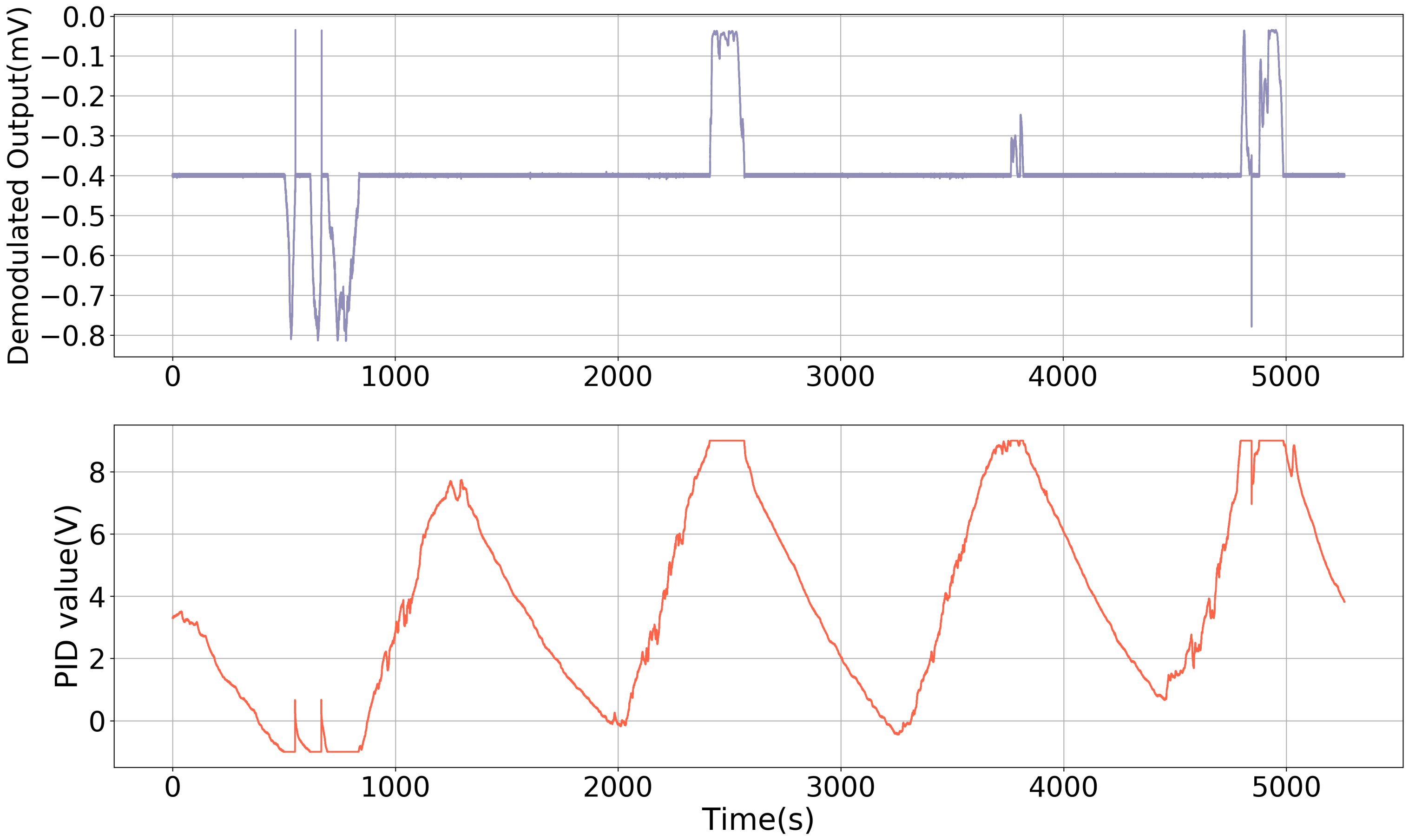
Device: UHF Lock-in Amplifier

dL = k*10^-6*dT*L
k~3 for silicon

dL = 13.88um
Then k~9.25

PID Value changed with temperature

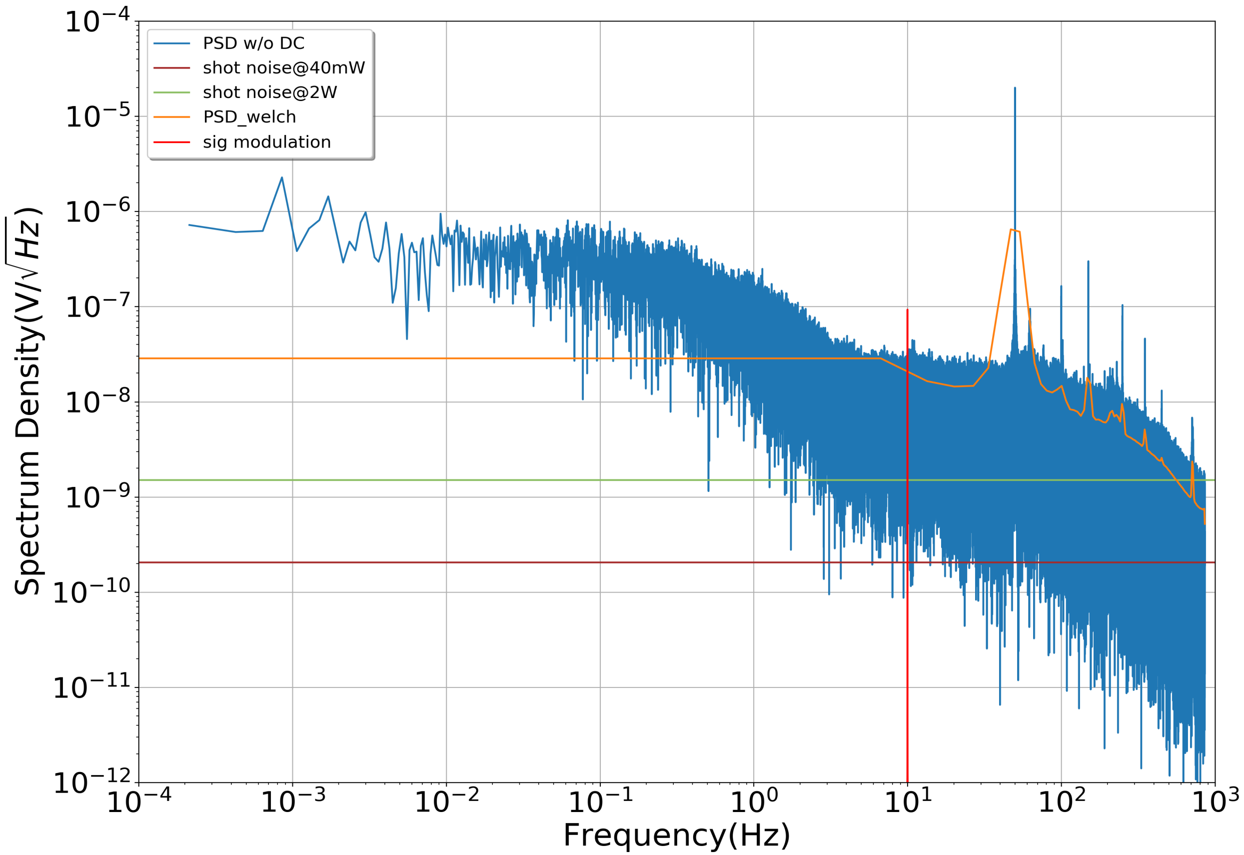
Prototype characterization

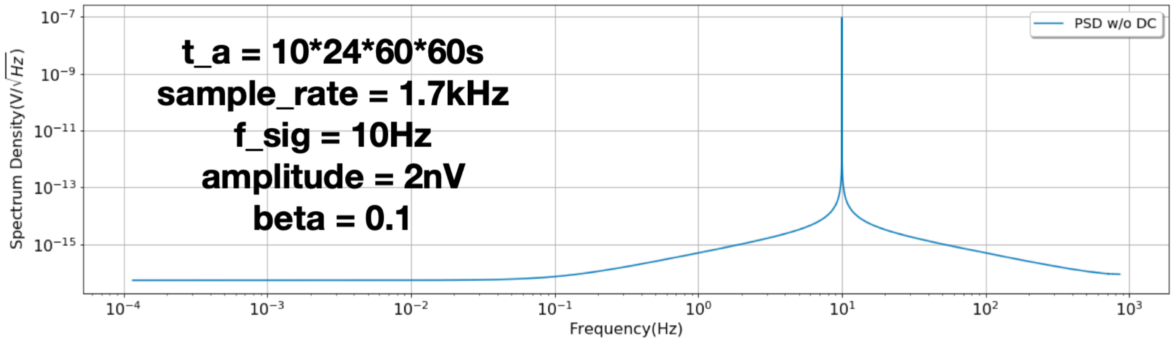


The interferometer is on locking

It breaks when temperature change is over the range

Prototype characterization





$$P_{(\gamma \to a)} \approx 2 \times 10^{-11}$$

$$\frac{\delta A}{A} \approx 2 \times 10^{-11}$$

$$K_{resp} = 1A/W$$

$$P_{\omega_m} \approx 4 \times 10^{-11} W$$

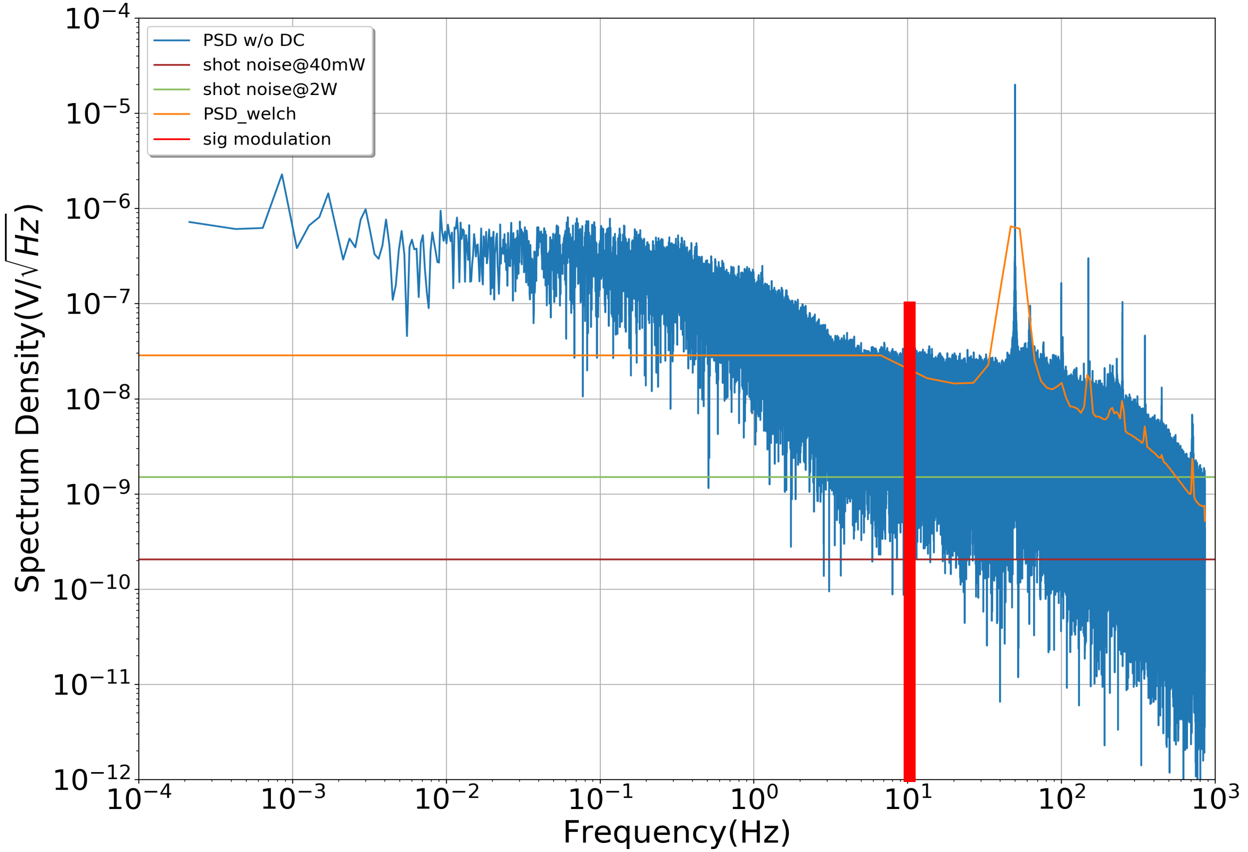
$$Z_{input} = 50\Omega$$

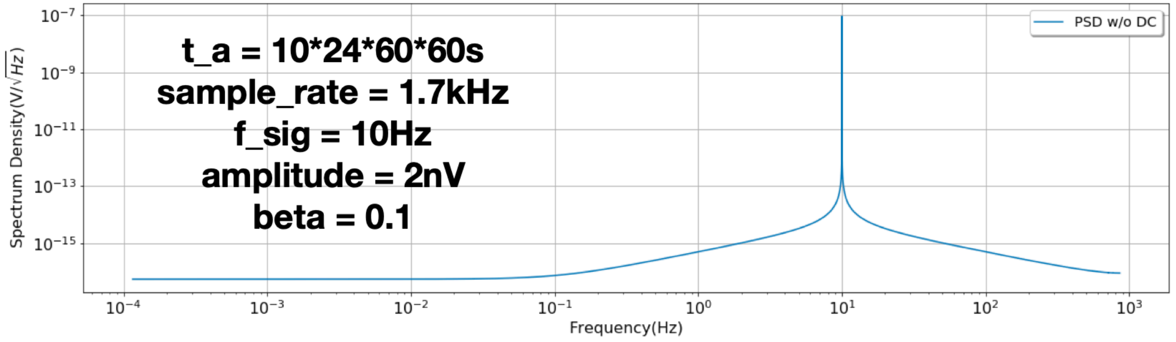
$$V_{demod} \approx P_{\omega_m} \times K_{resp} \times Z_{input}$$

$$V_{demod} = 2nV$$

$$SNR = \frac{\eta_{\gamma \to a} P_{tot} \beta_\omega K_{resp} Z_{input} \beta_{signal} / \sqrt{\Delta f}}{Noise_{demod}}$$

Prototype characterization





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Axion Electrodynamics on fiber

Classical duality symmetry

$$\nabla \cdot (\mathbf{E} - cga\mathbf{B}) = \rho_e/\epsilon_0$$
$$\nabla \cdot (c\mathbf{B} + ga\mathbf{E}) = 0$$
$$\nabla \times (c\mathbf{B} + ga\mathbf{E}) = \partial_t(\mathbf{E} - cga\mathbf{B})/c + c\mu_0 \boldsymbol{J_e}$$
$$\nabla \times (\mathbf{E} - cga\mathbf{B}) + \partial_t(c\mathbf{B} + ga\mathbf{E})/c = 0$$
$$\Box a = -\frac{g}{\mu_0 c}\mathbf{EB} - \frac{\partial U(a)}{\partial a}$$

Linear isotropic media

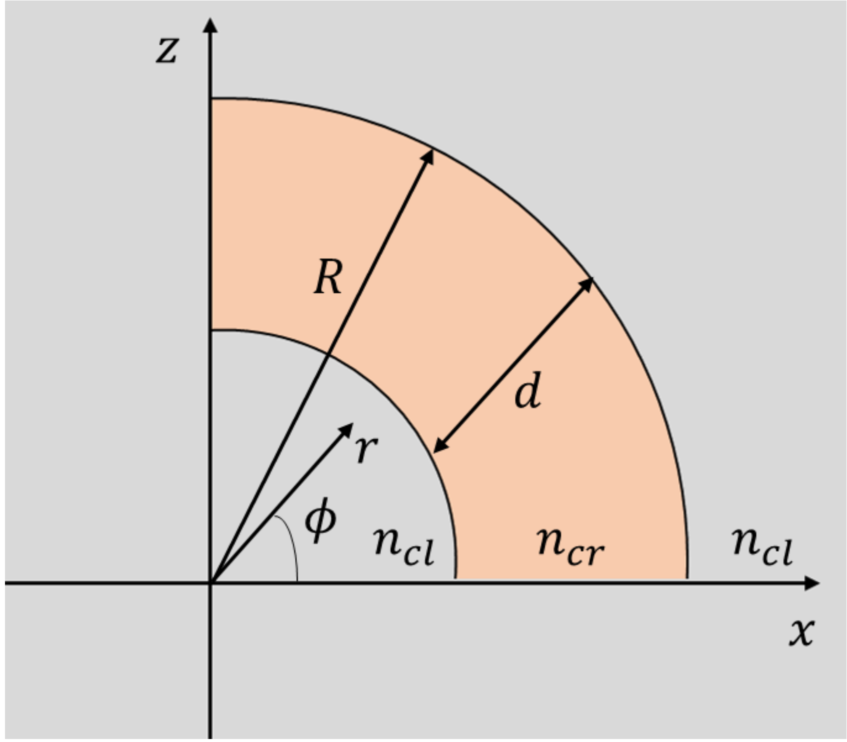
$$\nabla \cdot (\mathbf{D} - \tilde{g}a\mathbf{B_e}) = \rho_e$$
$$\nabla \cdot \left(\mathbf{B} + \tilde{g}^\dagger a\mathbf{D}\right) = 0$$
$$\nabla \times (\mathbf{H} + \tilde{g}a\mathbf{E}) - \partial t(\mathbf{D} - \tilde{g}a\mathbf{B_e}) = \mathbf{J_e}$$
$$\nabla \times \left(\mathbf{E} - \tilde{g}^\dagger a\mathbf{H_e}\right) + \partial t\left(\mathbf{B} + \tilde{g}^\dagger a\mathbf{D}\right) = 0$$
$$(\Box + m^2)a + \tilde{g}\mathbf{EB}_e = 0$$

(VISINELLI) [1]

$$where\ \tilde{g}\tilde{g}^\dagger = g_{a\gamma\gamma}^2, \tilde{g} = g_{a\gamma\gamma}\sqrt{\epsilon/\mu}, \tilde{g}^\dagger = g_{a\gamma\gamma}\sqrt{\mu/\epsilon},\ \mathbf{H_e} = \mathbf{B_e}/\mu,\ \mathbf{D} = \epsilon\,\mathbf{E},\ \mathbf{H} = \mathbf{B}/\mu$$

Axion Electrodynamics on fiber

Bend slab waveguide



Eq. of motion

$$\left[\partial_r^2 + \frac{1}{r^2}\partial_\phi^2 + \frac{1}{r}\partial_r + M(r)\right]\Psi(r,\phi) = 0$$

$$\tilde{\Psi}_\pm(r) = \begin{cases} \Psi_1 = AJ_\nu(k_{cl,\pm}r) & if\ \ 0 \le r \le R-d \quad (n_{cl}, substrate) \\ \Psi_2 = BJ_\nu(k_{cr,\pm}r) + CY_\nu(k_{cr,\pm}r) & if\ \ R-d \le x \le R\ \ (n_{cr}, core) \\ \Psi_3 = DH_\nu^{(2)}(k_{cl,\pm}r) & if\ x \ge R\ (n_{cl}, cladding) \end{cases}$$

(Hiremath et al.) [3]

$R \rightarrow Radius; d \rightarrow Core\ slab\ thicknessc, \nu = \delta_\pm R \rightarrow angular\ mode\ number$

Sensitivity overview

Axion-Photon Conversion Probability

- Straight case

$$P(\gamma \to a) = |E(z)|^2 = sin^2(2\theta)\, sin^2\left(\frac{\pi z}{L_{sf}}\right)$$

- Bending case

$$P(\gamma \to a) = |E(\phi)|^2 = sin^2(2\theta)\, sin^2\left(\frac{2\pi^2 RN}{L_{bf}}\right)$$

- Free-space case (Raffelt and Stodolsky) [2]

$$P(\gamma \to a) = |E(z)|^2 = sin^2(2\theta)\, sin^2\left(\frac{\pi z}{L_{free}}\right)$$

$$where\ tan(2\theta) = \frac{2G}{k_\gamma^2 - k_a^2}, L_{sf,bf} = \frac{2\pi}{\delta_+ - \delta_-}, L_{free} = \frac{2\pi}{k_+ - k_-}, k_\pm = \sqrt{\frac{k_\gamma^2 + k_a^2}{2} \pm \sqrt{\left(\frac{k_\gamma^2 - k_a^2}{2}\right)^2 + G^2}}, G = g_{a\gamma\gamma} B_{ext}\omega$$

Sensitivity overview

Axion-Photon Conversion Probability

- Straight case

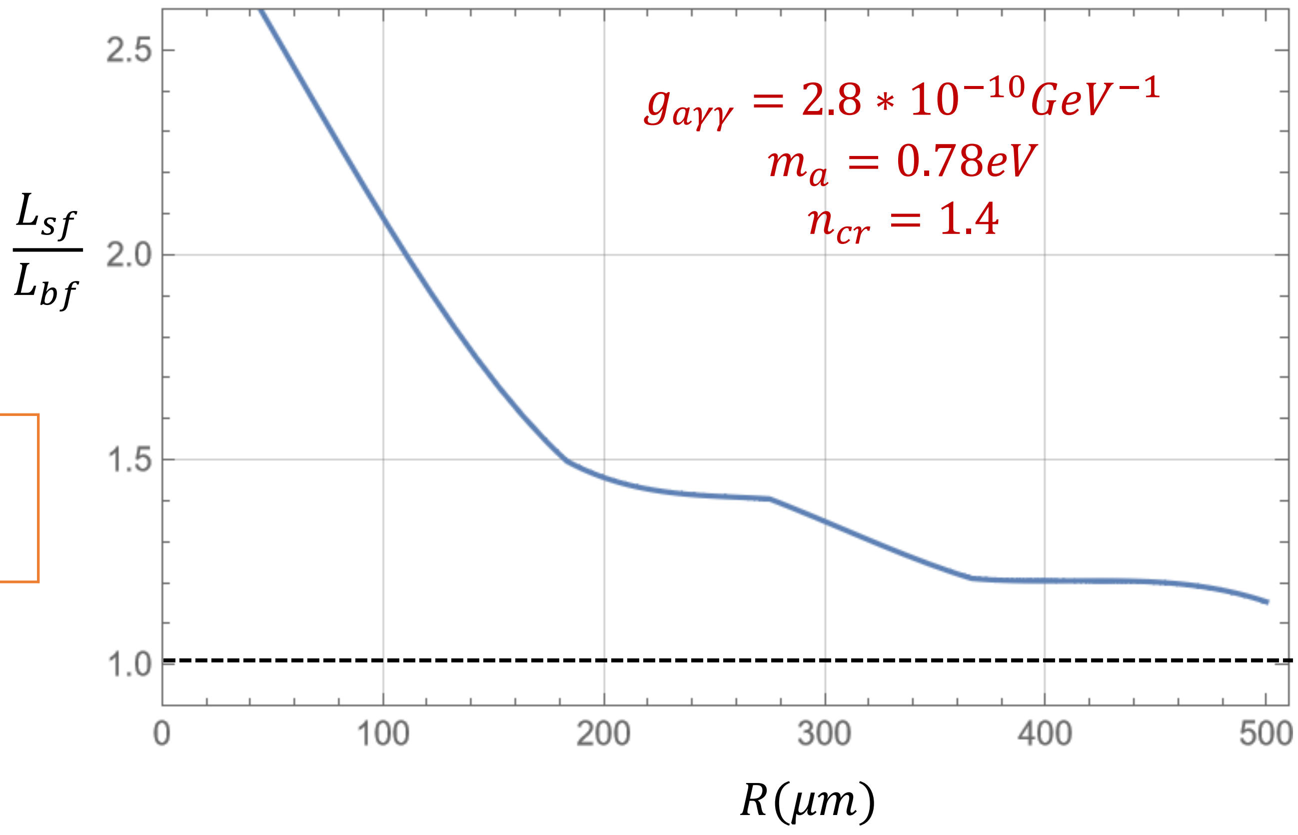
$$P(\gamma \rightarrow a) = |E(z)|^2 = sin^2(2\theta)\, sin^2\left(\frac{\pi z}{L_{sf}}\right)$$

- Bending case

$$P(\gamma \rightarrow a) = |E(\phi)|^2 = sin^2(2\theta)\, sin^2\left(\frac{2\pi^2 RN}{L_{bf}}\right)$$

$$where\ L_{sf,bf} = \frac{2\pi}{\delta_+ - \delta_-}$$

Oscillation Length vs Radius



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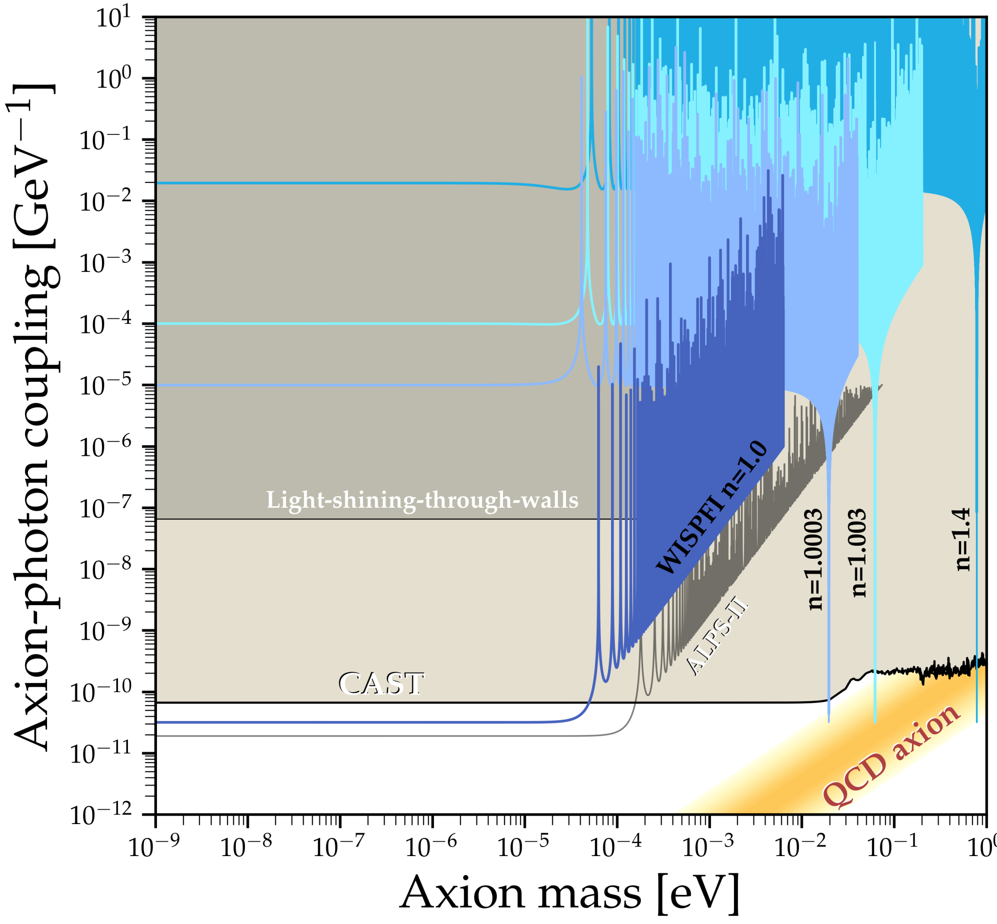
Sensitivity overview



- *In resonance, the axion – photon transfer momentum* $q = 0\ eV$

$$q = \frac{m_\gamma^2 - m_a^2}{\omega} = 0 \rightarrow k_\gamma = k_a$$

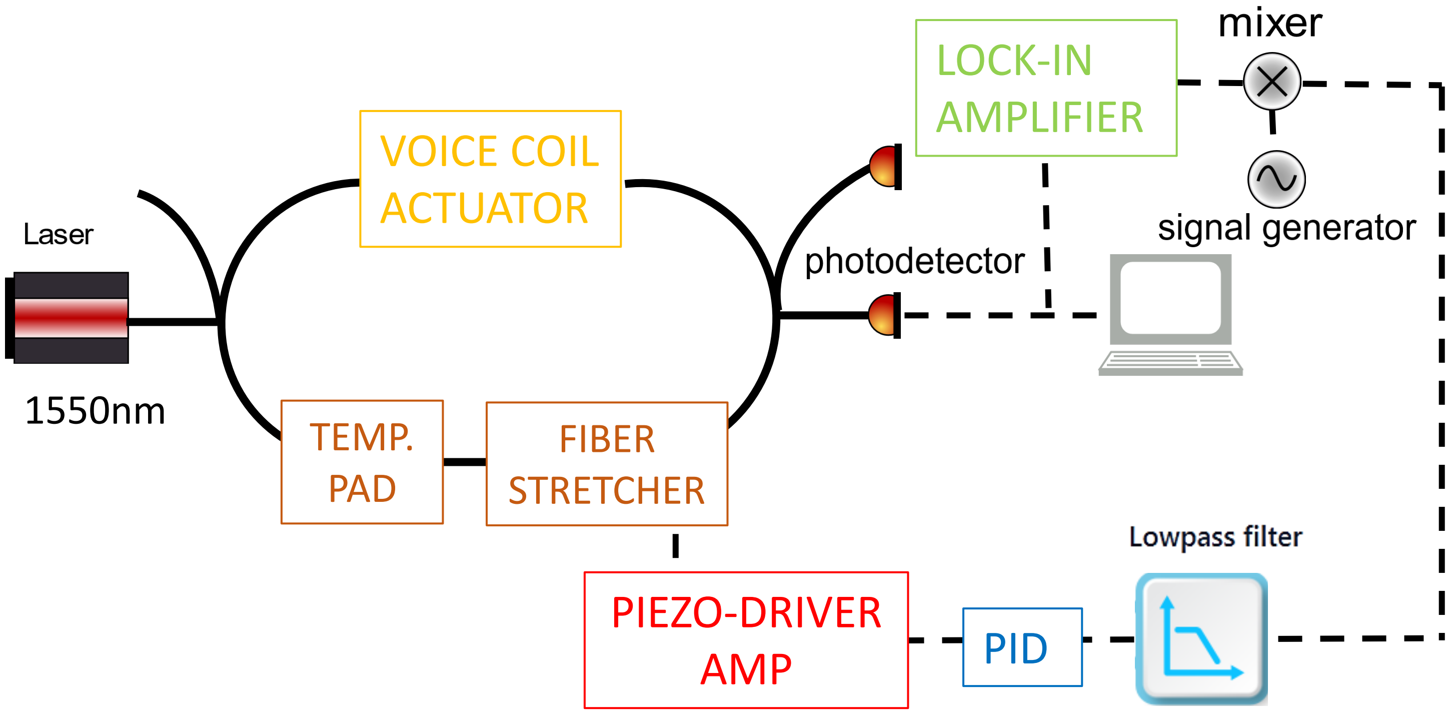
$$m_a = \sqrt{\omega^2 - n^2\omega^2}$$

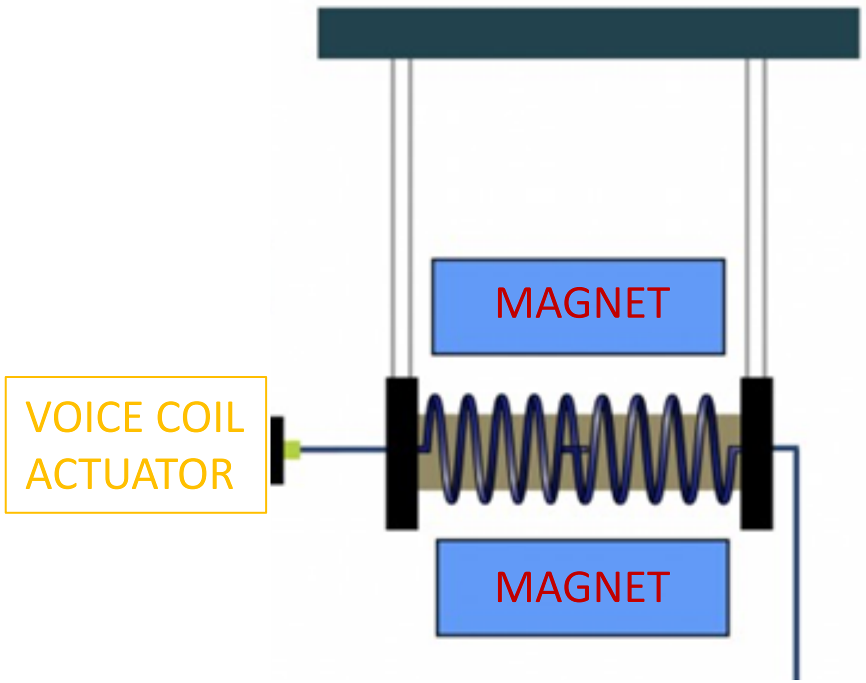
$\omega = 0.8eV$
$z = 500m$
$P = 2W$
$t = 100\ days$

Refractive index	Axion mass (eV)	Axion-photon coupling (GeV^{-1})
1.4 (step-index fiber)	0.78	$3.2 * 10^{-11}$ (shot noise limited)
1.003 (hollow-core fiber)	$6.2 * 10^{-3}$	
1.0003 (air)	$1.96 * 10^{-3}$	

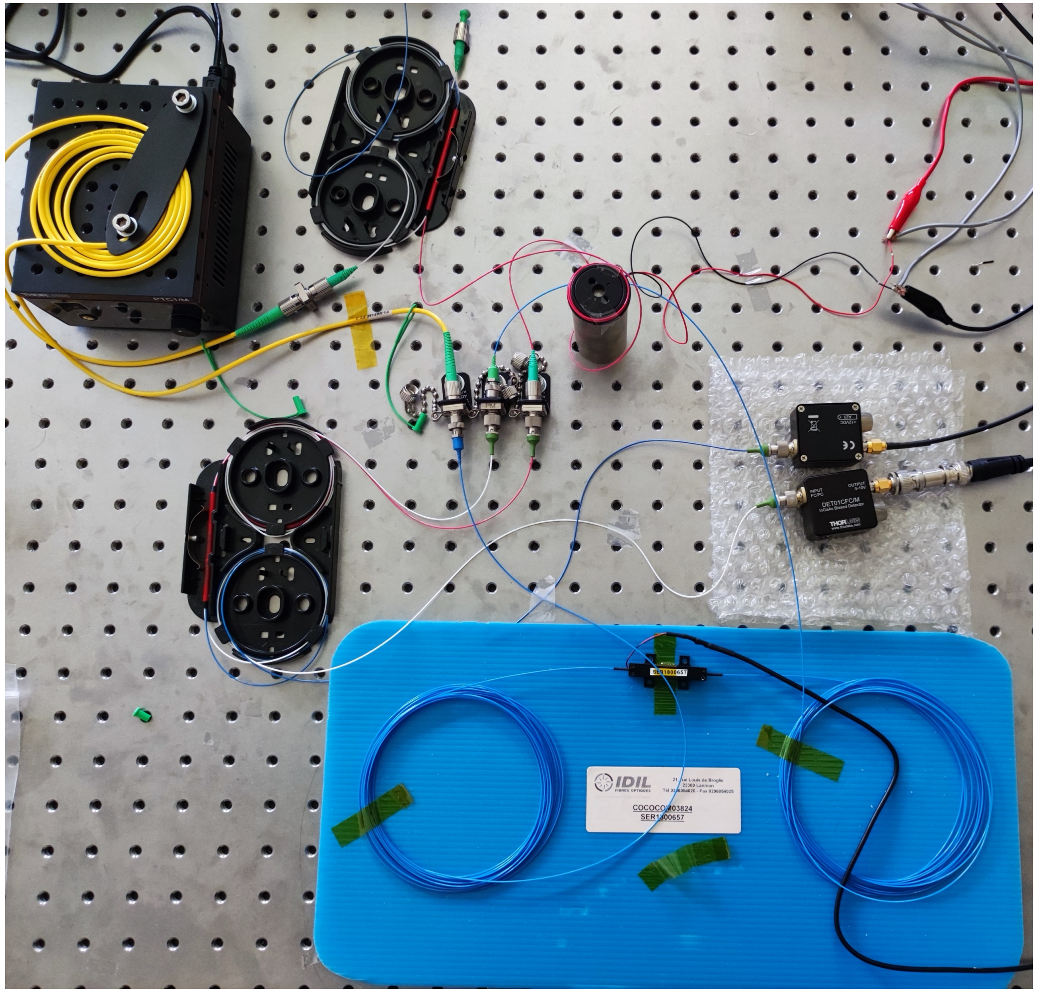
Current test

WISPFI: Long-fiber experimental setup





Current test



Next steps

- Long fiber setup ($\sim 20m - 100m$) using a fiber stretcher together with a thermal pad
- Optimize the setup to shot noise limited for squeezed light implementation
- Testing a linear voice coil actuator for magnetic field modulation in the 14T magnet
- Integration of 14T superconductor magnet in the fiber interferometer
- Hollow core photonic crystal fiber (HC-PCF) test and stabilization
- Electric field conversion experiment using a RF cavity


THANK YOU FOR YOUR ATTENTION!

References

[1] Tam, H., and Q. Yang. "Production and Detection of Axion-like Particles by Interferometry." *Physics Letters B*, vol. 716, no. 3-5, Oct. 2012, pp. 435–40, https://doi.org/10.1016/j.physletb.2012.08.050.

[2] VISINELLI, LUCA. "AXION-ELECTROMAGNETIC WAVES." *Modern Physics Letters A*, vol. 28, no. 35, Oct. 2013, p. 1350162, https://doi.org/10.1142/s0217732313501629.

[3] Hiremath, K. R., et al. "Analytic Approach to Dielectric Optical Bent Slab Waveguides." *Optical and Quantum Electronics*, vol. 37, no. 1-3, Jan. 2005, pp. 37–61, https://doi.org/10.1007/s11082-005-1118-3.

[4] Raffelt, Georg, and Leo Stodolsky. "Mixing of the Photon with Low-Mass Particles." *Physical Review D*, vol. 37, no. 5, Mar. 1988, pp. 1237–49, https://doi.org/10.1103/physrevd.37.1237.

Backup: Equation of motion

$$\left(\partial_r^2 + \frac{1}{r^2}\partial_\phi^2 + \frac{1}{r}\partial_r\right)a' + k_a^2 a' - GE' = 0$$
$$\left(\partial_r^2 + \frac{1}{r^2}\partial_\phi^2 + \frac{1}{r}\partial_r\right)E' + k_\gamma^2 E' - Ga' = 0$$

$$\left[\partial_r^2 + \frac{1}{r^2}\partial_\phi^2 + \frac{1}{r}\partial_r + M(r)\right]\Psi(r,\phi) = 0$$

$$\tilde{\Psi}_k(r) = \begin{pmatrix}\tilde{E}_k(r)\\ \tilde{a}_k(r)\end{pmatrix} \qquad \tilde{M} = \begin{pmatrix}k_+^2 & 0\\ 0 & k_-^2\end{pmatrix} = U(\theta)M(r)U^{-1}(\theta)$$

$$\left[\partial_r^2 + \frac{1}{r^2}\partial_\phi^2 + \frac{1}{r}\partial_r + \tilde{M}(r)\right]\tilde{\Psi}(r,\phi) = 0$$

$$where\ a' = a\omega_a^{\frac{1}{2}}, E' = E\omega_E^{-\frac{1}{2}}, \Psi(r,\phi) = \begin{pmatrix}E'(r,\phi)\\ a'(r,\phi)\end{pmatrix}, M(r) = \begin{pmatrix}k_\gamma^2 & -G\\ -G & k_a^2\end{pmatrix}, \tan(2\theta) = \frac{2G}{k_\gamma^2 - k_a^2}, G = g_{a\gamma\gamma}B_{ext}\omega$$

Backup: Conversion probability

The electric and axion fields can be therefore deduced by applying the rotation back

$$\Psi_\kappa(\theta) = \begin{pmatrix} E'_\kappa(\phi) \\ a'_\kappa(\phi) \end{pmatrix} = U(\theta)\Psi(\phi)U^{-1}(\theta) = \begin{pmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} e^{-i\nu_+\phi} & 0 \\ 0 & e^{-i\nu_-\phi} \end{pmatrix} \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} A_\gamma \\ A_a \end{pmatrix}$$

$$= \begin{pmatrix} cos^2\theta\, e^{-i\nu_+\phi} - sin^2\phi e^{-i\nu_-\phi} & sin\theta cos\theta\left(e^{-i\nu_+\phi} - e^{-i\nu_-\phi}\right) \\ sin\theta cos\theta\left(e^{-i\nu_+\phi} - e^{-i\gamma_-\phi}\right) & sin^2\theta\, e^{-i\nu_+R\phi} + cos^2\theta e^{-i\nu_-\phi} \end{pmatrix} \begin{pmatrix} A_\gamma \\ A_a \end{pmatrix}$$

$Where\ \boldsymbol{\nu}_\pm = \boldsymbol{\delta}_\pm \boldsymbol{R} \rightarrow Angular\ mode\ number;\ \boldsymbol{\delta}_\pm = \boldsymbol{\beta}_\pm - \boldsymbol{i\alpha}_\pm \rightarrow propagation\ constant; and$ $\begin{cases} a' = a\omega_a^{\frac{1}{2}} \\ E' = E\omega_E^{-\frac{1}{2}} \end{cases}$

Considering we begin with a pure axion beam $(A_\gamma = 0)$ the conversion probability accounting for bending losses is

$$\rho(a \rightarrow \gamma) = |E(\phi)|^2 = cos^2\theta\, sin^2\theta \left|e^{-i\nu_+\phi} - e^{-i\nu_-\phi}\right|^2$$

Backup: Electric field conversion

Axion-Maxwell equations (EFT approach)

(Anton Sokolov, arXiv: 2205.02605)

$$\nabla \times \mathbf{B}_a - \dot{\mathbf{E}}_a = g_{aAA}\left(\mathbf{E}_0 \times \nabla a - \dot{a}\mathbf{B}_0\right) + g_{aAB}\left(\mathbf{B}_0 \times \nabla a + \dot{a}\mathbf{E}_0\right)$$

$$\nabla \times \mathbf{E}_a + \dot{\mathbf{B}}_a = -g_{aBB}\left(\mathbf{B}_0 \times \nabla a + \dot{a}\mathbf{E}_0\right) - g_{aAB}\left(\mathbf{E}_0 \times \nabla a - \dot{a}\mathbf{B}_0\right)$$

$$\nabla \cdot \mathbf{B}_a = -g_{aBB}\,\mathbf{E}_0 \cdot \nabla a + g_{aAB}\,\mathbf{B}_0 \cdot \nabla a$$

$$\nabla \cdot \mathbf{E}_a = g_{aAA}\,\mathbf{B}_0 \cdot \nabla a - g_{aAB}\,\mathbf{E}_0 \cdot \nabla a$$

$$\left(\partial^2 - m_a^2\right) a = \left(g_{aAA} + g_{aBB}\right)\mathbf{E}_0 \cdot \mathbf{B}_0 + g_{aAB}\left(\mathbf{E}_0^2 - \mathbf{B}_0^2\right)$$

Possibility to modulate the electric field inside a RF cavity

$$E = 14T.\frac{10^4 G}{1T}\,\frac{(0.511 * 10^6 eV)^2}{3.77 * 10^{12} G}\,\frac{1.132 * 10^{17} V/m}{(0.511 * 10^6 eV)^2} = 4.2 * 10^9 \frac{V}{m} = 4.2\frac{GV}{m}$$

$$In\ CP-conserving\ case, E_0 \approx 10^{-3} B_0 = 4.2 MV/m$$