Photonics Group
ECE, AUTH
http://photonics.ee.auth.gr/

Multi-channel Nonlinear Interactions in Practical Graphene Components

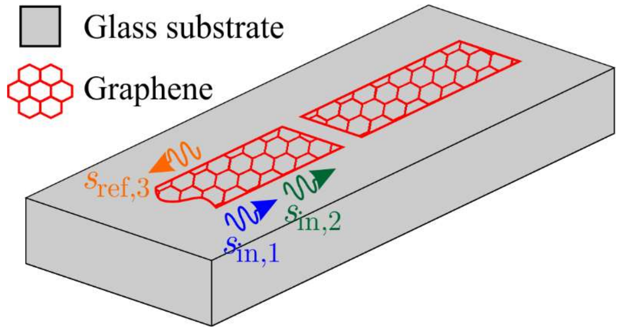
T. Christopoulos[1], **O. Tsilipakos**[2,*], V. G. Ataloglou[3], and E. E. Kriezis[1]

1 Electrical Engineering, AUTH, 54124 Thessaloniki, Greece   2 FORTH-IESL, 71110 Heraklion, Greece
3 Electrical Engineering, Univ. of Toronto, M5S 3G4 Toronto, ON, Canada
*otsilipakos@iesl.forth.gr

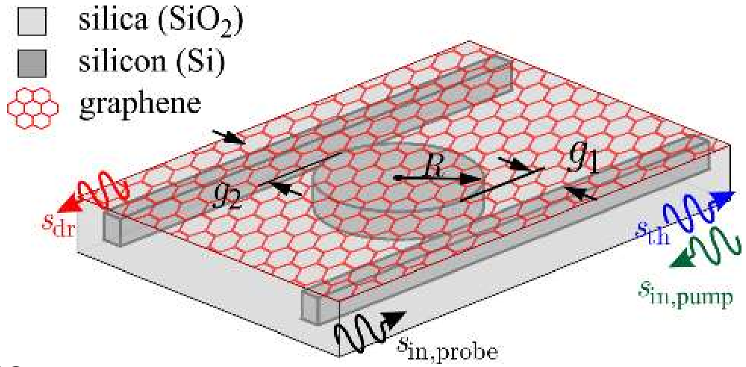
METANANO 2020
Poster Session VII, F1.7

Scope and Motivation

- Graphene as nonlinear material in integrated photonics
- High third-order nonlinearity from THz to NIR and low I_{sat}
- Practical graphene components with low power requirements and high performance
- Multi-channel processes for high functionality
  - Four-wave mixing for frequency generation
  - Saturable absorption for routing and switching
- Develop efficient perturbation/coupled-mode theory framework for 2D conductive materials and graphene
  - Extra stored energy in *dispersive* graphene
  - Electric and magnetic energies *not* equal on resonance



- Graphene micro-ribbon
- Glass substrate
- Tight plasmons
- FWM at 5 THz



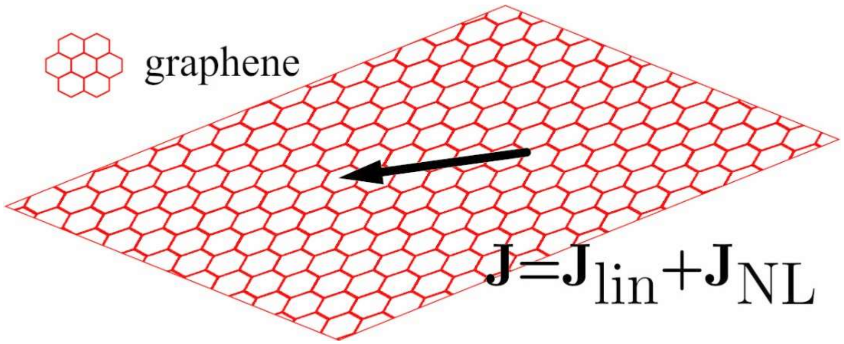
- Graphene on Si disk structure
- SOI substrate
- Sat. Absorption
- Routing at 1.55um

Photonics Group AUTH

Multi-channel Nonlinear Interactions in Practical Graphene Components

T. Christopoulos[1], **O. Tsilipakos**[2,*], V. G. Ataloglou[3], and E. E. Kriezis[1]
[* otsilipakos@iesl.forth.gr](mailto:otsilipakos@iesl.forth.gr) / http://photonics.ee.auth.gr/

Graphene as an infinitesimally-thin current sheet with linear and nonlinear contributions



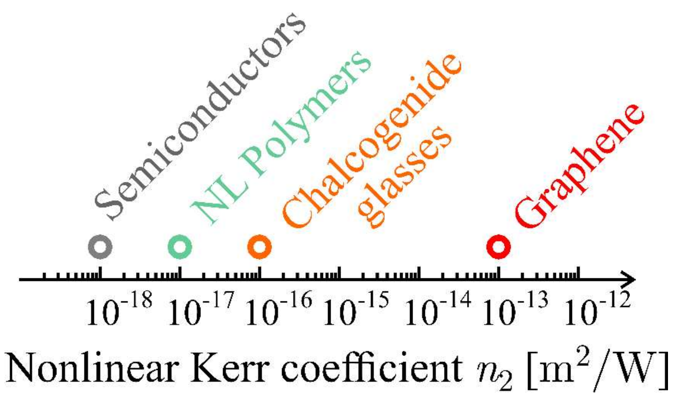
Linear current: conductivity saturates (SA)

$$\mathbf{J}_{\rm lin} = \sigma_1 \mathbf{E}_{\parallel} \qquad \mathrm{Re}\{\sigma_1(\mathbf{E}_{\parallel})\} \propto 1/(1+|\mathbf{E}_{\parallel}|^2/E_{\rm sat}^2)$$

	Ref.	I_{sat}
NIR	Bao, Nano Res. 4, 297, 2011	1 MW/cm^2

Third-order nonlinear current

$$J_{\mathrm{NL},\mu}(\omega_k+\omega_\ell+\omega_m) = \frac{1}{4}\sum_{\alpha\beta\gamma} \sigma^{(3)}_{\mu\alpha\beta\gamma} E_{k,\alpha} E_{\ell,\beta} E_{m,\gamma}$$



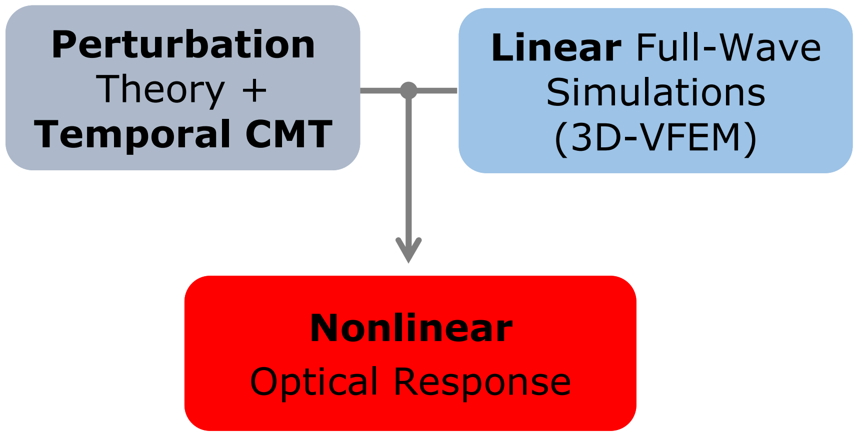
	Ref.	Surface conductivity σ_3 [S(m/V)^2]	Equivalent nonlinear index n_2 [m^2/W]
FIR	Mikhailov, *J. Phys.-Condes. Matter* **20**, 384204, 2008	j1.3 × 10^{-18}	3 × $\mathbf{10^{-13}}$
NIR	Vermeulen, *Phys. Rev. Applied* **6**, 044006, 2016	-j1.2 × 10^{-20}	-1 × $\mathbf{10^{-13}}$

Multi-channel Nonlinear Interactions in Practical Graphene Components

T. Christopoulos[1], **O. Tsilipakos**[2,*], V. G. Ataloglou[3], and E. E. Kriezis[1]
* otsilipakos@iesl.forth.gr / http://photonics.ee.auth.gr/

Photonics Group AUTH

Efficient and Accurate Theoretical Framework



Formulations for different phenomena and materials:

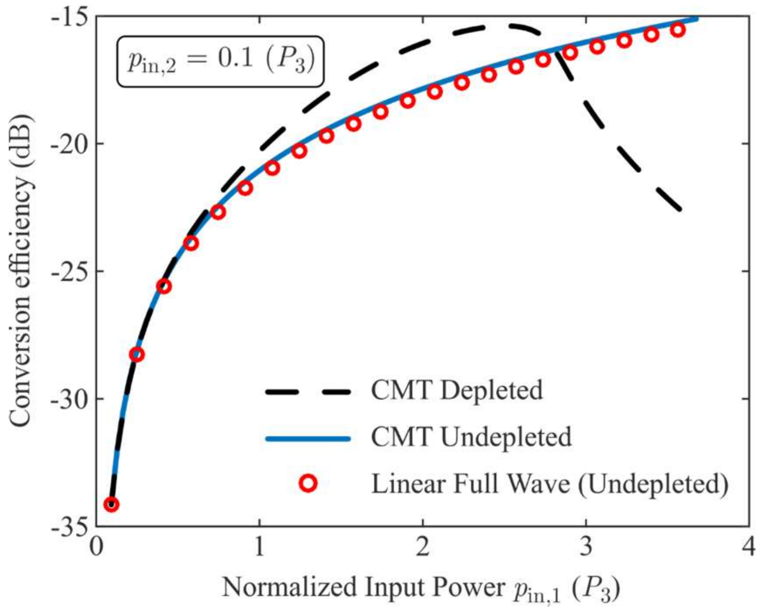
Tsilipakos, *J. Lightwave Technol.* **34**, 1333, 2016

Christopoulos, *Phys. Rev. E* **94**, 062219, 2016

Ataloglou, *Phys. Rev. A.* **97**, 063836, 2018

Verification against full-wave nonlinear simulations

Christopoulos, *Phys. Rev. B*, **98,** 235421, 2018



- Excellent agreement in FWM conversion efficiency
- CMT allows for efficiently studying complex NL phenomena

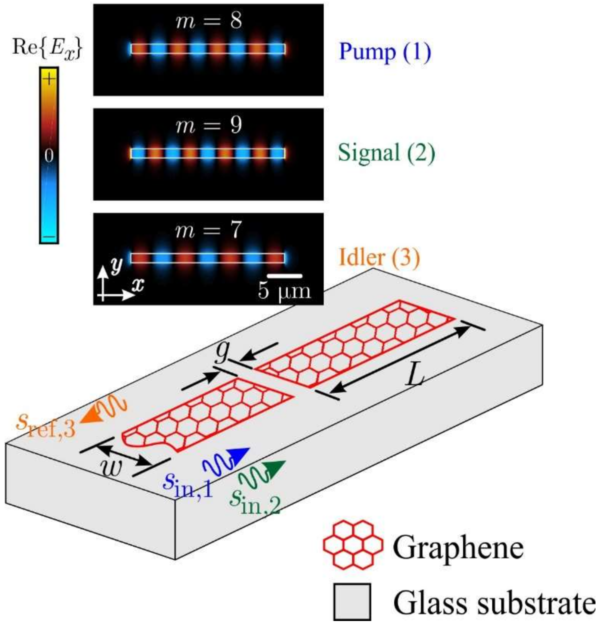
Multi-channel Nonlinear Interactions in Practical Graphene Components

Photonics Group AUTH

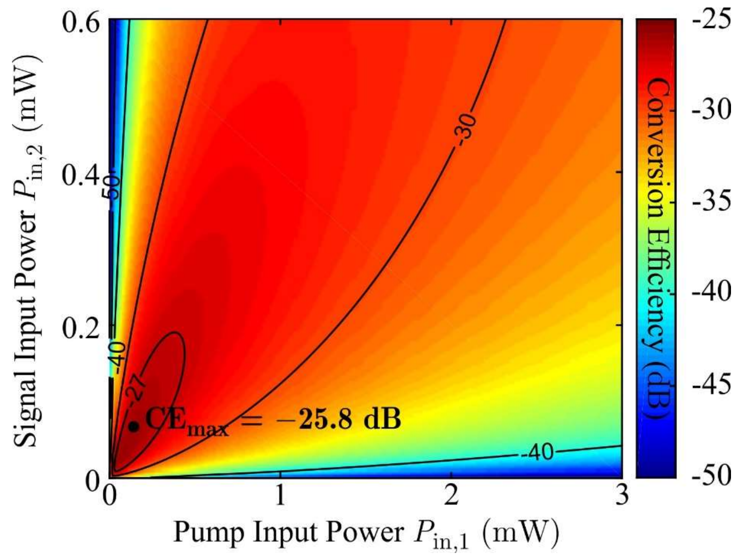
T. Christopoulos[1], **O. Tsilipakos**[2,*], V. G. Ataloglou[3], and E. E. Kriezis[1]

* otsilipakos@iesl.forth.gr / http://photonics.ee.auth.gr/

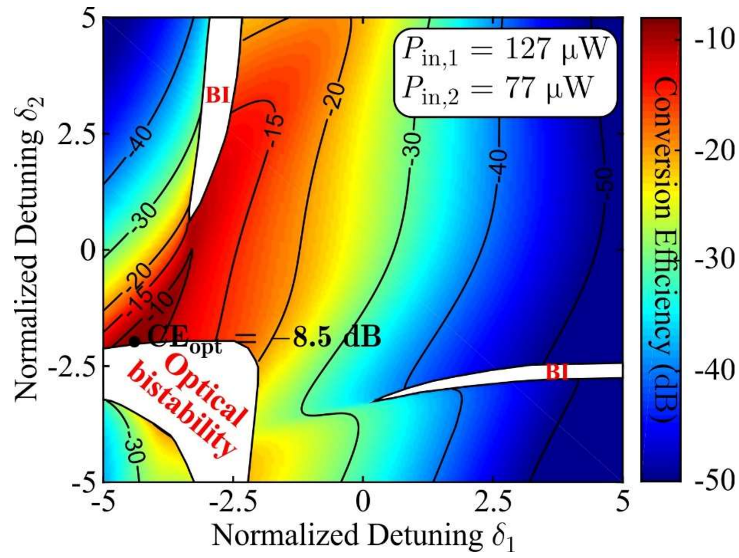
Efficient FWM at 5 THz by aligning pump and signal beams with the cavity resonances



- 1-μm-wide graphene ribbon
- Tight graphene plasmons
- Single-port, direct coupling



- **Pump** and **signal** at *m*=8 and *m*=9 modes
- Idler **not** exactly on *m*=7 due to dispersion
- **$P_{in,1}$ = 127 μW, $P_{in,2}$ = 77 μW**
- **CE_{max} = −25.8 dB**



- Tune input frequencies
  - Counteract dispersion
  - Counteract Kerr shifts
- **CE_{max} = −8.5 dB (14%)**

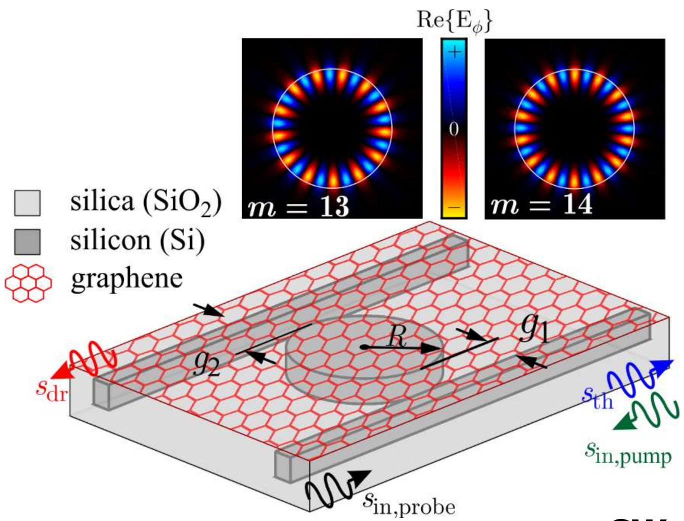
Multi-channel Nonlinear Interactions in Practical Graphene Components

T. Christopoulos[1], **O. Tsilipakos**[2,*], V. G. Ataloglou[3], and E. E. Kriezis[1]
* otsilipakos@iesl.forth.gr / http://photonics.ee.auth.gr/

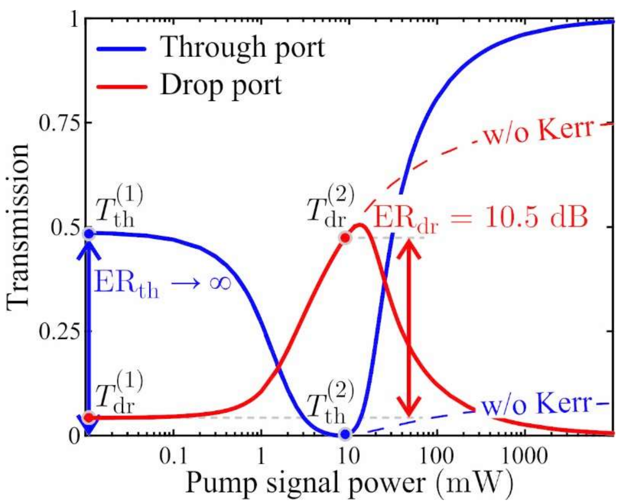
Photonics Group AUTH

Introduction | Graphene Properties | Theory framework | Four-wave mixing | Saturable Absorption | Conclusion

Graphene-covered add-drop Si disk for efficient routing via Saturable Absorption at NIR (1550 nm)

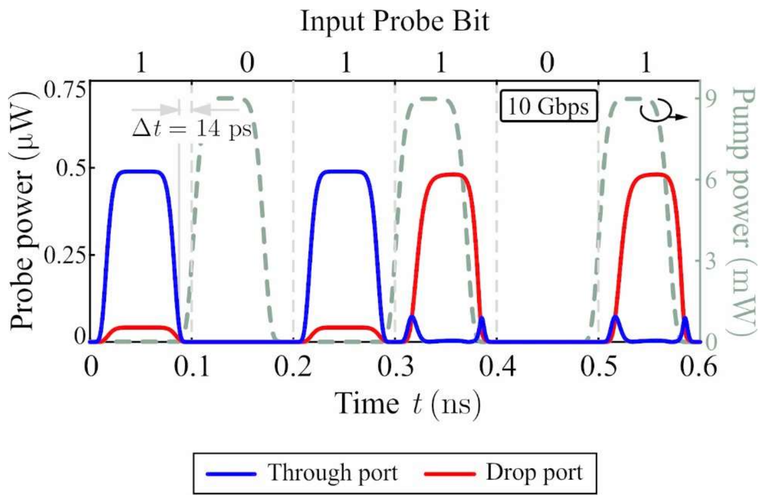


- Strong pump (re)routes weak signal
- Critical coupling condition under pump



CW operation

- Output to through and drop is power-dependent
- Low power requirements (***P*$_{pump}$ = 9 mW**).
- $ER_{th} \to \infty$, ER_{dr} = 10.5 dB
- Other nonlinearities appear for higher powers.



10 Gbps operation

- Perfect signal routing at 10Gbps
- Pump wave pulses should be applied 14 ps ahead to introduce the loss saturation effect in time

Photonics Group
ECE, AUTH
http://photonics.ee.auth.gr/

Multi-channel Nonlinear Interactions in Practical Graphene Components

T. Christopoulos[1], **O. Tsilipakos**[2,*], V. G. Ataloglou[3], and E. E. Kriezis[1]
1 Electrical Engineering, AUTH, 54124 Thessaloniki, Greece 2 FORTH-IESL, 71110 Heraklion, Greece
3 Electrical Engineering, Univ. of Toronto, M5S 3G4 Toronto, ON, Canada
* otsilipakos@iesl.forth.gr, http://photonics.ee.auth.gr/

METANANO 2020
Poster Session VII, F1.7

1. Graphene shows potential as a nonlinear material from THz to NIR
2. Exploit multi-channel processes for functional photonic components: frequency generation, routing/switching, memory operation
3. Low power requirements and high performance demonstrated
4. Perturbation/coupled mode theory frameworks allow for efficient and accurate nonlinear response

For more info:

[Christopoulos, Ataloglou, Kriezis, J. Appl. Phys. 127(22), 223102, 2020]

[Christopoulos, Tsilipakos, Kriezis, J. Opt. Soc. Am. B 37(9), 2626, 2020]

http://photonics.ee.auth.gr/

cthomasa@ece.auth.gr
otsilipakos@iesl.forth.gr
mkriezis@auth.gr

ARISTOTLE UNIVERSITY OF THESSALONIKI

H.F.R.I. Hellenic Foundation for Research & Innovation

The research work was supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the "First Call for H.F.R.I. Research Projects to support Faculty members and Researchers and the procurement of high-cost research equipment grant." (Project Number: HFRI-FM17-2086)