# ISOPOD

# **Iso**lating **P**oled **O**n-chip **D**evice

**PHYS 559 Final Project**

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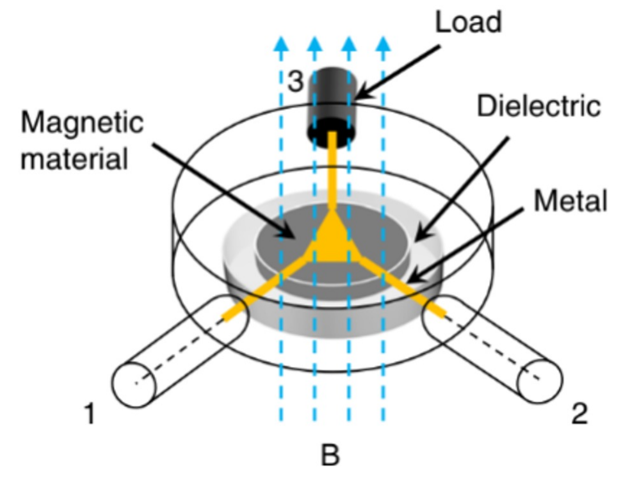
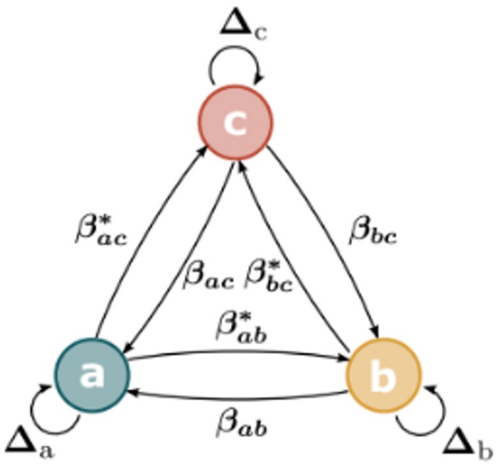
# Motivation

- Isolation of microwaves is essential for the qubit readout and amplification chain
  - Protect qubit from backpropagating noise
  - We **need** nonreciprocity
- Current isolators are: bulky, highly magnetic, and lossy




Bulk ferrite isolators
Abdo et al, *Nature Comm* (2019)




Nonreciprocal phase relations
Lecoq et al, *Phys Rev Appl* (2017)

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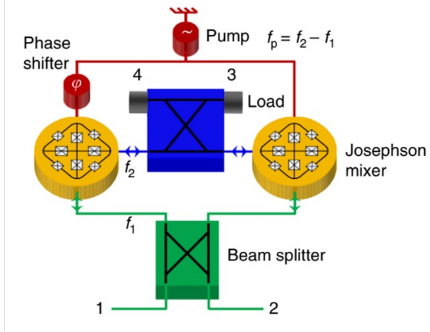
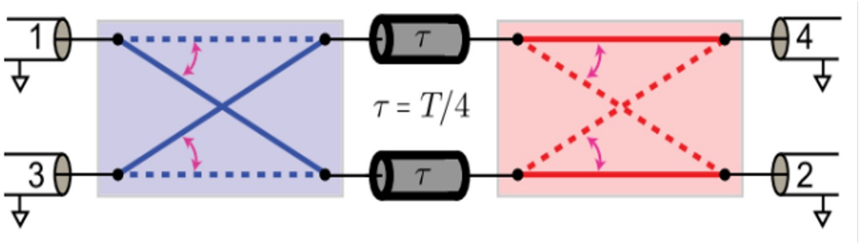
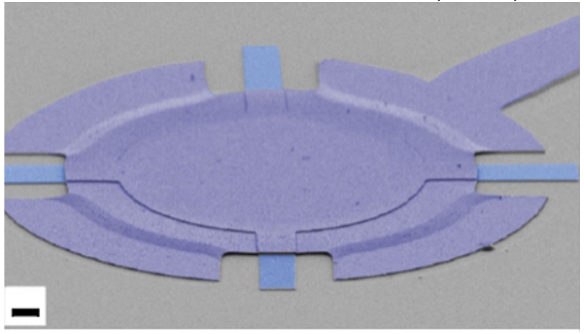
# Literature Background: State of the Art Approaches



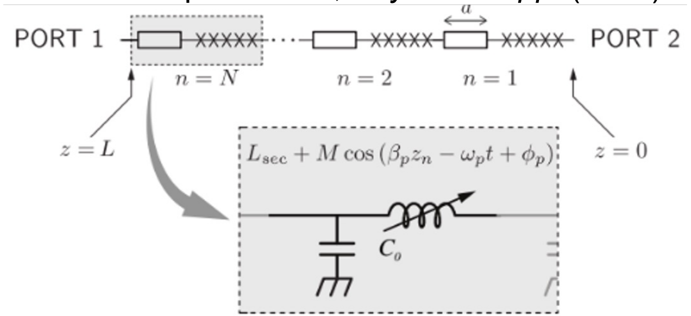

Interferometric Isolator
Abdo et al, *Nature Comm* (2019)




Active Modulation-based Isolator
Chapman et al, *Phys Rev Appl* (2019)



Optomechanical Isolator
Bernier et al, *Nature Comm* (2017)




Unidirectional Frequency Conversion
Ranzani et al, *Phys Rev Appl* (2017)

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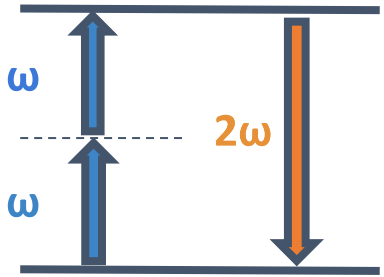
# Physics Background: Parametric Interactions

- Nonlinearity can provide frequency mixing
  - A Josephson junction is a nonlinear inductor
  - We need to control **phase matching** and **dispersion**
- Second harmonic generation can allow us to create 2ω light from ω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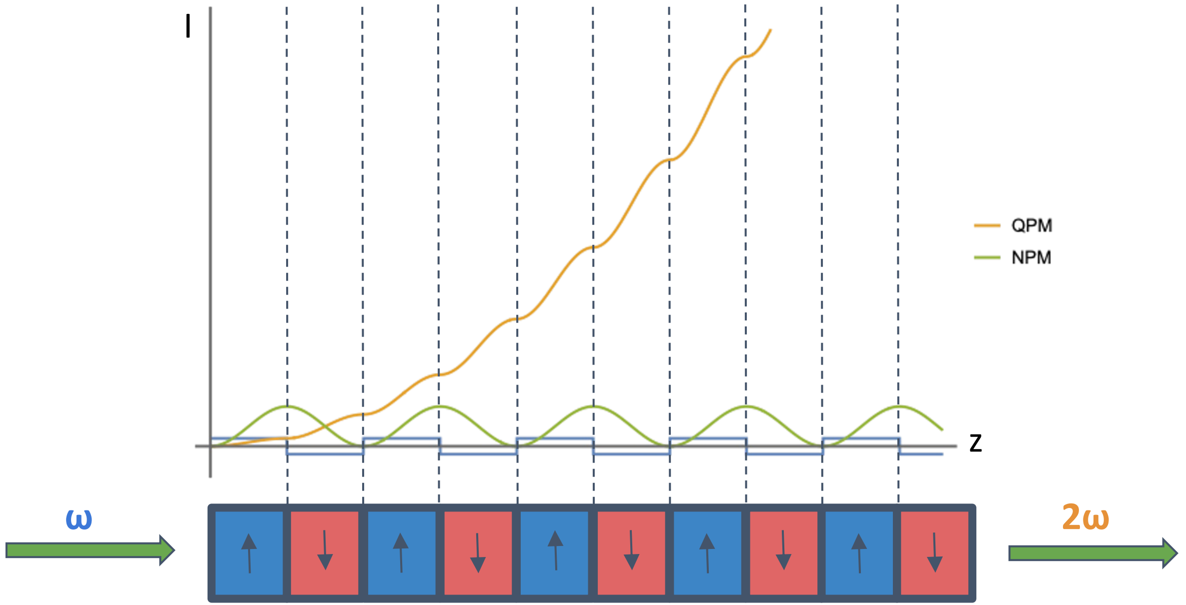
# Physics Background: Poling

- Kerr reversal can *invert* the sign of our nonlinearity
  - Typically used to quasi-phase match in photonic systems
- Poling period($\Lambda_{coh}$) can control phase mismatch $\Delta k=k_2-2k_1-2\pi/\Lambda_{coh}$

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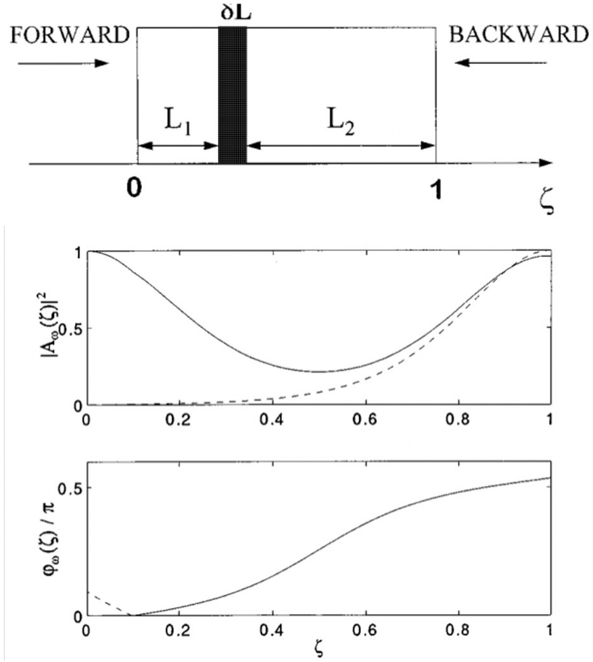
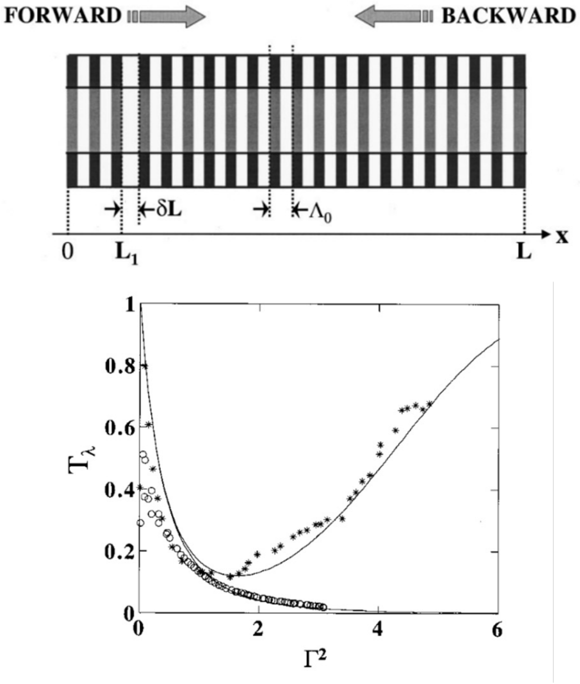
# Inspiration: Optical

- *Poling* defects can create **isolation** in optics




Theoretical poling-inspired defect
Gallo et al., *Optica* (1998)




Experimental quasi phase matched isolator
Gallo et al., *Appl. Phys. Lett.* (2001)

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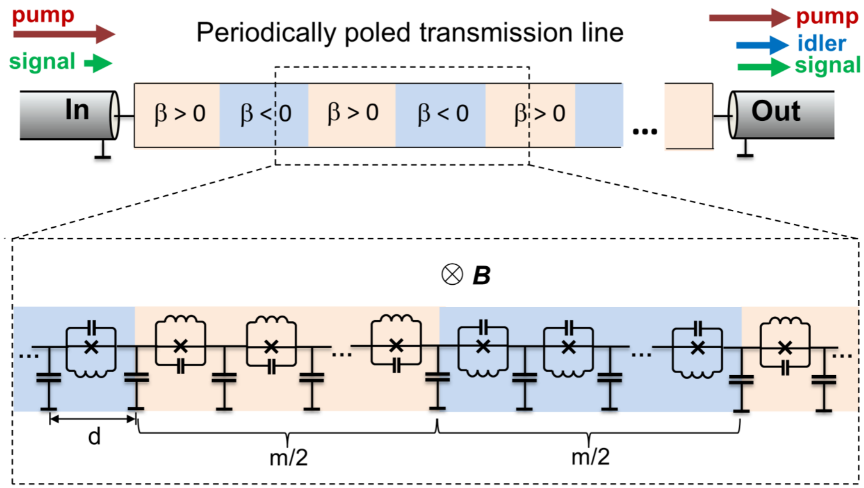
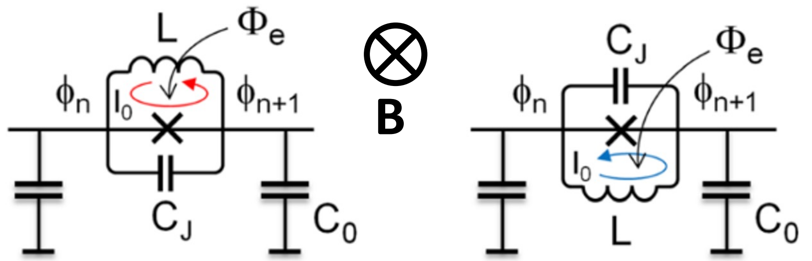
# Inspiration: Superconducting Circuits

- Transmission lines and optical waveguides are both wave-propagation media
  - They can also be nonlinear (JJs here, ferroelectric crystals in optics)
- Just like optics, we can “pole” our transmission lines with flux-biased SQUIDs




Periodic poling in superconducting transmission line
A.B. Zorin, *Appl Phys Lett* (2021)




Kerr reversal with RF SQUIDs
A.B. Zorin, *Appl Phys Lett* (2021)

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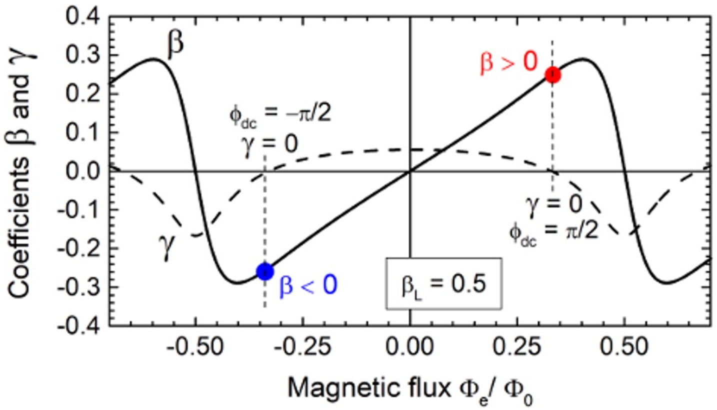
O

# Inspiration: Important Parameters

- Our 2nd order nonlinearity is related to the *SQUID screening parameter* ($\beta_L$) and DC flux bias ($\varphi_{DC}$)
  - We can bias into the three-wave mixing (3WM)/second harmonic generation (SHG) regime via $\varphi_{DC}=\pi/2$




Plot of $\beta$ and $\gamma$ against flux
A.B. Zorin, *Appl. Phys. Lett.* (2021)

$$I(\varphi) = \frac{I_c\varphi}{\beta_L} + I_c\left(\sin(\varphi_{dc}+\varphi) - \sin(\varphi)\right)$$

$$\frac{I}{I_c} = (\beta_L^{-1} + \cos\varphi_{dc})\varphi - \tilde{\beta}\varphi^2 - \tilde{\gamma}\varphi^3 \cdots$$

$$\beta = \frac{\beta_L}{2}\sin(\varphi_{dc}) \quad \gamma = \frac{\beta_L}{6}\cos(\varphi_{dc})$$

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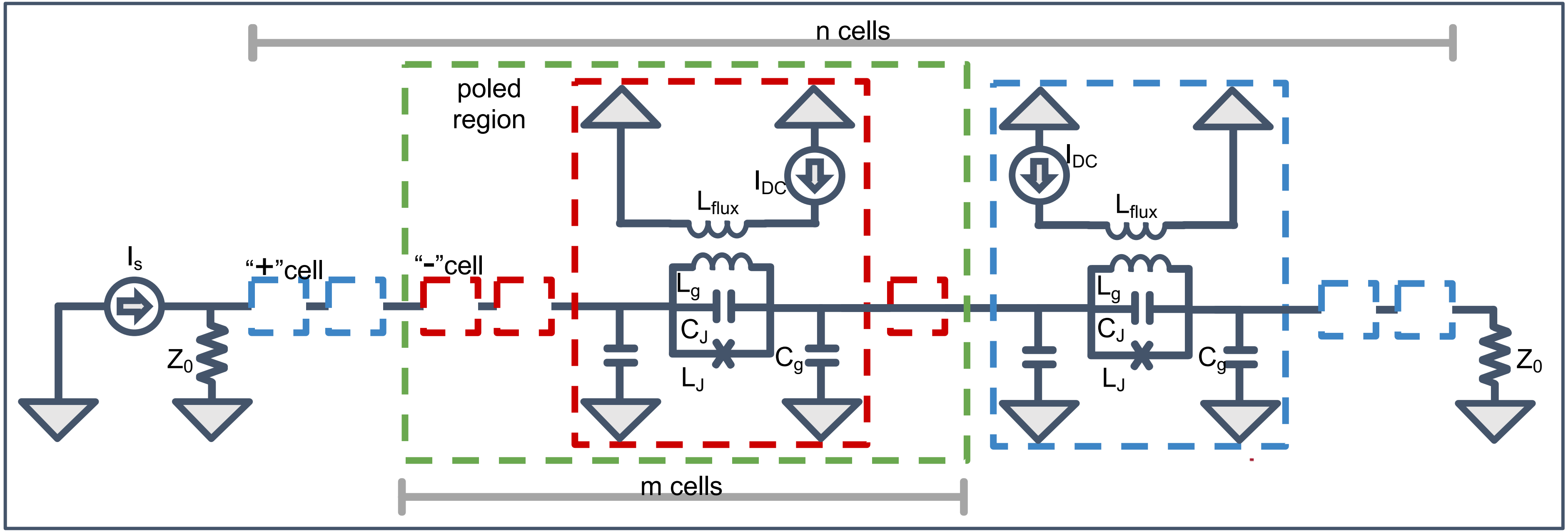
# Our Device

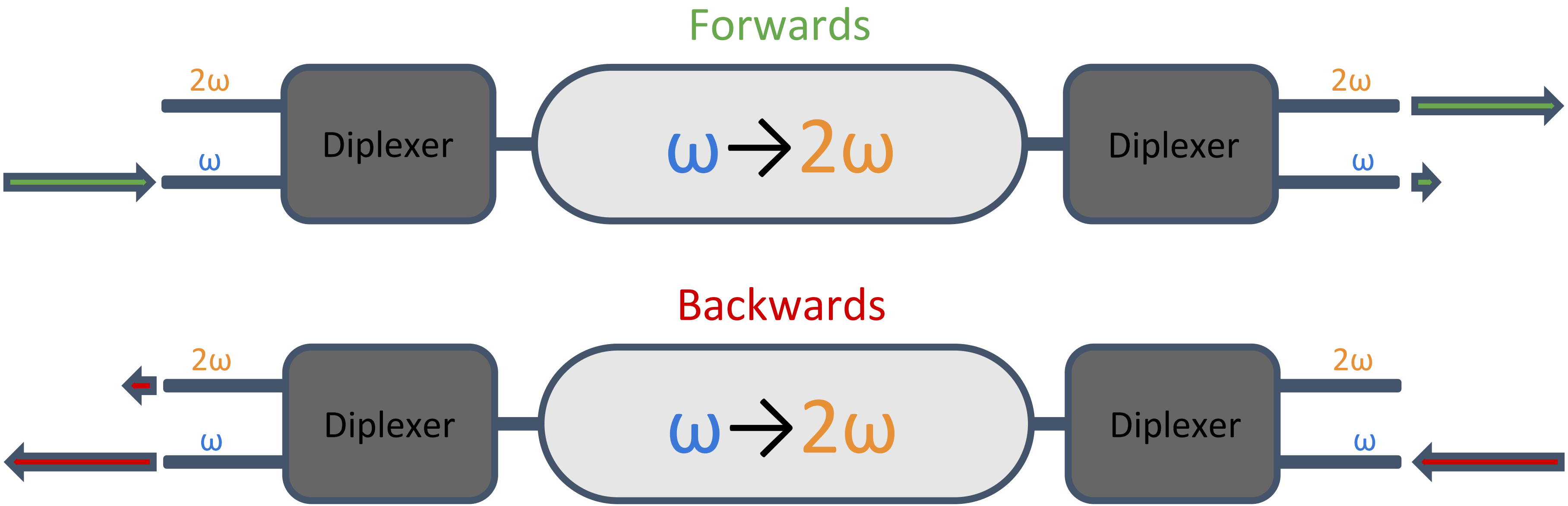
O

- We propose an on-chip microwave isolator on a superconducting platform
  - Our device realizes **unidirectional frequency conversion**
    - Combine that with filtering/diplexing to achieve **isolation**
  - **On-chip** and **scalable**
  - **Integratable** with traveling wave parametric amplifiers (TWPAs)



# Extension to Isolation

- With filters and/or frequency diplexers, we can harness our nonreciprocal frequency conversion for isolation



## Simulation: Coupled-Mode Equations

- Coupled mode equations describe frequency conversion and power transfer
  - To accurately simulate, we need very high harmonics = Many equations...

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# How many equations, you ask?

$$
\begin{aligned}
\frac{dA_i}{dx} = \frac{\beta}{2}\Big(& k_s k_p A_p A_s^* e^{i\left(k_p-k_s\right)x} + k_{p+i}k_p A_{p+i}A_p^* e^{i\left(k_{p+i}-k_p\right)x} \\
&+ k_{2p}k_{p+s}A_{2p}A_{p+s}^* e^{i\left(k_{2p}-k_{p+s}\right)x} + k_{2p+i}k_{2p}A_{2p+i}A_{2p}^* e^{i\left(k_{2p+i}-k_{2p}\right)x} \\
&+ k_{3p}k_{2p+s}A_{3p}A_{2p+s}^* e^{i\left(k_{3p}-k_{2p+s}\right)x} + k_{3p+i}k_{3p}A_{3p+i}A_{3p}^* e^{i\left(k_{3p+i}-k_{3p}\right)x} \\
&+ k_{4p}k_{3p+s}A_{4p}A_{3p+s}^* e^{i\left(k_{4p}-k_{3p+s}\right)x} + k_{4p+i}k_{4p}A_{4p+i}A_{4p}^* e^{i\left(k_{4p+i}-k_{4p}\right)x} \\
&+ k_{5p}k_{4p+s}A_{5p}A_{4p+s}^* e^{i\left(k_{5p}-k_{4p+s}\right)x}\Big) e^{-ik_i x},
\end{aligned} \tag{B.2}
$$

$$
\begin{aligned}
\frac{dA_s}{dx} = \frac{\beta}{2}\Big(& k_i k_p A_p A_i^* e^{i\left(k_p-k_i\right)x} + k_{p+s}k_p A_{p+s}A_p^* e^{i\left(k_{p+s}-k_p\right)x} \\
&+ k_{2p}k_{p+i}A_{2p}A_{p+i}^* e^{i\left(k_{2p}-k_{p+i}\right)x} + k_{2p+s}k_{2p}A_{2p+s}A_{2p}^* e^{i\left(k_{2p+s}-k_{2p}\right)x} \\
&+ k_{3p}k_{2p+i}A_{3p}A_{2p+i}^* e^{i\left(k_{3p}-k_{2p+i}\right)x} + k_{3p+s}k_{3p}A_{3p+s}A_{3p}^* e^{i\left(k_{3p+s}-k_{3p}\right)x} \\
&+ k_{4p}k_{3p+i}A_{4p}A_{3p+i}^* e^{i\left(k_{4p}-k_{3p+i}\right)x} + k_{4p+s}k_{4p}A_{4p+s}A_{4p}^* e^{i\left(k_{4p+s}-k_{4p}\right)x} \\
&+ k_{5p}k_{4p+i}A_{5p}A_{4p+i}^* e^{i\left(k_{5p}-k_{4p+i}\right)x}\Big) e^{-ik_s x},
\end{aligned} \tag{B.3}
$$

$$
\begin{aligned}
\frac{dA_p}{dx} = \frac{\beta}{2}\Big(& -k_i k_s A_i A_s e^{i(k_i+k_s)x} + k_{p+i}k_i A_{p+i}A_i^* e^{i\left(k_{p+i}-k_i\right)x} \\
&+ k_{p+s}k_s A_{p+s}A_s^* e^{i\left(k_{p+s}-k_s\right)x} + k_{2p}k_p A_{2p}A_p^* e^{i\left(k_{2p}-k_p\right)x} \\
&+ k_{2p+i}k_{p+i}A_{2p+i}A_{p+i}^* e^{i\left(k_{2p+i}-k_{p+i}\right)x} + k_{2p+s}k_{p+s}A_{2p+s}A_{p+s}^* e^{i\left(k_{2p+s}-k_{p+s}\right)x} \\
&+ k_{3p}k_{2p}A_{3p}A_{2p}^* e^{i\left(k_{3p}-k_{2p}\right)x} + k_{3p+i}k_{2p+i}A_{3p+i}A_{2p+i}^* e^{i\left(k_{3p+i}-k_{2p+i}\right)x} \\
&+ k_{3p+s}k_{2p+s}A_{3p+s}A_{2p+s}^* e^{i\left(k_{3p+s}-k_{2p+s}\right)x} + k_{4p}k_{3p}A_{4p}A_{3p}^* e^{i\left(k_{4p}-k_{3p}\right)x} \\
&+ k_{4p+i}k_{3p+i}A_{4p+i}A_{3p+i}^* e^{i\left(k_{4p+i}-k_{3p+i}\right)x} + k_{4p+s}k_{3p+s}A_{4p+s}A_{3p+s}^* e^{i\left(k_{4p+s}-k_{3p+s}\right)x} \\
&+ k_{5p}k_{4p}A_{5p}A_{4p}^* e^{i\left(k_{5p}-k_{4p}\right)x}\Big) e^{-ik_p x}
\end{aligned} \tag{B.4}
$$

$$
\begin{aligned}
\frac{dA_{p+i}}{dx} = \frac{\beta}{2}\Big(& -k_i k_p A_i A_p e^{i\left(k_i+k_p\right)x} + k_{2p}k_s A_{2p}A_s^* e^{i\left(k_{2p}-k_s\right)x} \\
&+ k_{2p+i}k_p A_{2p+i}A_p^* e^{i\left(k_{2p+i}-k_p\right)x} + k_{3p}k_{p+s}A_{3p}A_{p+s}^* e^{i\left(k_{3p}-k_{p+s}\right)x} \\
&+ k_{3p+i}k_{2p}A_{3p+i}A_{2p}^* e^{i\left(k_{3p+i}-k_{2p}\right)x} + k_{4p}k_{2p+s}A_{4p}A_{2p+s}^* e^{i\left(k_{4p}-k_{2p+s}\right)x} \\
&+ k_{4p+i}k_{3p}A_{4p+i}A_{3p}^* e^{i\left(k_{4p+i}-k_{3p}\right)x} + k_{5p}k_{3p+s}A_{5p}A_{3p+s}^* e^{i\left(k_{5p}-k_{3p+s}\right)x}\Big) e^{-ik_{p+i}x},
\end{aligned} \tag{B.5}
$$

$$
\begin{aligned}
\frac{dA_{p+s}}{dx} = \frac{\beta}{2}\Big(& -k_s k_p A_s A_p e^{i\left(k_s+k_p\right)x} + k_{2p}k_i A_{2p}A_i^* e^{i\left(k_{2p}-k_i\right)x} \\
&+ k_{2p+s}k_p A_{2p+s}A_p^* e^{i\left(k_{2p+s}-k_p\right)x} + k_{3p}k_{p+i}A_{3p}A_{p+i}^* e^{i\left(k_{3p}-k_{p+i}\right)x} \\
&+ k_{3p+s}k_{2p}A_{3p+s}A_{2p}^* e^{i\left(k_{3p+s}-k_{2p}\right)x} + k_{4p}k_{2p+i}A_{4p}A_{2p+i}^* e^{i\left(k_{4p}-k_{2p+i}\right)x} \\
&+ k_{4p+s}k_{3p}A_{4p+s}A_{3p}^* e^{i\left(k_{4p+s}-k_{3p}\right)x} + k_{5p}k_{3p+i}A_{5p}A_{3p+i}^* e^{i\left(k_{5p}-k_{3p+i}\right)x}\Big) e^{-ik_{p+s}x},
\end{aligned} \tag{B.6}
$$

$$
\begin{aligned}
\frac{dA_{2p}}{dx} = \frac{\beta}{2}\Big(& -k_i k_{p+s} A_i A_{p+s} e^{i(k_i+k_{p+s})x} - k_s k_{p+i} A_s A_{p+i} e^{i(k_s+k_{p+i})x} \\
&- \frac{k_p^2}{A_p^2} 2e^{i(k_p+k_p)x} + k_{2p+i}k_i A_{2p+i}A_i^* e^{i(k_{2p+i}-k_i)x} \\
&+ k_{2p+2}k_s A_{2p+s}A_s^* e^{i(k_{2p+s}-k_s)x} + k_{3p}k_p A_{3p}A_p^* e^{i(k_{3p}-k_p)x} \\
&+ k_{3p+i}k_{p+i}A_{3p+i}A_{p+i}^* e^{i(k_{3p+i}-k_{p+i})x} + k_{3p+s}k_{p+s}A_{3p+s}A_{p+s}^* e^{i(k_{3p+s}-k_{p+s})x} \\
&+ k_{4p}k_{2p}A_{4p}A_{2p}^* e^{i(k_{4p}-k_{2p})x} + k_{4p+i}k_{2p+i}A_{4p+i}A_{2p+i}^* e^{i(k_{4p+i}-k_{2p+i})x} \\
&+ k_{4p+s}k_{2p+s}A_{4p+s}A_{2p+s}^* e^{i(k_{4p+s}-k_{2p+s})x} + k_{5p}k_{3p}A_{5p}A_{3p}^* e^{i(k_{5p}-k_{3p})x}\Big) e^{-ik_{2p}x}
\end{aligned} \tag{B.7}
$$

$$
\begin{aligned}
\frac{dA_{2p+i}}{dx} = \frac{\beta}{2}\Big(& -k_i k_{2p} A_i A_{2p} e^{i\left(k_i+k_{2p}\right)x} - k_p k_{p+i} A_p A_{p+i} e^{i\left(k_p+k_{p+i}\right)x} \\
&+ k_{3p}k_s A_{3p}A_s^* e^{i\left(k_{3p}-k_s\right)x} + k_{3p+i}k_p A_{3p+i}A_p^* e^{i\left(k_{3p+i}-k_p\right)x} \\
&+ k_{4p}k_{p+s}A_{4p}A_{p+s}^* e^{i\left(k_{4p}-k_{p+s}\right)x} + k_{4p+i}k_{2p}A_{4p+i}A_{2p}^* e^{i\left(k_{4p+i}-k_{2p}\right)x} \\
&+ k_{5p}k_{2p+s}A_{5p}A_{2p+s}^* e^{i\left(k_{5p}-k_{2p+s}\right)x}\Big) e^{-ik_{2p+i}x},
\end{aligned} \tag{B.8}
$$

$$
\begin{aligned}
\frac{dA_{2p+s}}{dx} = \frac{\beta}{2}\Big(& -k_s k_{2p} A_s A_{2p} e^{i\left(k_s+k_{2p}\right)x} - k_p k_{p+s} A_p A_{p+s} e^{i\left(k_p+k_{p+s}\right)x} \\
&+ k_{3p}k_i A_{3p}A_i^* e^{i\left(k_{3p}-k_i\right)x} + k_{3p+s}k_p A_{3p+s}A_p^* e^{i\left(k_{3p+s}-k_p\right)x} \\
&+ k_{4p}k_{p+i}A_{4p}A_{p+i}^* e^{i\left(k_{4p}-k_{p+i}\right)x} + k_{4p+s}k_{2p}A_{4p+s}A_{2p}^* e^{i\left(k_{4p+s}-k_{2p}\right)x} \\
&+ k_{5p}k_{2p+i}A_{5p}A_{2p+i}^* e^{i\left(k_{5p}-k_{2p+i}\right)x}\Big) e^{-ik_{2p+s}x},
\end{aligned} \tag{B.9}
$$

$$
\begin{aligned}
\frac{dA_{3p}}{dx} = \frac{\beta}{2}\Big(& -k_i k_{2p+s} A_i A_{2p+s} e^{i\left(k_i+k_{2p+s}\right)x} - k_s k_{2p+i} A_s A_{2p+i} e^{i\left(k_s+k_{2p+i}\right)x} \\
&- k_p k_{2p} A_p A_{2p} e^{i\left(k_p+k_{2p}\right)x} - k_{p+i}k_{p+s} A_{p+i} A_{p+s} e^{i\left(k_{p+i}+k_{p+s}\right)x} \\
&+ k_{3p+i}k_i A_{3p+i}A_i^* e^{i\left(k_{3p+i}-k_i\right)x} + k_{3p+s}k_s A_{3p+s}A_s^* e^{i\left(k_{3p+s}-k_s\right)x} \\
&+ k_{4p}k_p A_{4p}A_p^* e^{i\left(k_{4p}-k_p\right)x} + k_{4p+i}k_{p+i}A_{4p+i}A_{p+i}^* e^{i\left(k_{4p+i}-k_{p+i}\right)x} \\
&+ k_{4p+s}k_{p+s}A_{4p+s}A_{p+s}^* e^{i\left(k_{4p+s}-k_{p+s}\right)x} + k_{5p}k_{2p}A_{5p}A_{2p}^* e^{i\left(k_{5p}-k_{2p}\right)x}\Big) e^{-ik_{3p}x},
\end{aligned} \tag{B.10}
$$

$$
\begin{aligned}
\frac{dA_{3p+i}}{dx} = \frac{\beta}{2}\Big(& -k_i k_{3p} A_i A_{3p} e^{i\left(k_i+k_{3p}\right)x} - k_p k_{2p+i} A_p A_{2p+i} e^{i\left(k_p+k_{2p+i}\right)x} \\
&- k_{p+i}k_{2p} A_{p+i} A_{2p} e^{i\left(k_{p+i}+k_{2p}\right)x} + k_{4p}k_S A_{4p}A_S^* e^{i\left(k_{4p}-k_s\right)x} \\
&+ k_{4p+i}k_p A_{4p+i}A_p^* e^{i\left(k_{4p+i}-k_p\right)x} + k_{5p}k_{p+s}A_{5p}A_{p+s}^* e^{i\left(k_{5p}-k_{p+s}\right)x}\Big) e^{-ik_{3p+i}x}
\end{aligned} \tag{B.11}
$$

$$
\begin{aligned}
\frac{dA_{3p+s}}{dx} = \frac{\beta}{2}\Big(& -k_s k_{3p} A_s A_{3p} e^{i\left(k_s+k_{3p}\right)x} - k_p k_{2p+s} A_p A_{2p+s} e^{i\left(k_p+k_{2p+s}\right)x} \\
&- k_{p+s}k_{2p} A_{p+s} A_{2p} e^{i\left(k_{p+s}+k_{2p}\right)x} + k_{4p}k_i A_{4p}A_i^* e^{i\left(k_{4p}-k_i\right)x} \\
&+ k_{4p+s}k_p A_{4p+s}A_p^* e^{i\left(k_{4p+s}-k_p\right)x} + k_{5p}k_{p+i}A_{5p}A_{p+i}^* e^{i\left(k_{5p}-k_{p+i}\right)x}\Big) e^{-ik_{3p+s}x},
\end{aligned} \tag{B.12}
$$

$$
\begin{aligned}
\frac{dA_{4p}}{dx} = \frac{\beta}{2}\Big(& -k_i k_{3p+s} A_i A_{3p+s} e^{i\left(k_i+k_{3p+s}\right)x} - k_s k_{3p+i} A_s A_{3p+i} e^{i\left(k_s+k_{3p+i}\right)x} \\
&- k_p k_{3p} A_p A_{3p} e^{i\left(k_p+k_{3p}\right)x} - k_{p+i}k_{2p+s} A_{p+i} A_{2p+s} e^{i\left(k_{p+i}+k_{2p+s}\right)x} \\
&- k_{p+s}k_{2p+i} A_{p+s} A_{2p+i} e^{i\left(k_{p+s}+k_{2p+i}\right)x} - \frac{k_{2p}^2 A_{2p}^2}{2} e^{i\left(k_{2p}+k_{2p}\right)x} \\
&+ k_{4p+i}k_i A_{4p+i}A_i^* e^{i\left(k_{4p+i}-k_i\right)x} + k_{4p+s}k_s A_{4p+s}A_s^* e^{i\left(k_{4p+s}-k_s\right)x} \\
&+ k_{5p}k_p A_{5p}A_p^* e^{i\left(k_{5p}-k_p\right)x}\Big) e^{-ik_{4p}x},
\end{aligned} \tag{B.13}
$$

$$
\begin{aligned}
\frac{dA_{4p+i}}{dx} = \frac{\beta}{2}\Big(& -k_i k_{4p} A_i A_{4p} e^{i\left(k_i+k_{4p}\right)x} - k_p k_{3p+i} A_p A_{3p+i} e^{i\left(k_p+k_{3p+i}\right)x} \\
&- k_{p+i}k_{3p} A_{p+i} A_{3p} e^{i\left(k_{p+i}+k_{3p}\right)x} - k_{2p}k_{2p+i} A_{2p} A_{2p+i} e^{i\left(k_{2p}+k_{2p+i}\right)x} \\
&+ k_{5p}k_s A_{5p}A_s^* e^{i\left(k_{5p}-k_s\right)x}\Big) e^{-ik_{4p+i}x},
\end{aligned} \tag{B.14}
$$

$$
\begin{aligned}
\frac{dA_{4p+s}}{dx} = \frac{\beta}{2}\Big(& -k_s k_{4p} A_s A_{4p} e^{i\left(k_s+k_{4p}\right)x} - k_p k_{3p+s} A_p A_{3p+s} e^{i\left(k_p+k_{3p+s}\right)x} \\
&- k_{p+s}k_{3p} A_{p+s} A_{3p} e^{i\left(k_{p+s}+k_{3p}\right)x} - k_{2p}k_{2p+s} A_{2p} A_{2p+s} e^{i\left(k_{2p}+k_{2p+s}\right)x} \\
&+ k_{5p}k_i A_{5p}A_i^* e^{i\left(k_{5p}-k_i\right)x}\Big) e^{-ik_{4p+s}x},
\end{aligned} \tag{B.15}
$$

$$
\begin{aligned}
\frac{dA_{5p}}{dx} = \frac{\beta}{2}\Big(& -k_i k_{4p+s} A_i A_{4p+s} e^{i\left(k_i+k_{4p+s}\right)x} - k_s k_{4p+i} A_s A_{4p+i} e^{i\left(k_s+k_{4p+i}\right)x} \\
&- k_p k_{4p} A_p A_{4p} e^{i\left(k_p+k_{4p}\right)x} - k_{p+i}k_{3p+s} A_{p+i} A_{3p+s} e^{i\left(k_{p+i}+k_{3p+s}\right)x} \\
&- k_{p+s}k_{3p+i} A_{p+s} A_{3p+i} e^{i\left(k_{p+s}+k_{3p+i}\right)x} - k_{2p}k_{3p} A_{2p} A_{3p} e^{i\left(k_{2p}+k_{3p}\right)x} \\
&- k_{2p+i}k_{2p+s} A_{2p+i} A_{2p+s} e^{i\left(k_{2p+i}+k_{2p+s}\right)x}\Big) e^{-ik_{5p}x}.
\end{aligned} \tag{B.16}
$$

Still just a bad approximation with error.

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# Simulation: Coupled-Mode Equations

- Coupled mode equations describe frequency conversion and power transfer
  - To accurately simulate, we need very high harmonics = Many equations...
- These coupled equations below describe second harmonic generation
- If β depends on the position, you get nonreciprocity

$$\frac{dA_\omega}{dx} = -\beta A_{2\omega} A_\omega^* k_{2\omega} k_\omega e^{i(k_{2\omega} - 2k_\omega)x}$$

$$\frac{dA_{2\omega}}{dx} = \beta A_\omega^2 k_\omega^2 e^{-i(k_{2\omega} - 2k_\omega)x}$$

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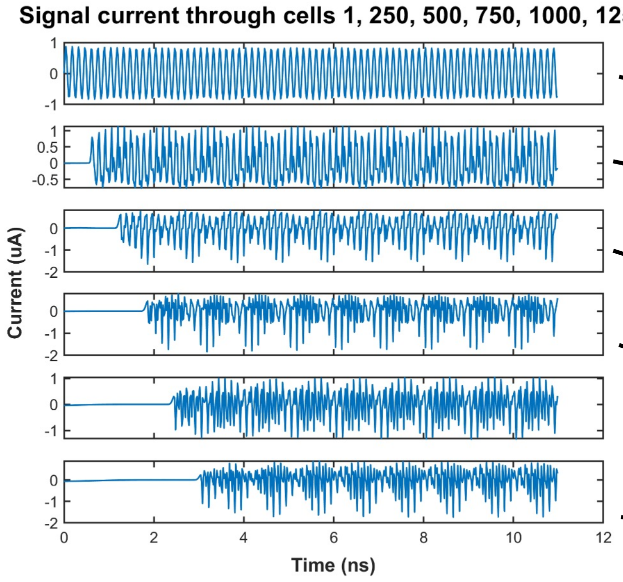
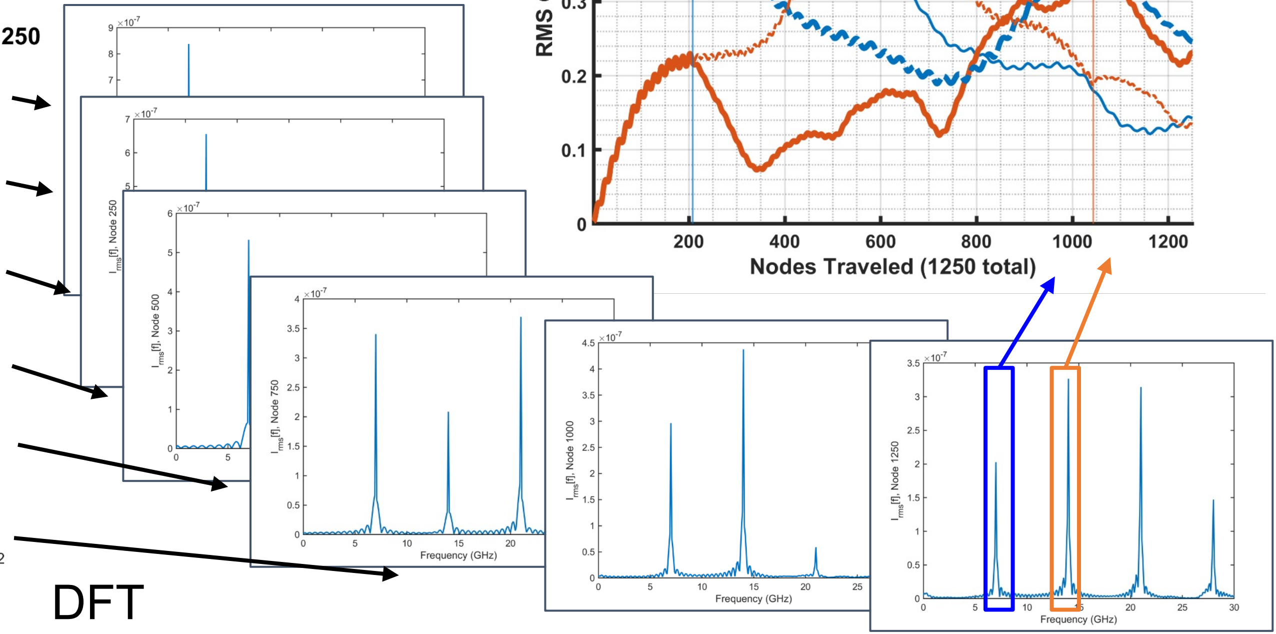
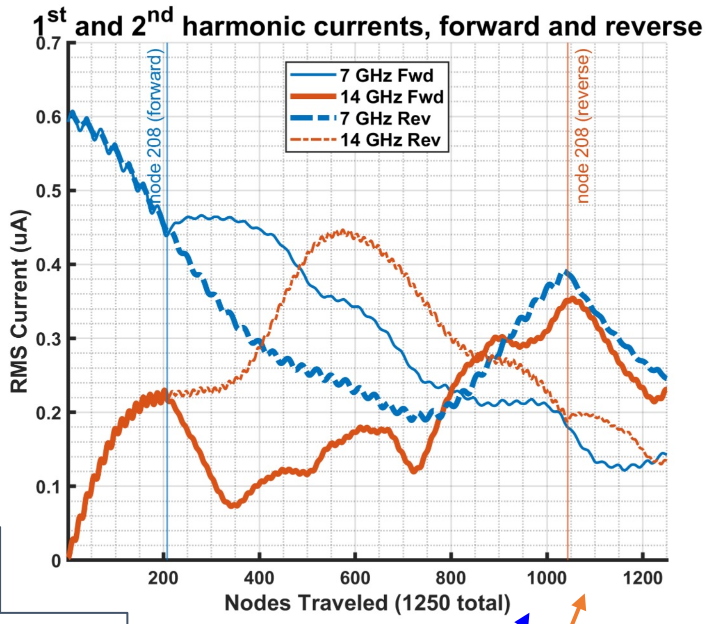
# Simulation: Circuit Level

- We use *WRspice* to simulate our device
- Lumped elements, passive and nonlinear
- Post-process to obtain frequency-domain data



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# Simulation: Circuit Level Parameters

- These are the parameters we used:
- The length of our device is 1250 nodes with 1μm/node

| | |
|---|---|
| n | 1250 |
| a | 1 |
| b | 208 / 500 |
| m | 208 /500 |

| | |
|---|---|
| $L_g$ | 57 pH |
| $L_J$ | |
| $C_g$ | 50 fF |
| $C_J$ | 60 fF |

| | |
|---|---|
| $I_p$ | 0 A |
| $I_s$ | 0.6 μA |
| $I_{dc}$ | 14.068 μA |
| $I_{crit}$ | 5 μA |

| | |
|---|---|
| $f_p$ | 14 GHz |
| $f_s$ | 7 GHz |

| | |
|---|---|
| $R_{term}$ | 23.8747 Ω |

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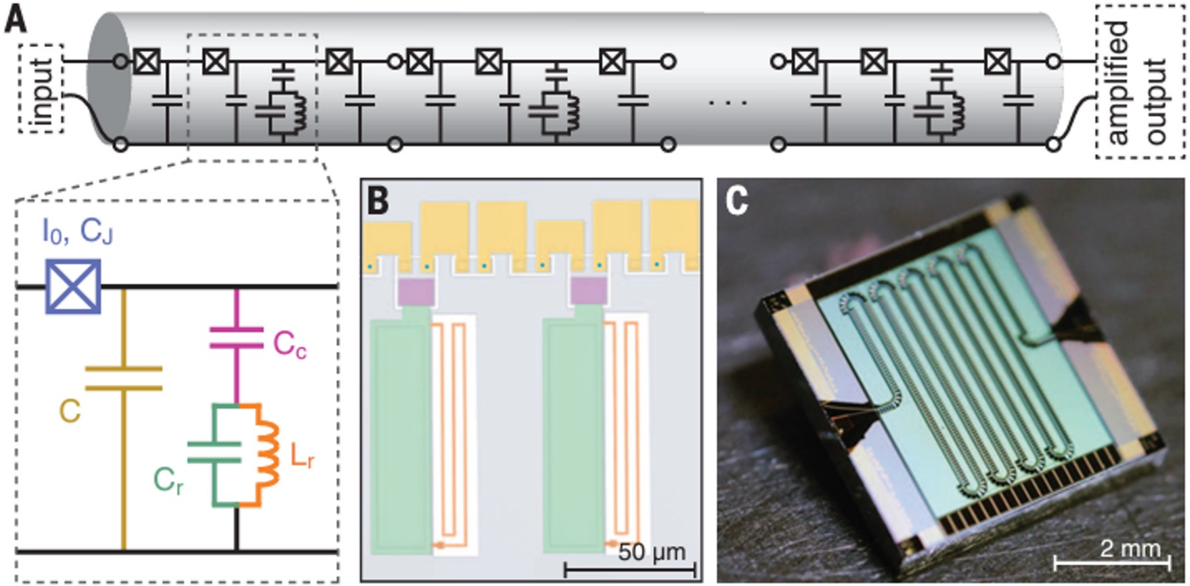
# Fabrication and Design

- Our device is essentially a modified Josephson traveling wave parametric amplifier (JTWPA) and the parameters we use reflect this




Schematic of a JTWPA in which we obtain our circuit parameters
Macklin et al., *Science* (2015)

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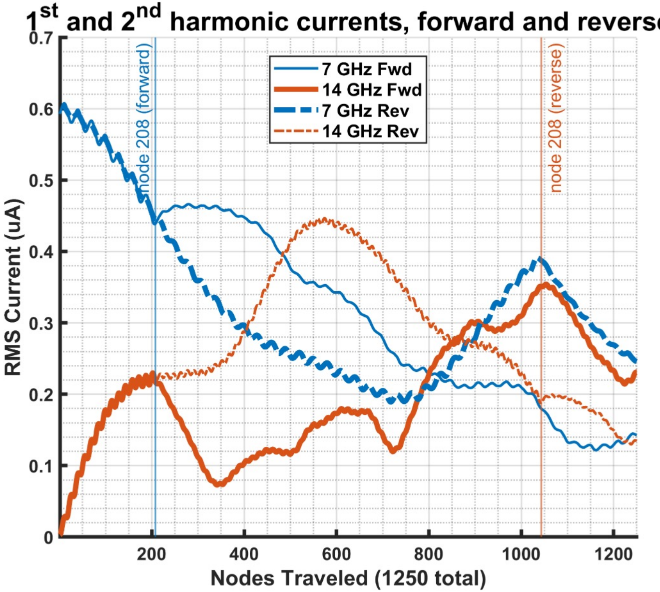
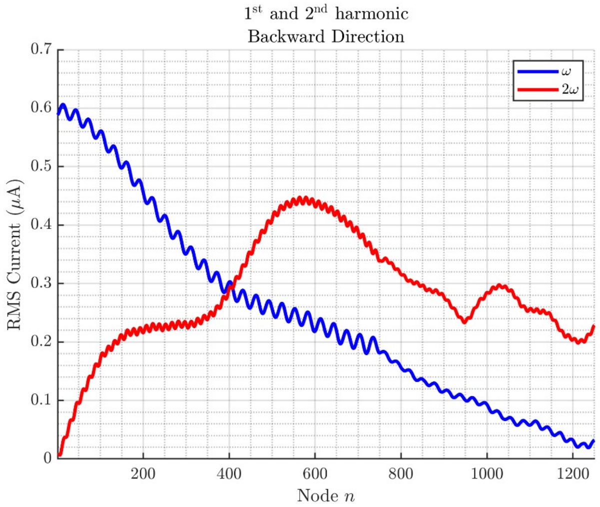
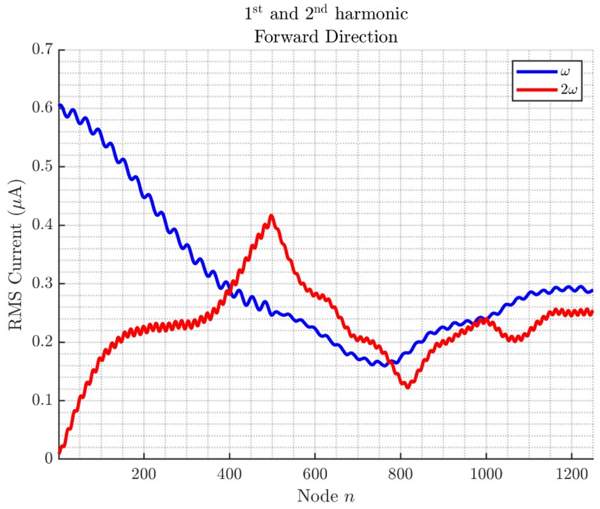
# Refresher on our device

# Results: Plots of Two Device Iterations

- Bottom: Poled region from cells 0 to 208
- Right: Poled region from cells 0 to 500
- (Total of 1250 cells)
- We *thought* these would be optimal, based on the differential equations…

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## Results

- We care about **isolation, insertion loss,** and **bandwidth**
  - 3dB bandwidth is 200MHz
  - Insertion loss is 7.7dB
  - Isolation is 4.75dB

| | $\|S_{21}\|^2$(dB) | $\|S_{12}\|^2$(dB) |
|---|---|---|
| **ω→ω** | -12.33 | -7.70 |
| **ω→2ω** | -8.18 | -12.93 |
| **2ω→ω** | 33.27 | 39.74 |
| **2ω→2ω** | 37.42 | 34.51 |

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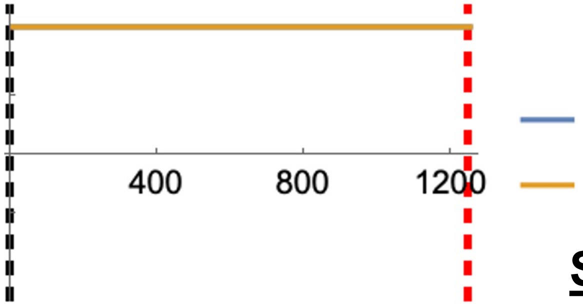
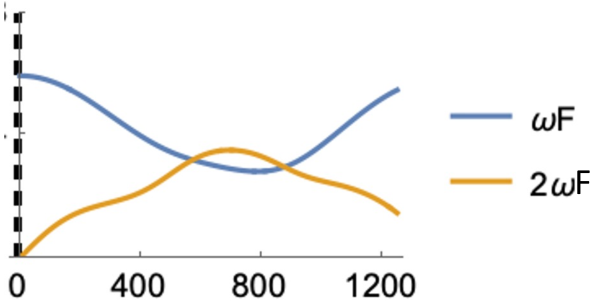
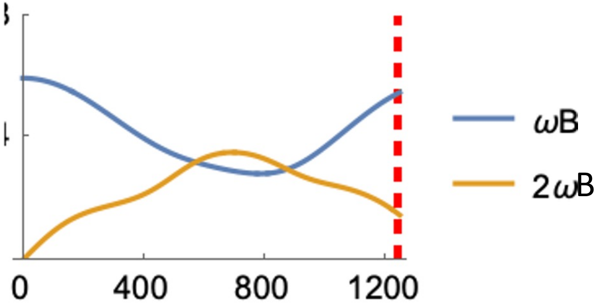
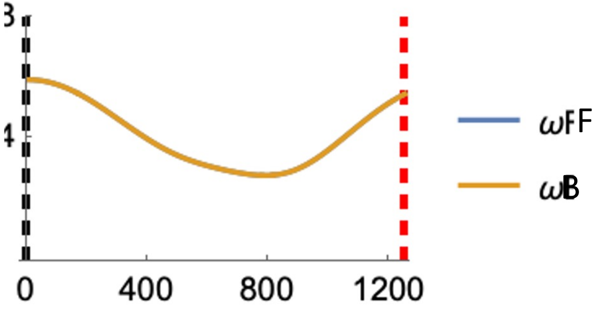
Node = 0

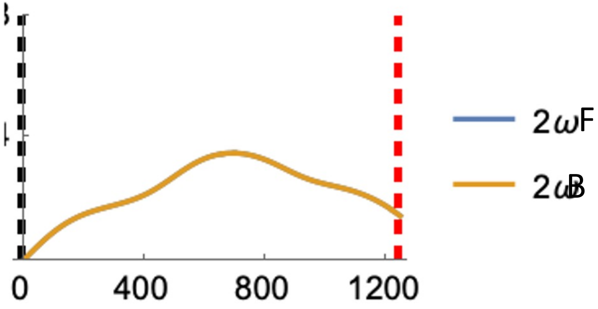
# Sweeping for optimal poled region



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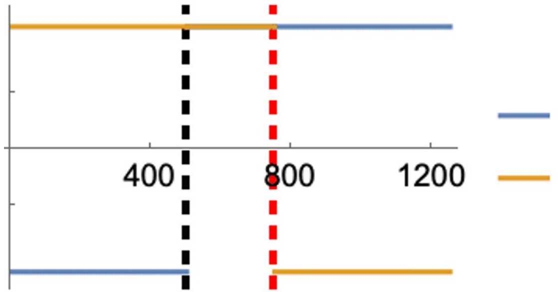
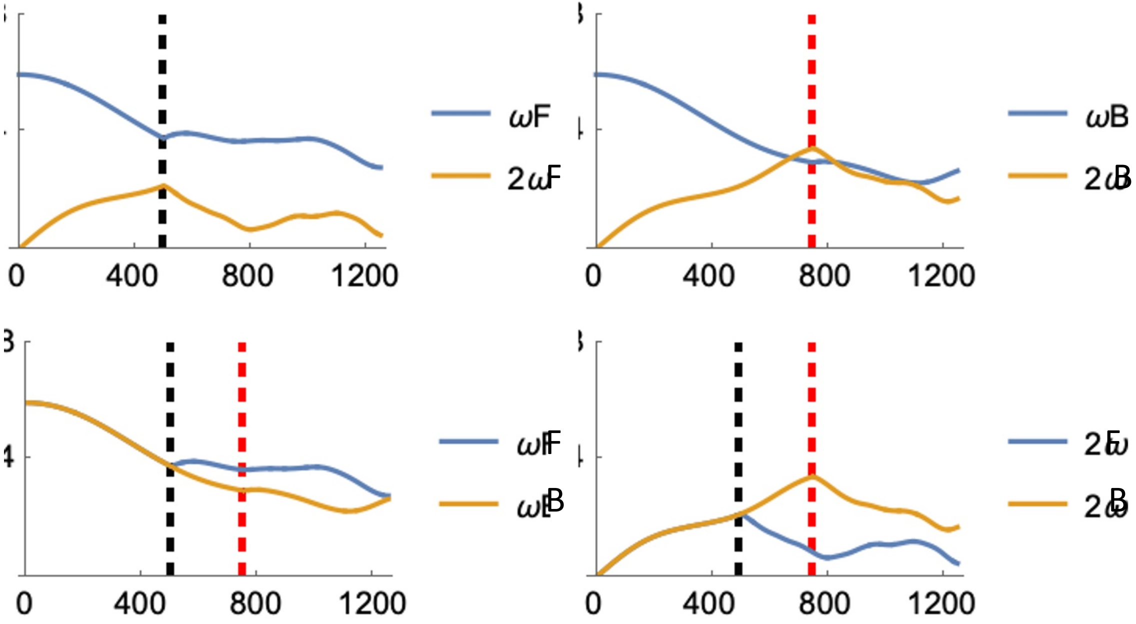



freq(GHz) =6.5

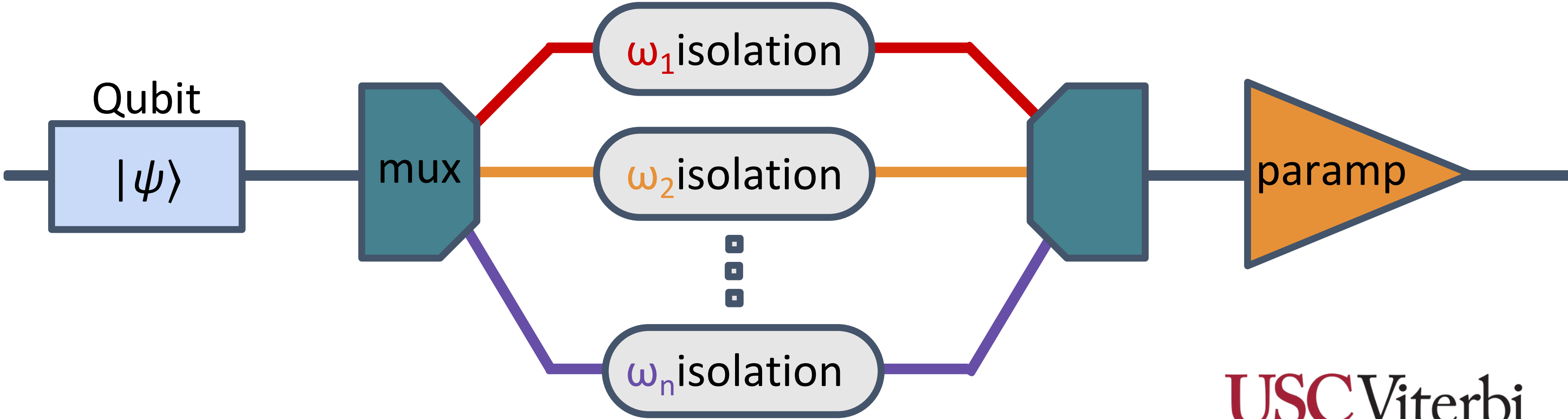
$|S_{21}{}^{\omega\to\omega}|$=0.372501

## Sweeping for bandwidth



# Drawbacks on our Design

- Our device combines this optical isolator on a superconducting platform
  - Not **impedance matched**
  - Even **harder to fabricate** compared to a JTWPA
  - Narrow **bandwidth** due to sensitivity to initial signal frequency
    - May be resolvable with an array of isolators with frequency multiplexing




Frequency multiplexing for broadband isolation



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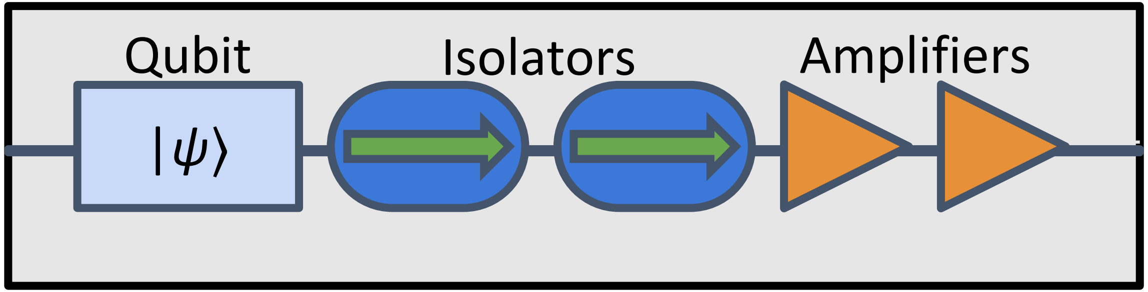
# Future Directions

- We need to sweep all our design parameters: circuit elements, defect location, SQUID screening parameter value, etc. at once to optimize
- A full 4x4 S-parameter matrix
  - Requires sweeping group delay to obtain phase information
  - Requires reflectometry to obtain $S_{11}$ and $S_{22}$
- We can attach this to a TWPA to create a **directional parametric amplifier**
  - Towards fully on-chip qubit readout

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**Thank you!**