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AN OSA VIRTUAL MEETING

Non-reciprocal Silicon Photonic Coupler Exploiting Graphene Saturable Absorption

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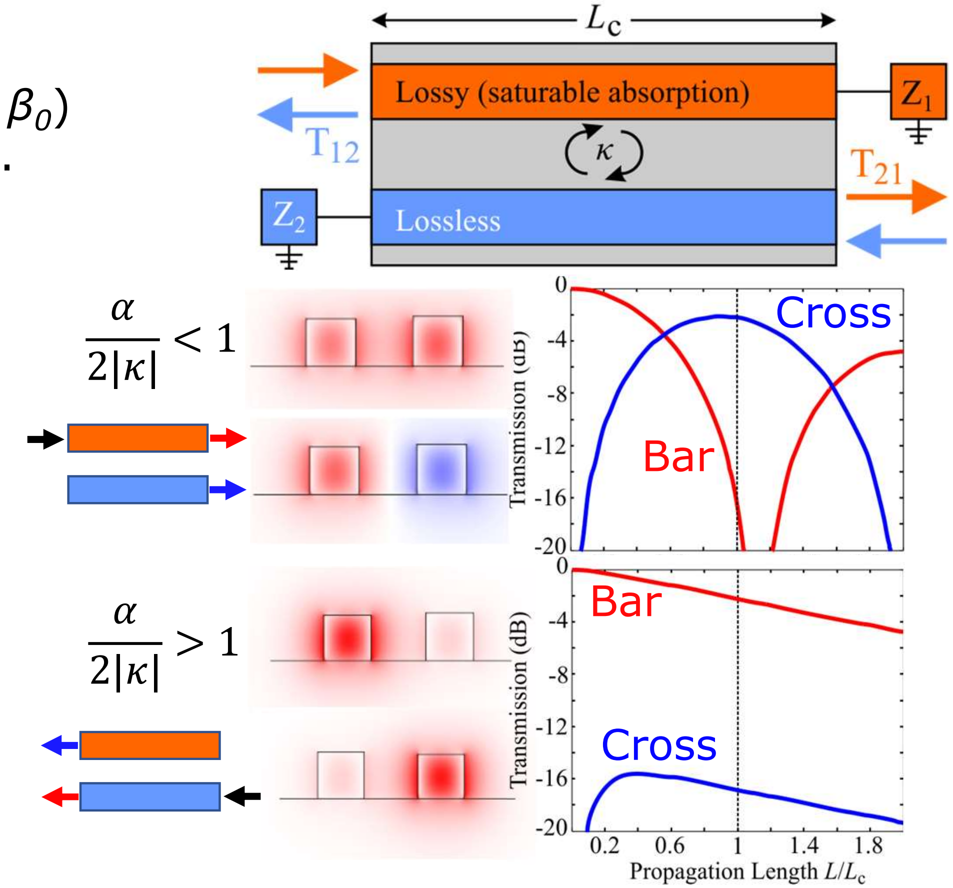
Introduction

- ❑ Demand for on chip **integrated optical isolators**
    - ❖ Magneto-optic components are bulky/expensive/hard to integrate.
- ✓ **Non-linear non-reciprocity** : Non-linearity + asymmetry breaks reciprocity.
    - ❖ Common implementation: **Resonant components** + **Kerr effect.**
        - ✗ Resonators: **high isolation** but **low bandwidth.**
- ❑ This work: **Directional coupler** + **Saturable Absorption (SA).**
    - ❖ The **asymmetry** is enhanced by the **Exceptional Point (EP)** of the non-Hermitian (lossy) coupler.
    - ❖ Non-linearity (SA) is provided by **Graphene**.
    - ✓ Compatible **integration** with SOI platforms.
    - ✓ Relaxed **bandwidth** limiting factors.

Concept (1/2) – The Linear Regime

- Lossy Photonic Coupler
  - Two identical waveguides (same phase constant β_0)
  - Top waveguide has saturable losses (non-linear).
  - Bottom waveguide is lossless (linear).
  - Two port configuration.
  - Length = Coupling length L_c
- Linear Regime (without SA)
  - Super-modes $\beta = \beta_0 - j\frac{\alpha}{2} \pm \sqrt{|\kappa|^2 - \left(\frac{\alpha}{2}\right)^2}$
  - Exceptional Point at $\frac{\alpha}{2|\kappa|} = 1$.
  - When $\alpha/2|\kappa| > 1$ one supermode is lossy and the other is lossless (asymptotically).
  - The lossy supermode vanishes very fast: **Light remains in the lossless waveguide**.

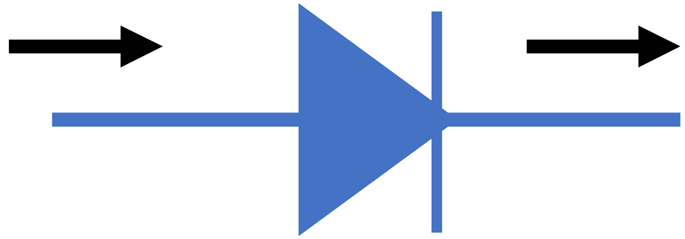


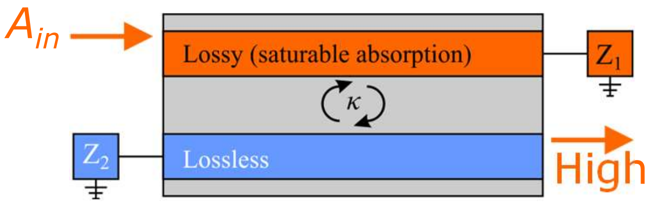
Chatzidimitriou *et al.*, JOSA B **35**, 1525-1535, 2018

Concept (2/2) – The Non-linear (SA) Regime

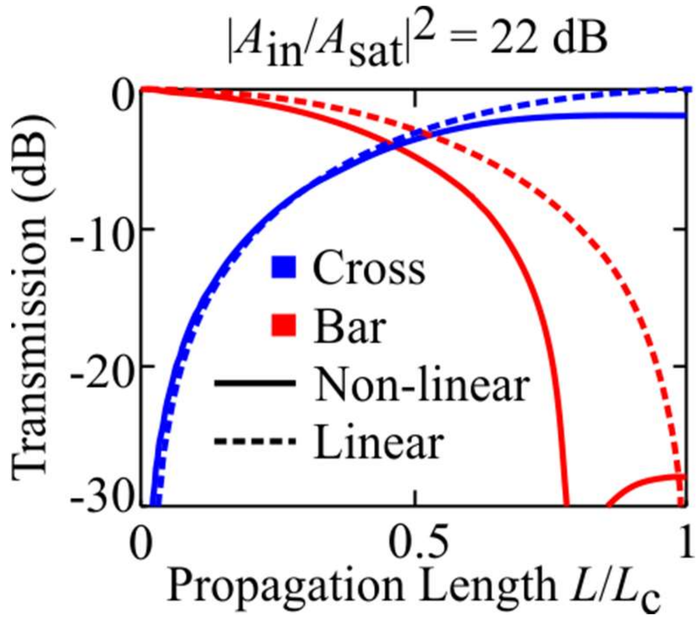
$$\alpha \rightarrow \frac{\alpha}{1 + |A_1|^2/|A_{sat}|^2}$$

Assume that for $|A_1| \ll |A_{sat}| \rightarrow \frac{\alpha}{2|\kappa|} \gg 1$ and half-duplex operation.





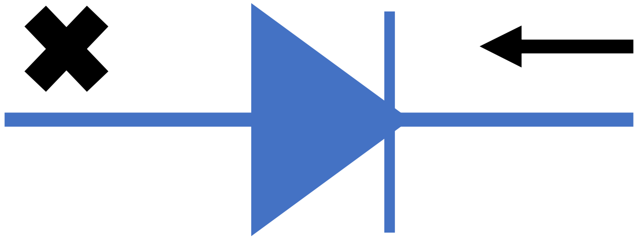
- High-power excitation **from the lossy (SA) waveguide**:
  - **High overlap** with the non-linear waveguide.
  - Due to SA: $\alpha \rightarrow 0$, $\alpha/2|\kappa| < 1$. **Below EP**.
  - Light **can couple** to opposite waveguide **(forward)**.

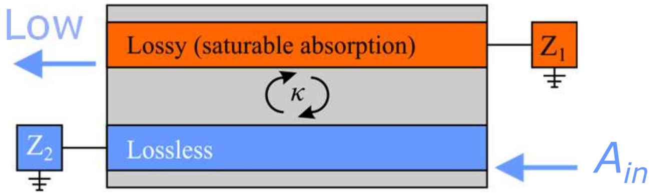


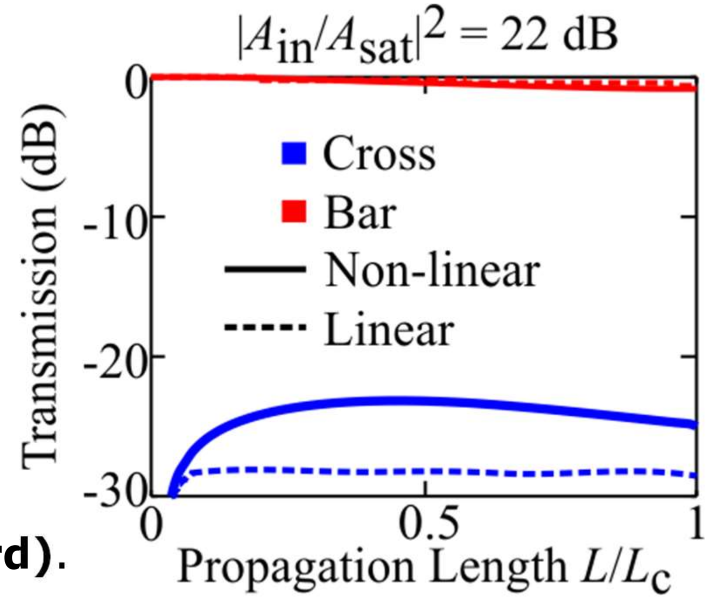
Concept (2/2) – The Non-linear (SA) Regime

$$\alpha \to \frac{\alpha}{1+|A_1|^2/|A_{sat}|^2}$$

Assume that for $|A_1| \ll |A_{sat}| \to \frac{\alpha}{2|\kappa|} \gg 1$ and half-duplex operation.





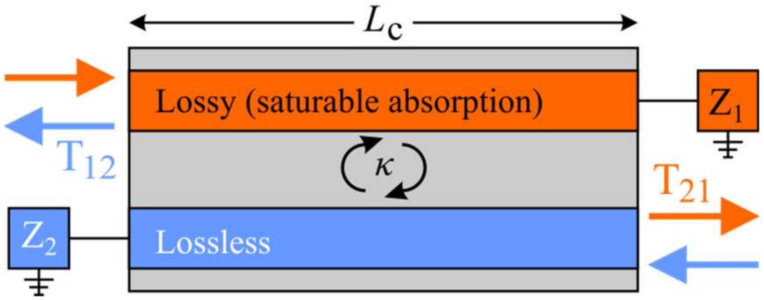


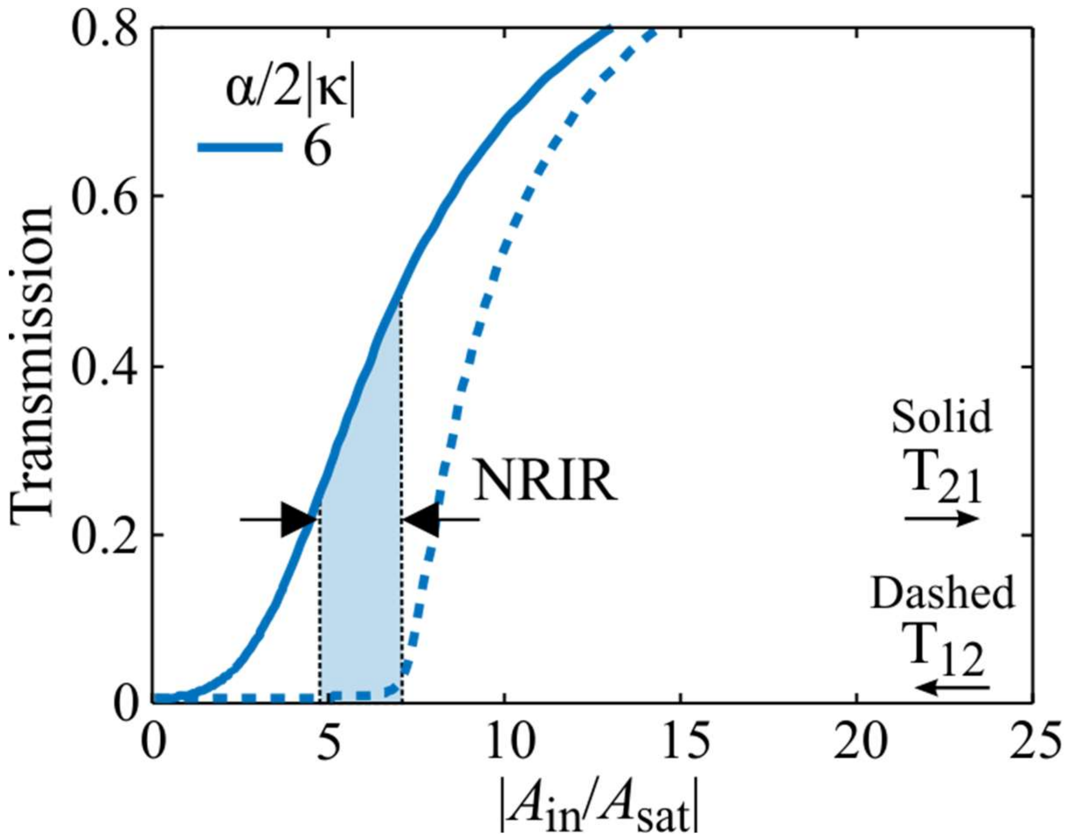
- High-power excitation **from the lossless waveguide**:
  - **Little overlap** with the non-linear waveguide
  - Losses are **not saturated,** $\alpha/2|\kappa| \gg 1$. **Above EP**.
  - Light **cannot couple** to opposite waveguide **(backward)**.

Concept Results – Coupled Mode Theory

- Simple CMT model

$$\frac{\partial}{\partial z}\begin{bmatrix}A_1\\A_2\end{bmatrix}=\begin{bmatrix}-j\beta_0-\dfrac{\alpha}{1+|A_1|^2/|A_{\mathrm{sat}}|^2} & \kappa\\ -\kappa^* & -j\beta_0\end{bmatrix}\begin{bmatrix}A_1\\A_2\end{bmatrix}$$





- The **Non-Reciprocal Intensity Range** (NRIR) is bound by:
  a) **Forward** transmission > -6 dB.
  b) **Backward** transmission < -15 dB.

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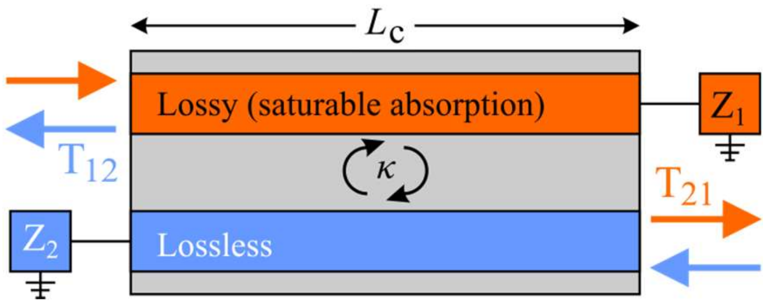

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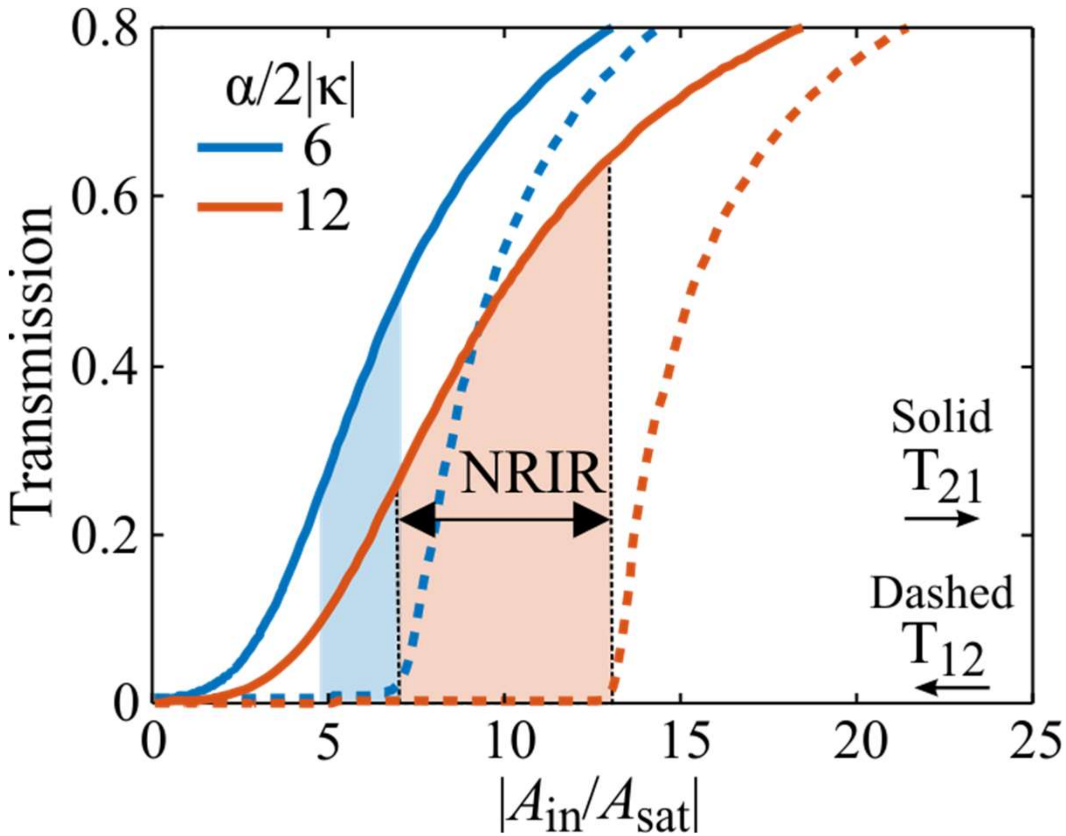


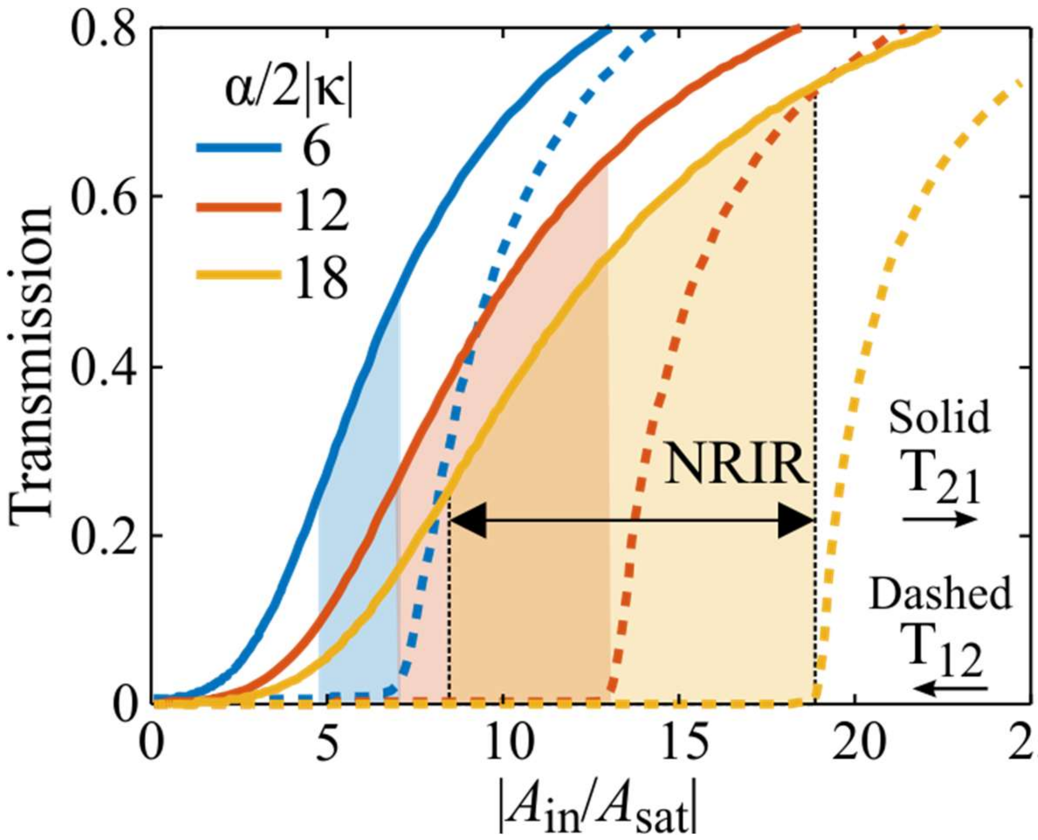
Concept Results – Coupled Mode Theory

Conclusions from concept model:

✓ Increasing $\alpha/2|\kappa|$ increases NRIR but also increases NL threshold
- Higher losses are better!
- Small $|\kappa|$ leads to large devices

✗ Ideal performance (high transmission and/or perfect isolation) is inherently prohibited
- A compromise must be made:
- Narrow NRIR or high NL threshold

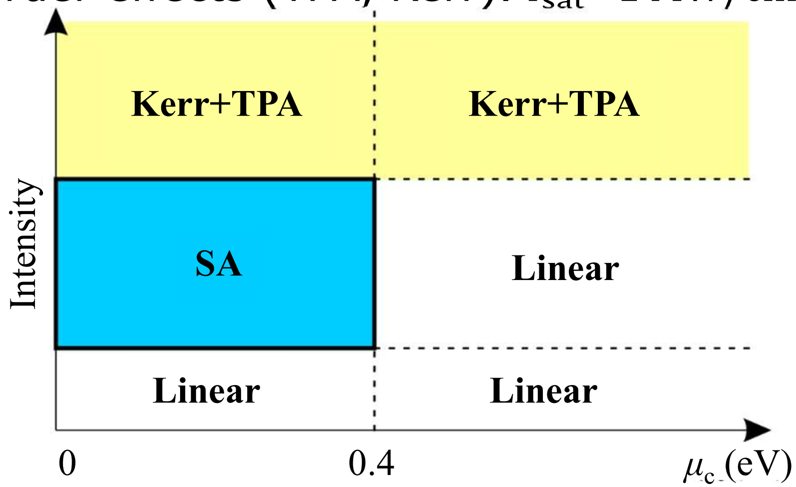
❖ At low and at very high powers the device is again reciprocal

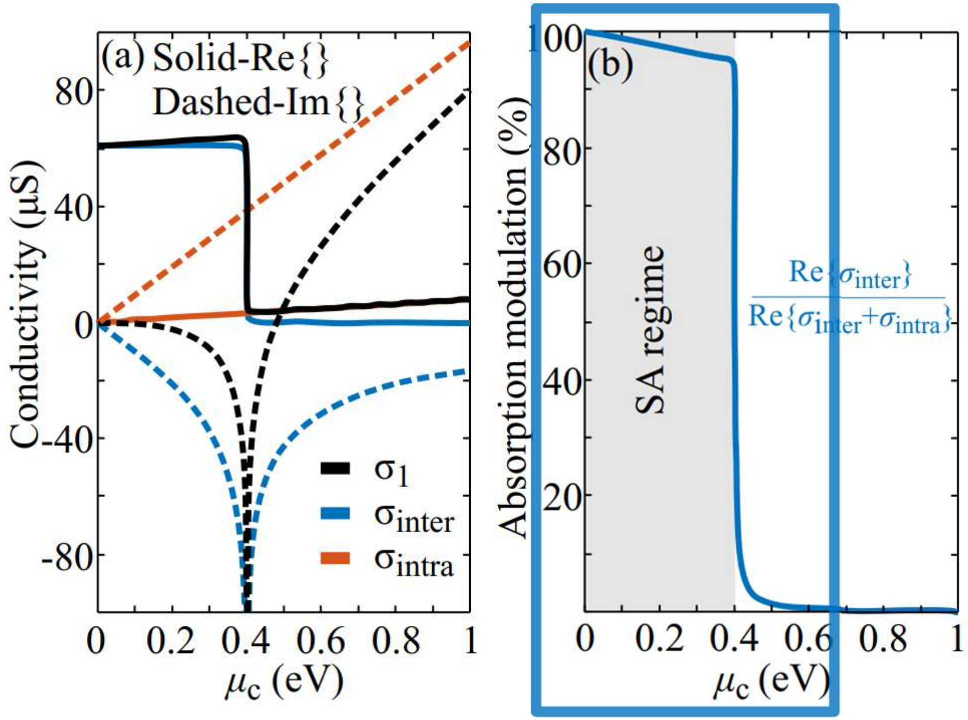


Physical implementation with graphene (1/3)

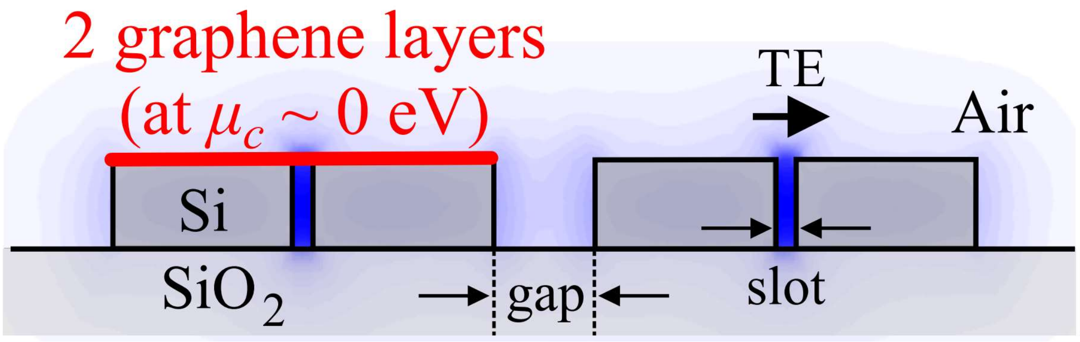
❑ Graphene monolayer characteristics at 1550 nm

- Linear conductivity $\sigma_1 = \sigma_{\text{intra}} + \sigma_{\text{inter}}$.
- Saturation of the **interband conductivity**.
- $|\mu_c| < 0.4$ eV, ideally **totally saturable.**
- **SA has lower power threshold** than other third order effects (TPA, Kerr). I_{sat}~1 MW/cm^2





Physical implementation with graphene (3/3)



- Pair of identical **silicon slot waveguides**.
  - Left waveguide overlaid with **two graphene monolayers**
  - Graphene is **unbiased** $\mu_c = 0\ \mathrm{eV}$, so that $\sigma \approx \sigma_{\mathrm{inter}} \approx$ 122 μS
- The dimensions chosen ensure that:
  - Field is mainly guided in the slot area: **high confinement**.
  - TE polarization parallel to graphene: **high interaction**.
- Waveguide dimensions:
  - Height = 180 nm
  - Width = 360 nm
  - Slot = 40 nm
  - Gap = 640 nm
- Parameters
  - Coupling length $L_c = 0.5\pi/|\kappa| = 800\ \mu\mathrm{m}$
  - Unsaturated losses $\alpha = 0.42\ \mathrm{dB}/\mu\mathrm{m}$

CMT parameter
$\alpha/2|\kappa| \approx 12$

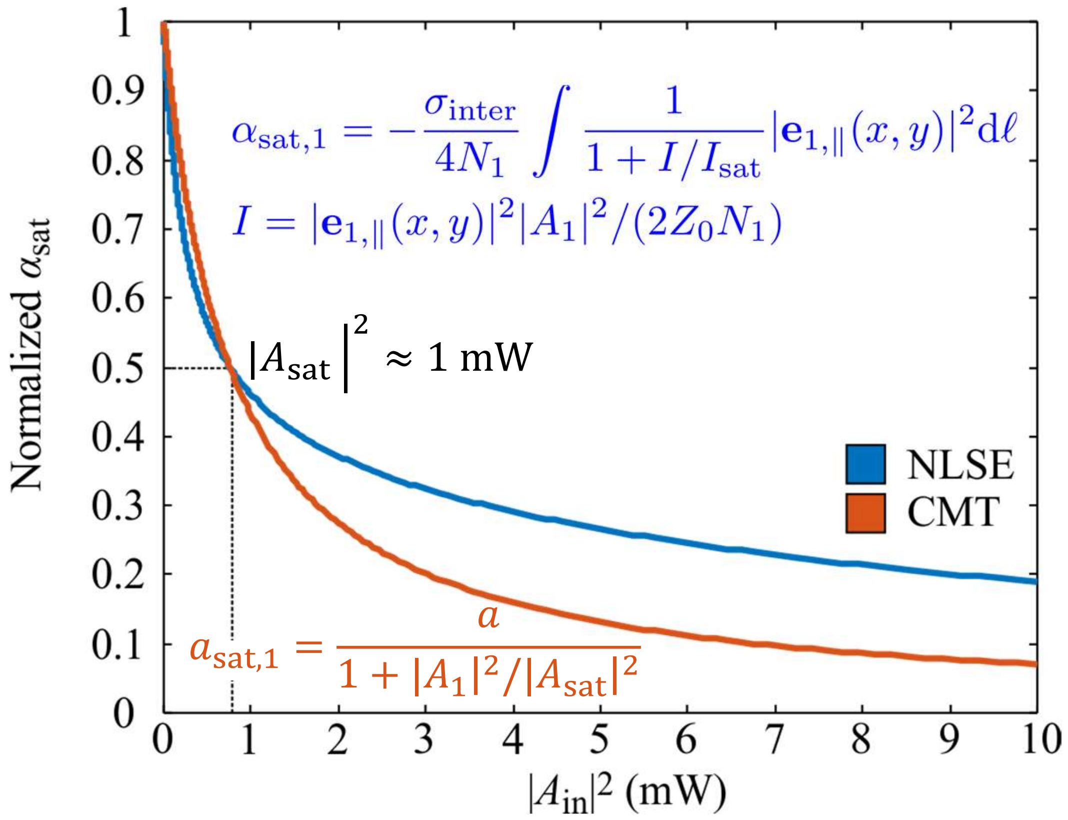
Improving the CMT approximation

❑ **Non-Linear Schrodinger Equations** (NLSE)

$$\frac{\partial A_1}{\partial z} = \alpha_{\mathrm{sat},1}(|A_1|^2)A_1 + \alpha_{\mathrm{nsat},1}A_1 + i\kappa A_2,$$
$$\frac{\partial A_2}{\partial z} = \alpha_{\mathrm{nsat},2}A_2 + i\kappa A_1,$$

- Graphene saturation intensity $I_{\mathrm{sat}} = 1\ \mathrm{MW/cm^2}$
- Non-saturable losses $a_{\mathrm{nsat},i} = 0$
- Coupling coefficient $\kappa = \pi/2L_c$
- Normalization constant N_i

- Each equation is derived for **a specific waveguide/mode** (uncoupled) and then coupled **heuristically**
- Approximation stands due to **weak coupling**



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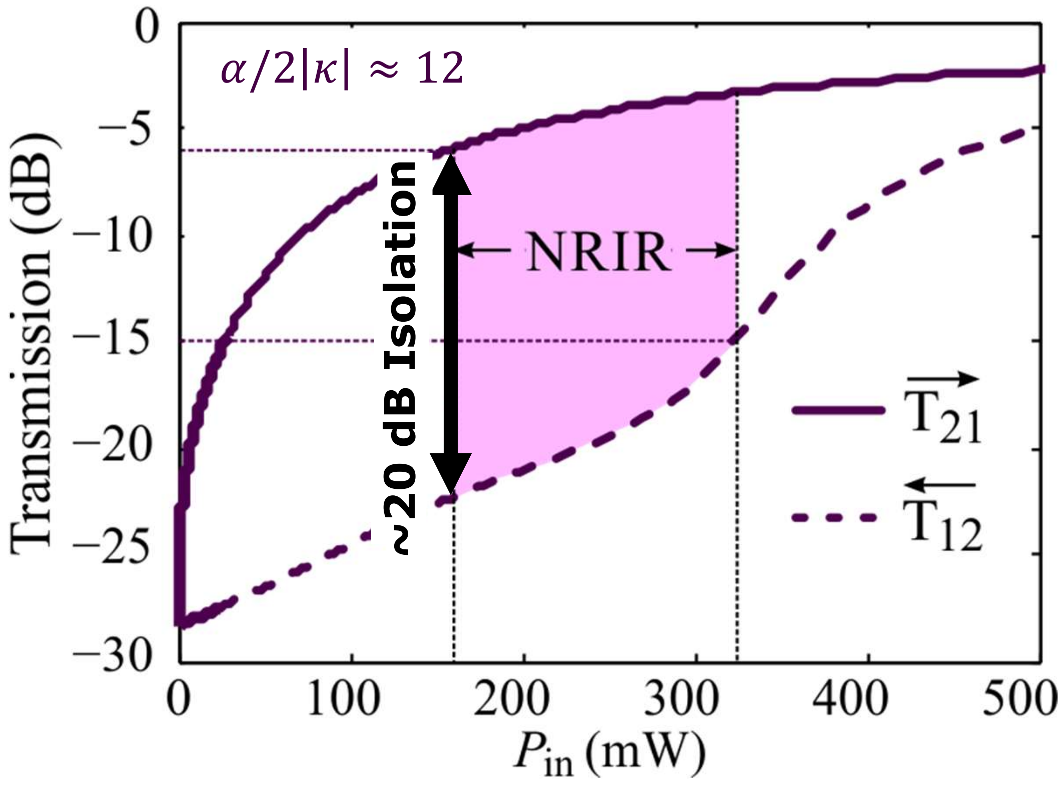

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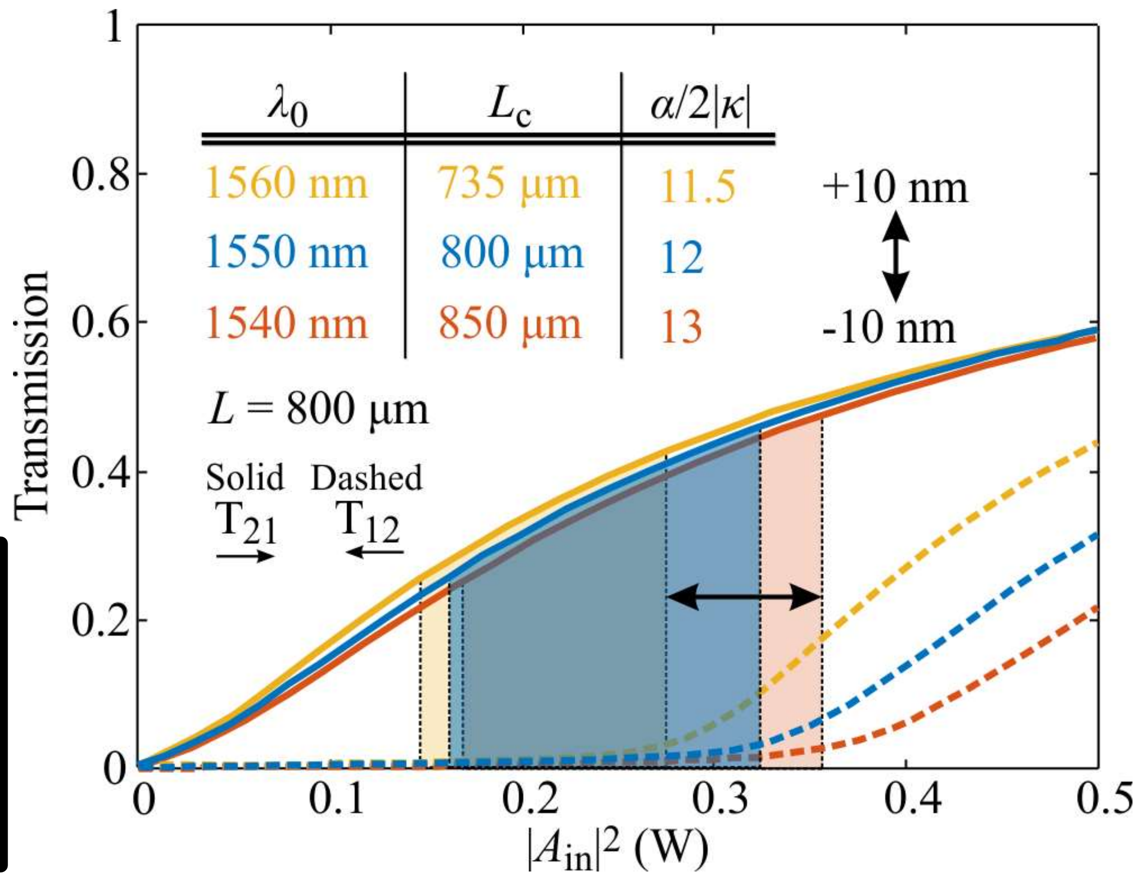

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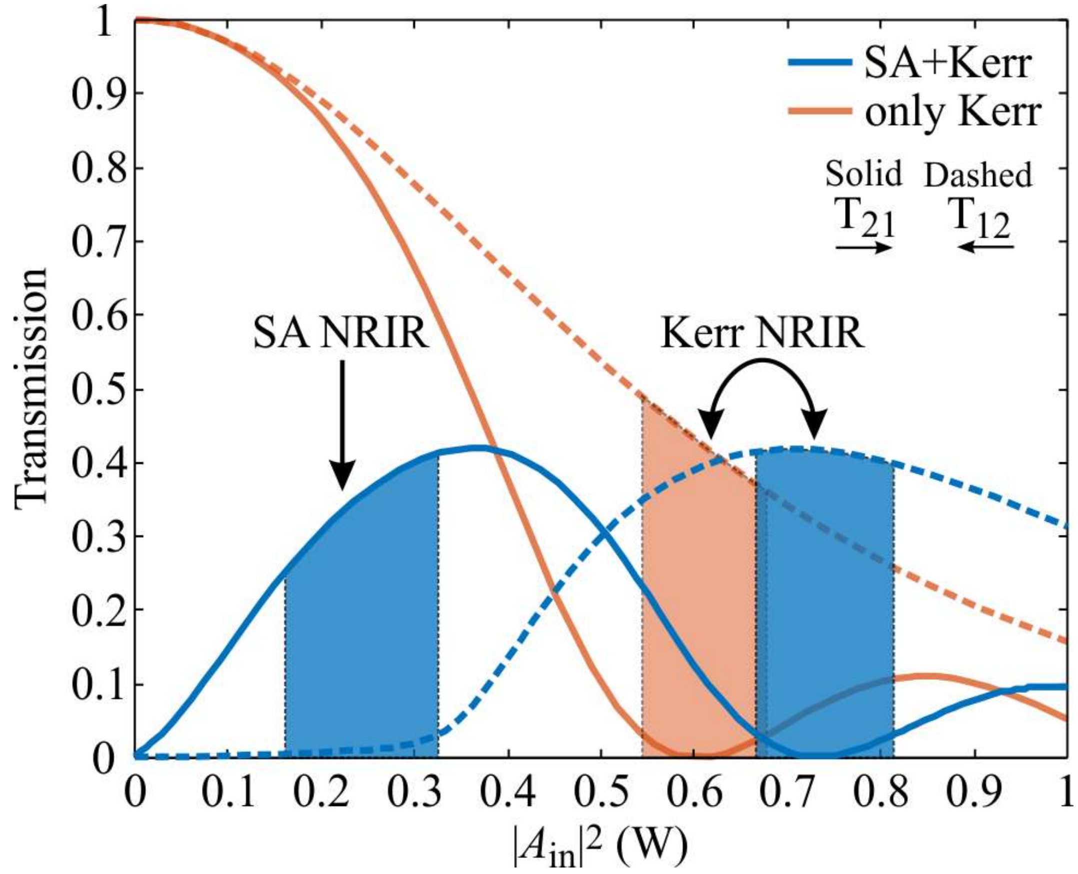


Validating coupled NLSE

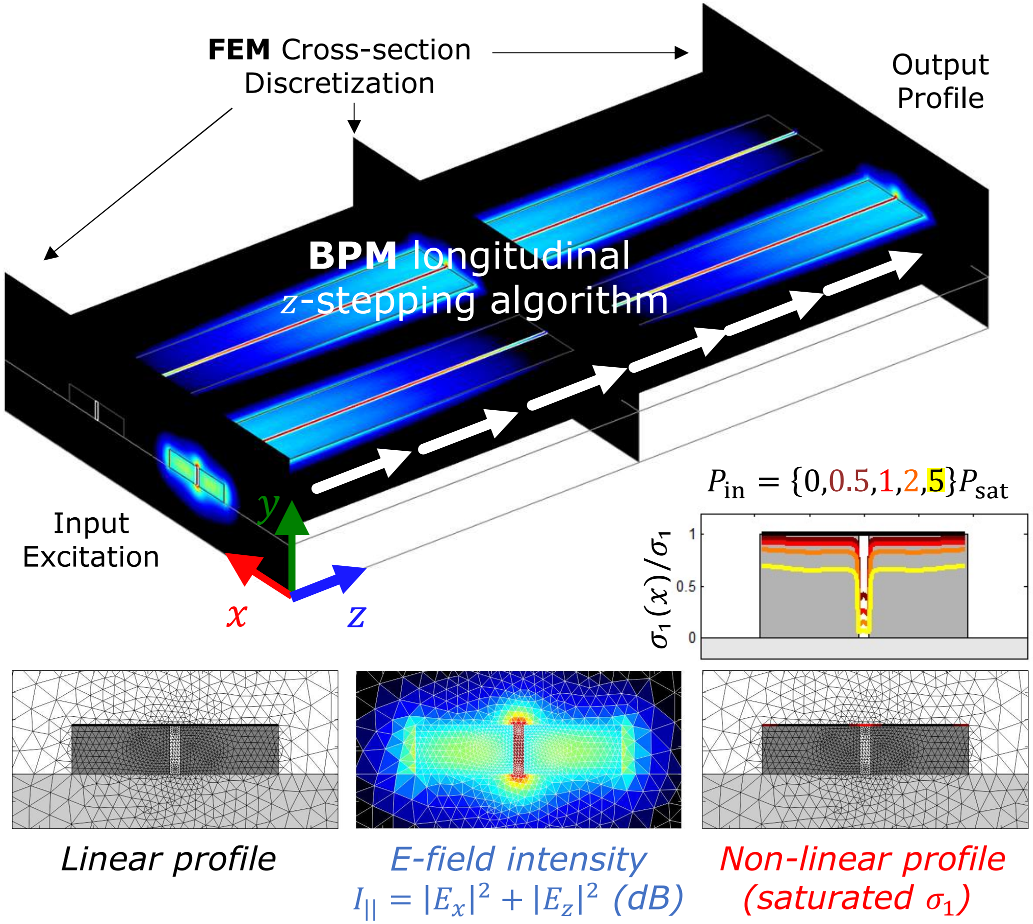
❑ **Beam Propagation Method** (BPM)

Numerical step-wise propagation of an input excitation along a slowly varying waveguide

- ✓ **Frequency-domain (CW) method**
- ✓ **Cross-section** (xy plane)**:** Hybrid higher-order vector/nodal finite-elements (FEM)
- ✓ z**-propagation:** Finite-difference Crank-Nicolson stepping scheme

Non-linear BPM

- Material EM properties (n for bulk materials and σ for sheet materials) depend on E-field intensity
- Graphene SA: $\Delta\sigma(x,y,z) = -\sigma_{1,inter}(x,y) \cdot I_n/(1+I_n)$
  - ❖ Normalized intensity: $I_n = \left|\vec{E}_{||}(x,y,z)\right|^2/(2Z_0 I_{sat})$
- In-step iterations for stability (2-3 are enough)



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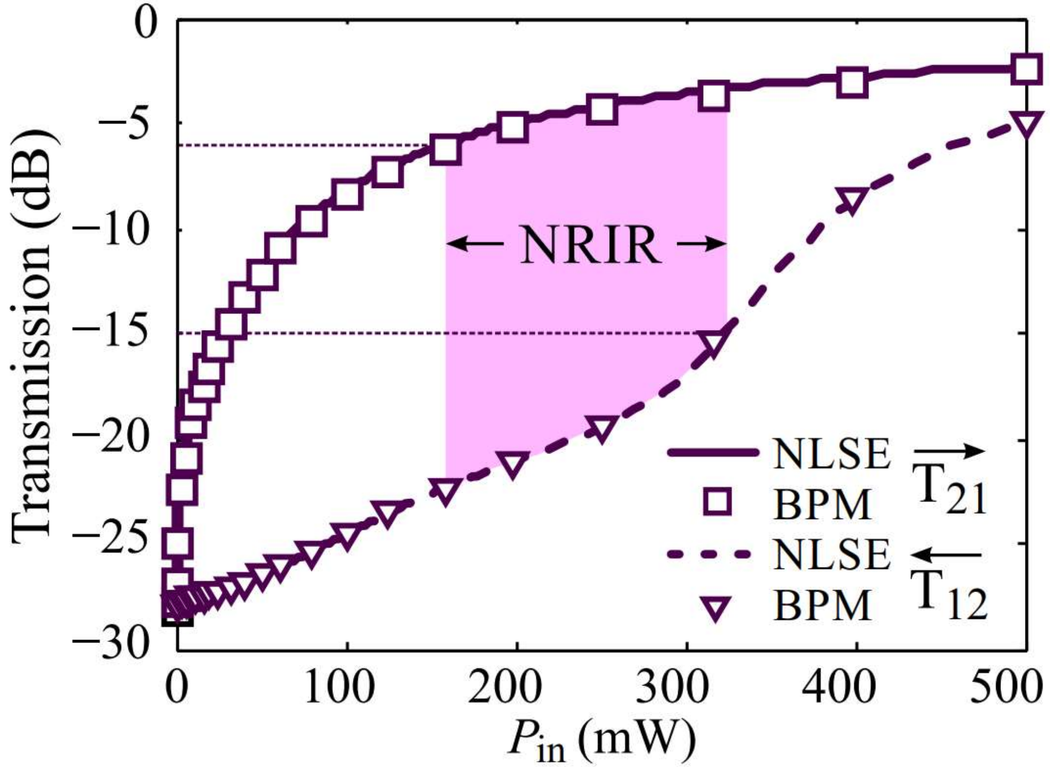
Excellent agreement (0.2 dB) w/ NLSE

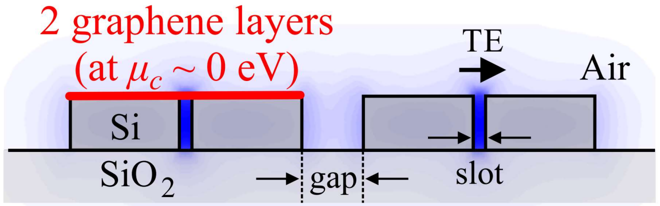


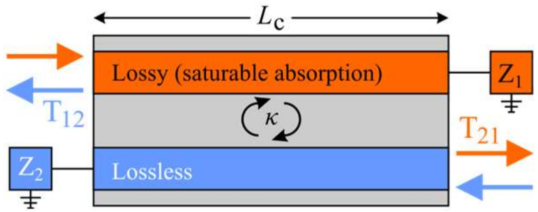
Summary and Conclusions

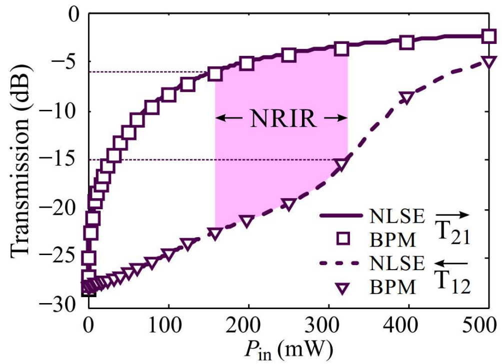
To summarize:

- ❑ Studied the **breaking of reciprocity** by utilizing EPs and SA.

- ❑ Proposed a physical implementation using a **silicon slot waveguide** (SOI platform) and **graphene**







Conclusions:

- ❑ **SA combined with EPs** as an **alternative to the Kerr** effect.
  - **Lower power** threshold than the Kerr effect.
  - **Compatible** with standard **integration** techniques.
  - **Bandwidth** is limited mainly by waveguide coupling!

Thank You!

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