PT Symmetry breaking in graphene-comprising photonic devices

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Presentation outline

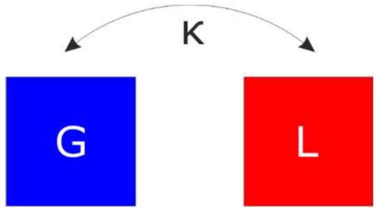
1. **PT-Symmetry in photonics**
   a. Basic PT-Symmetry concepts
   b. Passive PT-Symmetry
2. **Graphene conductivity**
3. **Graphene Enhanced Coupler**
4. **Electro-optic switch**
   a. Graphene impact on waveguide modes
   b. Evolution of coupler super-modes
   c. 1×2 switch
5. **Polarization dependent switching**

PT-Symmetry in photonics

PT-Symmetry in photonics

PT-Symmetry in photonics

- A coupled system:
  - ✓ coupled waveguides
  - ✓ coupled resonators
  - ✓ forward and backward modes

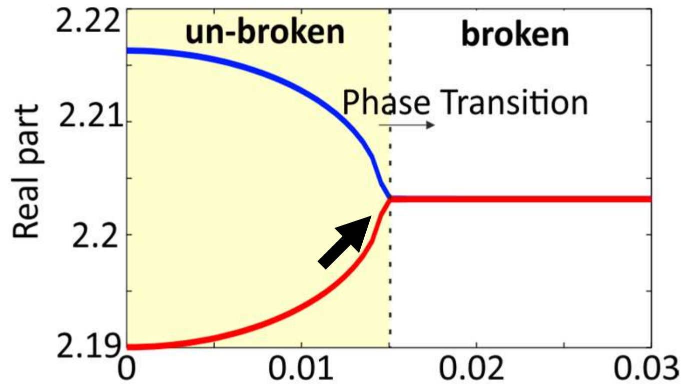


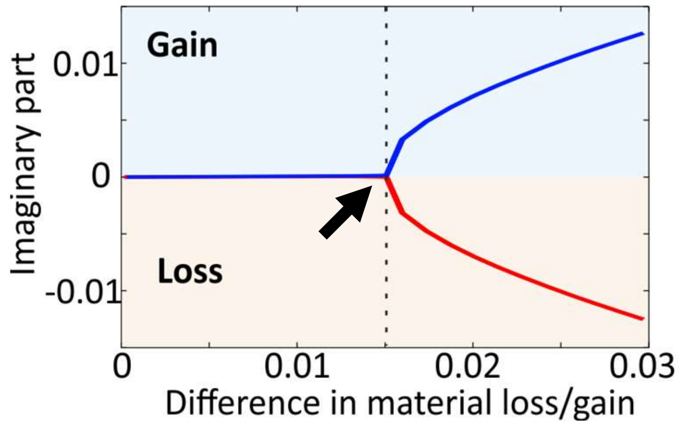
- Balanced gain and loss: $\beta_1 = \beta_2^* \Rightarrow \alpha_1 = -\alpha_2$
- Super-modes $\beta = \beta_0 - j\frac{\alpha_1 + \alpha_2}{2} \pm \sqrt{|\kappa|^2 - \left(\frac{\Delta\alpha}{2}\right)^2}, \Delta\alpha = \alpha_1 - \alpha_2$
- Exceptional Point at $\Delta\alpha = 2|\kappa|$ Eigenvalues coalesce!

$$\Delta\alpha \to \infty \begin{cases} \beta_S = \beta_0 - j\alpha_1 \\ \beta_A = \beta_0 - j\alpha_2 \end{cases}$$

Super-modes asymptotically evolve into the individual propagation constants

- Exceptional point can be reached even when $\alpha_1, \alpha_2 \geq 0$

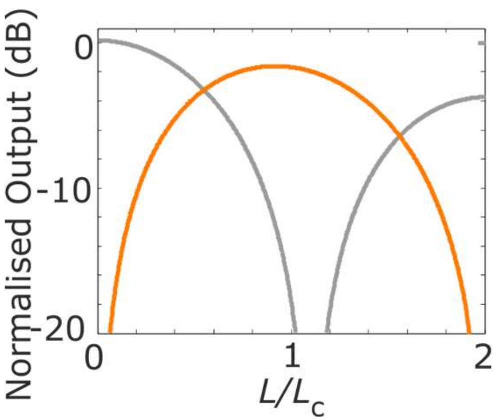




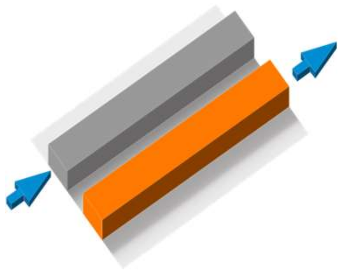
PT-Symmetry in photonics

Passive PT-Symmetry

Operation in the normal regime $\Delta\alpha < 2|\kappa|$



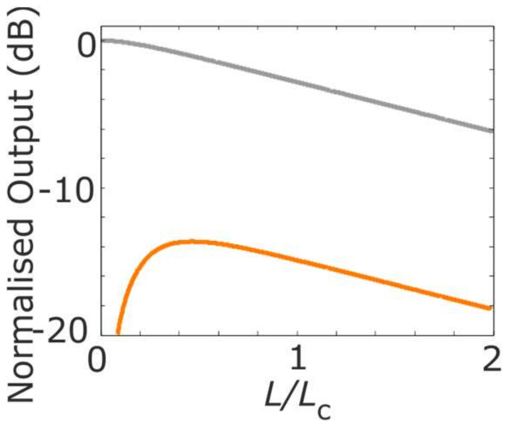
Light is coupled @ L_c intervals



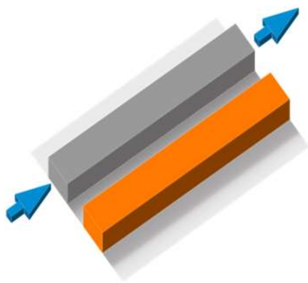
Waveguide 1 (lossy) Waveguide 2 (lossless)

- We assumed that $\alpha_2 = 0$ and $\alpha_1 = \alpha_L$
- Losses at the normal regime
- Ideally $\alpha_L \to 0$

Operation in the broken symmetry regime $\Delta\alpha > 2|\kappa|$



Light is confined to the low-loss waveguide



Waveguide 1 (lossy) Waveguide 2 (lossless)

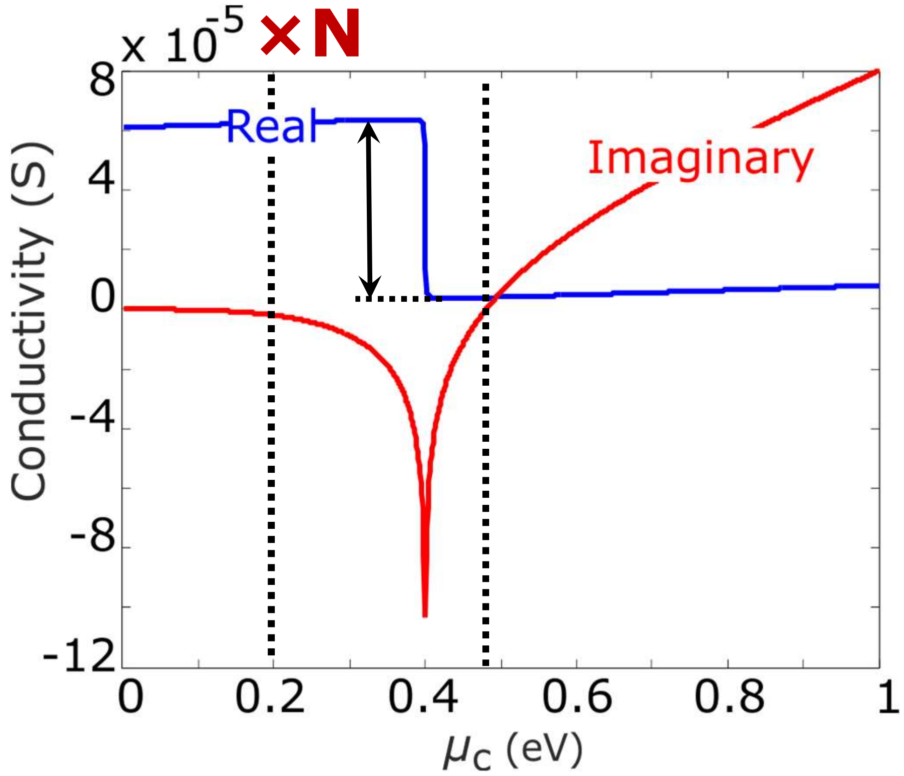
- We assumed that $\alpha_2 = 0$ and $\alpha_1 = \alpha_H$
- Symmetry is broken BUT the modes are lossy!
- Losses depend on $\Delta\alpha = a_H$
- Ideally $\alpha_H \to \infty$

Graphene conductivity

Graphene surface conductivity

Monolayer
- ✓ High and low conductivity regimes
- ✓ Interband transition are prohibited above ~0.4 eV
  - Corresponds to $\hbar\omega/2$ @ 1550 nm
- ✓ Imaginary part should be the same
  - PT requirement $\mathrm{Re}\{\beta_1\} = \mathrm{Re}\{\beta_2\}$
- ✓ **Conductivity control** through external electrostatic biasing

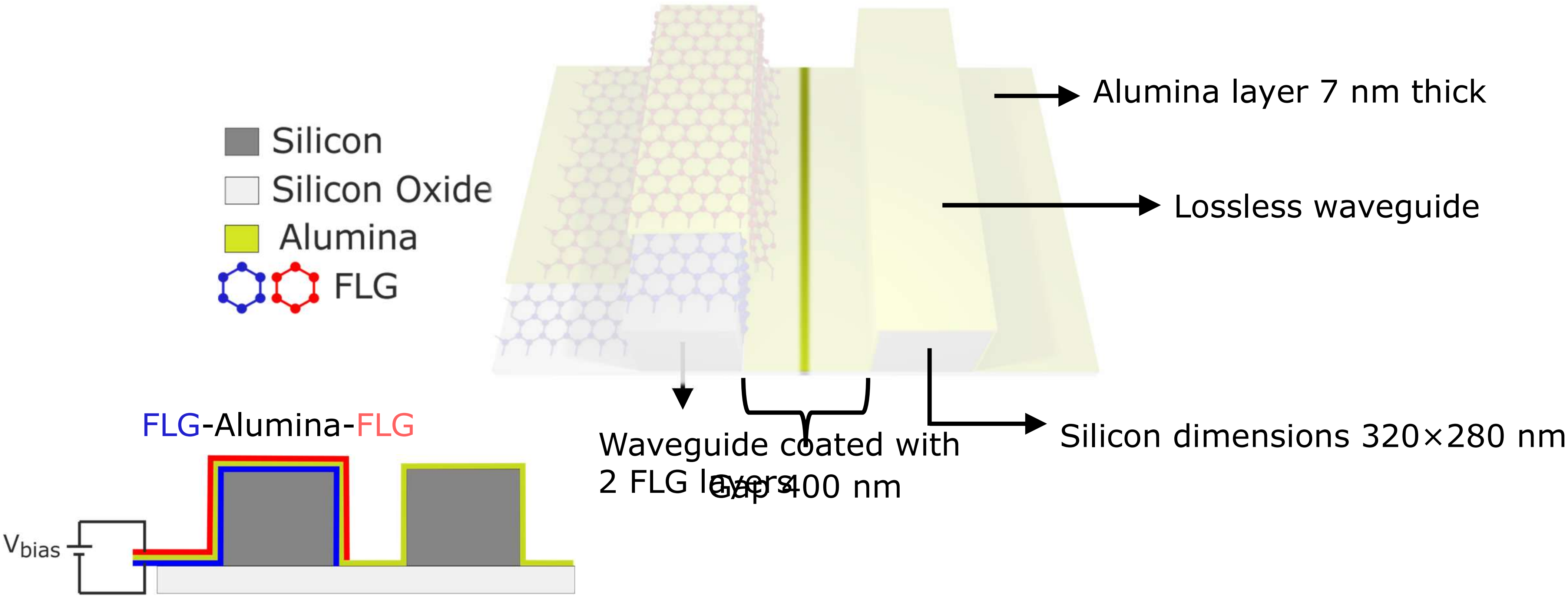
Few Layer Graphene (FLG)
- ✓ **N times** the monolayer conductivity (N<9)
- ✓ N=3 in this work



Graphene enhanced coupler

Graphene enhanced coupler

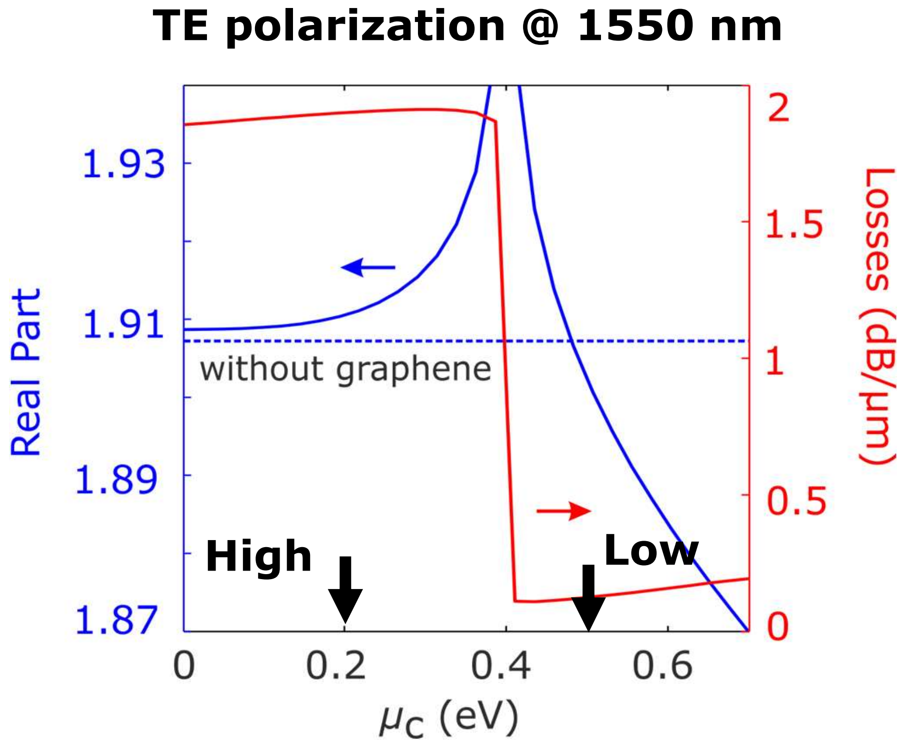
Coupler set-up



Electro-optic switch

Graphene enhanced coupler

Impact on n_{eff} of individual waveguides



High loss state $\alpha_{\rm H}$ @ 0.2 eV
Low loss state $\alpha_{\rm L}$ @ 0.5 eV

❖ There exist μ_c values with higher/lower losses **BUT** Real part of $n_{\rm eff}$ needs to be the same
✓ PT requirement
✓ no coupling de-tuning

$\alpha_{\rm H}$ and $\alpha_{\rm L}$ define the device length (L_c) through the IL!

❖ For an arbitrary IL level *A:*

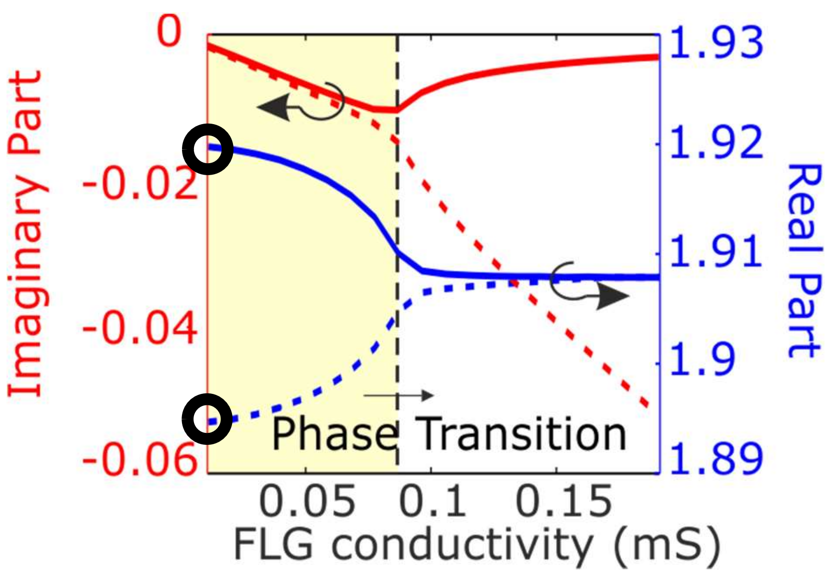
$$\left.\begin{array}{l} \alpha_{\rm L} L_{\rm c} < A \\ \alpha_{\rm H} L_{\rm c} > \dfrac{A^2+\pi^2}{2A} \end{array}\right\}$$

Trade off: achievable high loss state vs device length

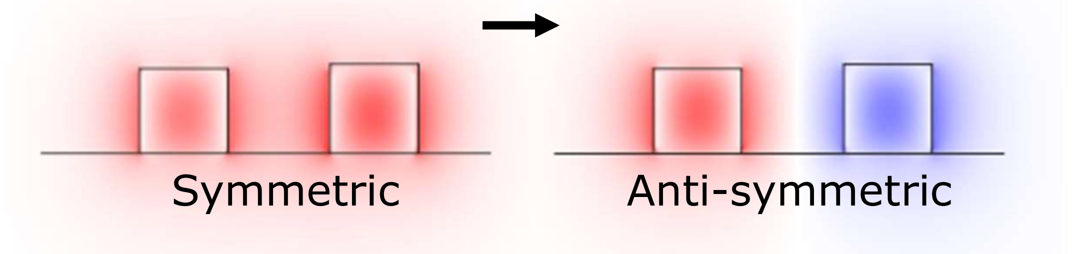
Electro-optic switch

Evolution of super-modes

Unbroken symmetry regime, μ_c=0.5 eV



Electric field norm
TE polarization

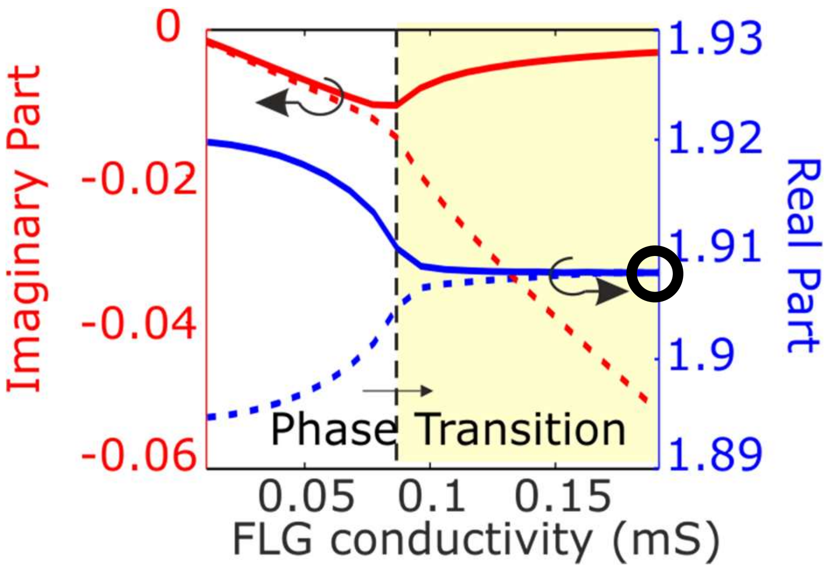


- Injection in one of the waveguides excites in general both super-modes
- Propagation is governed by the superposition of super-modes: constructive/destructive interference
- **Light is normally coupled (cross state)**

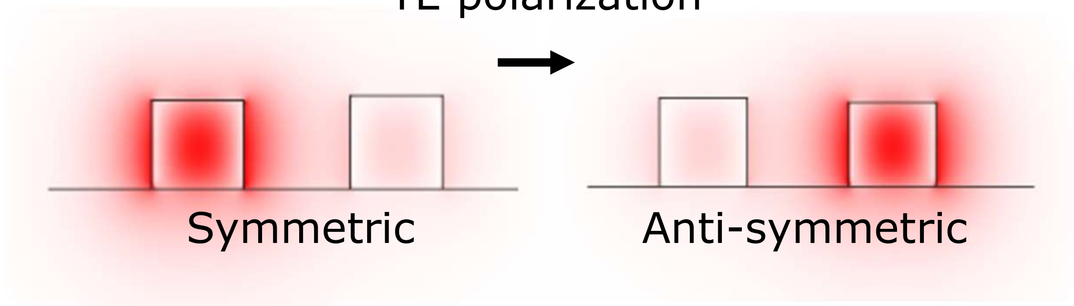
Electro-optic switch

Evolution of super-modes

Broken symmetry regime, μ_c=0.2 eV



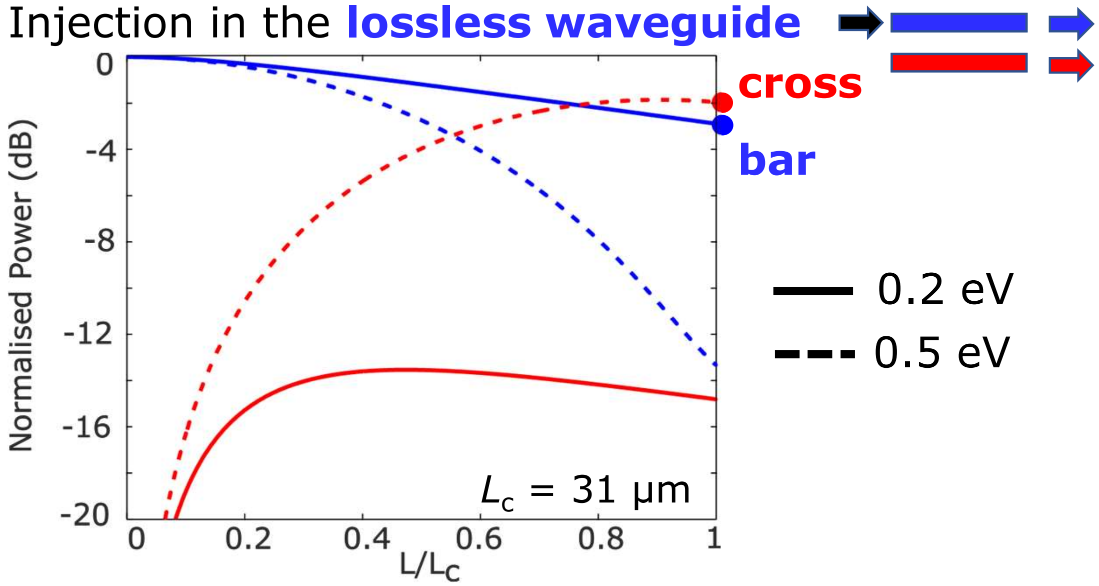
Electric field norm
TE polarization



- Super-modes are now confined in the individual waveguides
- They experience high and low losses respectively
- The high loss super-mode vanishes
- **Light mainly exits from the low loss waveguide (bar state)**

Electro-optic switch

Injection in the **lossless waveguide**

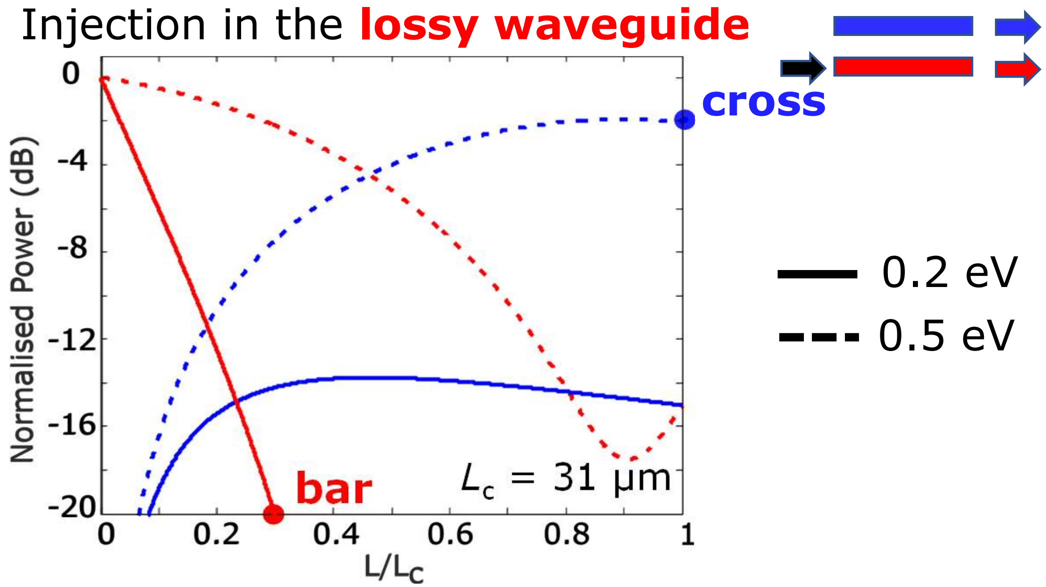


	μ_c	IL
Cross	0.5 eV	2 dB
Bar	0.2 eV	2.7 dB

1×2 functionality

- Cross and bar states are close
- Acceptable losses

Injection in the **lossy waveguide**



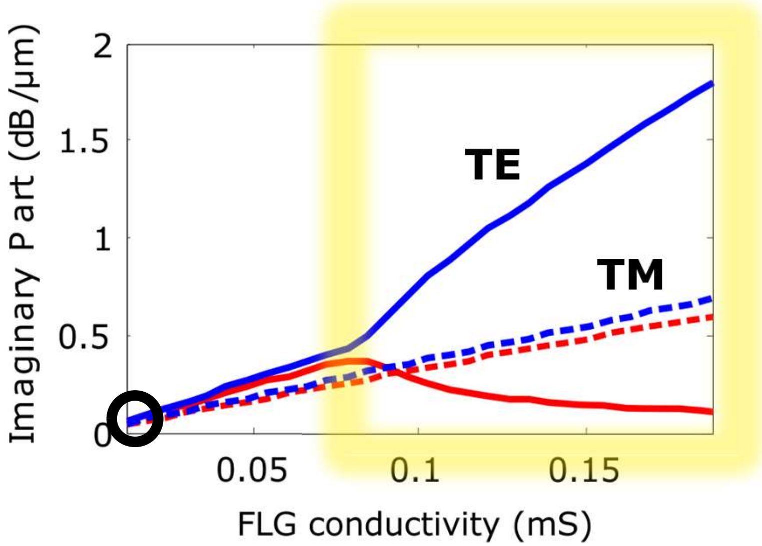
	μ_c	IL
Cross	**0.5 eV**	**2 dB**
Bar	**0.2 eV**	**>20 dB**

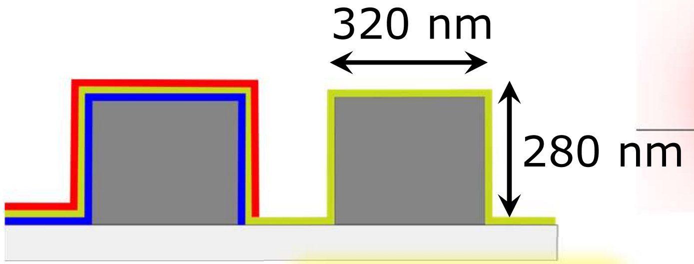
No switching

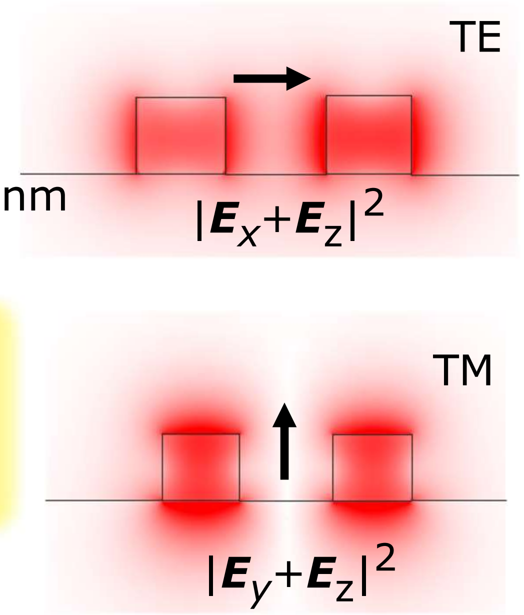
- Light exits from the lossless waveguide
- Cross transmission identical→Reciprocity

Polarization dependent switching

Polarization dependent switching



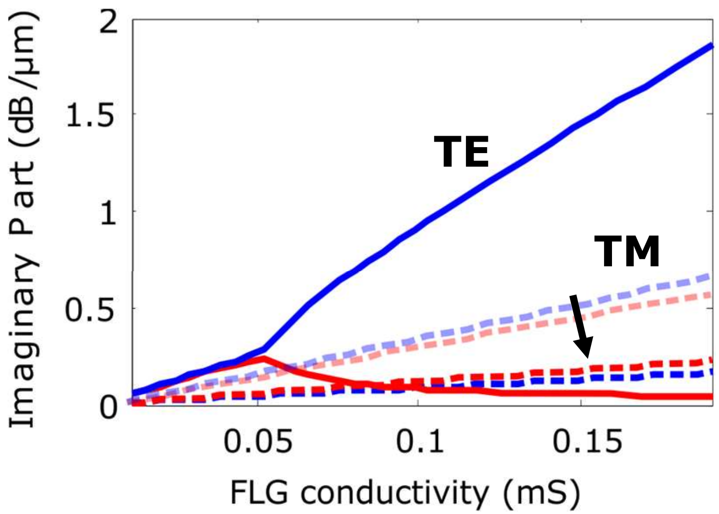


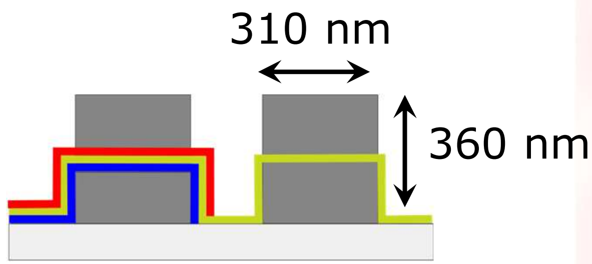


$$\beta = \beta_0 - j\frac{\alpha_1+\alpha_2}{2} \pm \sqrt{|\kappa|^2 - \left(\frac{\Delta\alpha}{2}\right)^2}$$

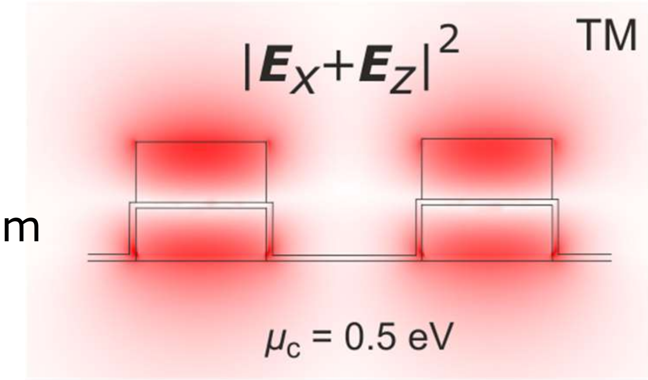
- TM mode does not enter the broken symmetry regime
- Because graphene is coated both polarization have equivalent overlap
- TM **κ is almost double** of TE, needs **double the losses**
- We need a layout where one polarization weakly overlaps with graphene

Polarization dependent switching





Bilayer / Alumina /Bilayer

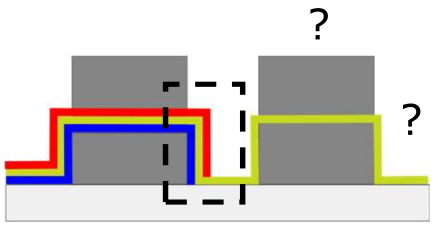


- ✓ Graphene is placed so that TM modes have weak overlap
- ✓ Waveguide dimensions are chosen so that modes have the same $L_c \sim 40$ μm
- ✓ Due to weaker coupling only 2 bilayers are used

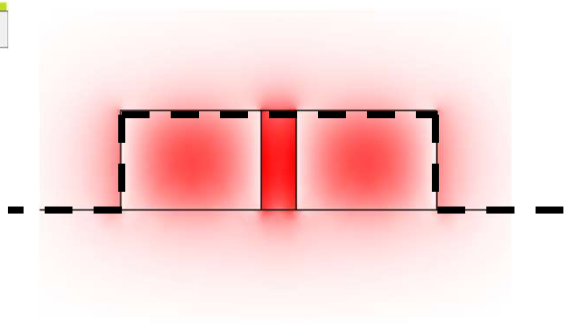
μ_c	TE		TM	
0.5 eV	**cross**	1.6 db	**cross**	0.3 dB
0.2 eV	**bar**	2.8 dB	**cross**	3.7 dB

Injection in lossless waveguide

Future Prospects



- Polarization dependent switch improvements
  - Waveguide dimensions
  - Graphene placement



- Investigation of different waveguide types e.g. slot waveguides
  - Lower IL
  - Smaller footprint

- Nonlinear absorption phenomena
  - **Two photon absorption** (TPA)→ Losses **increase** with optical power
  - **Saturable absorption** (SA)→ Losses **decrease** with optical power
  - All-optical applications

Thank You!

Any questions?