Coherent and broadband enhanced optical absorption in graphene

Giuseppe Pirruccio

pirruccio@amolf.nl

www.amolf.nl/surfacephotonics

Acknowledgments

Luis Martin Moreno

Gabriel Lozano

Jaime Gomez Rivas

FOM Institute AMOLF

Funding:

NWO

PHILIPS

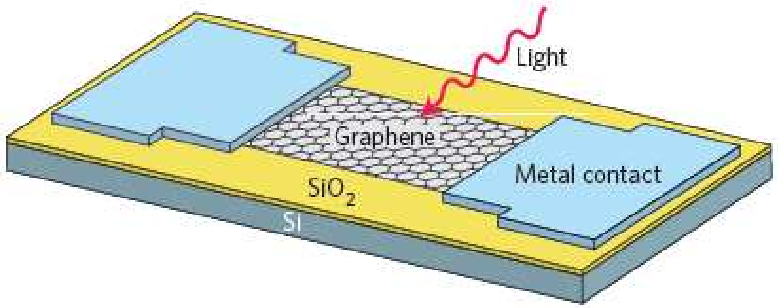
Outline

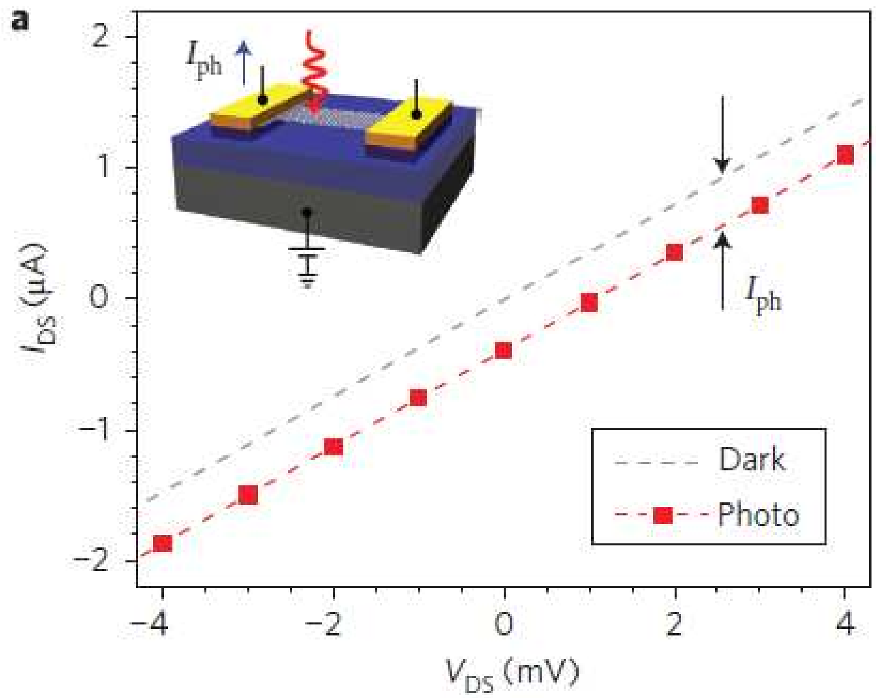
- Motivation and introduction
- Coherent absorption
- Measurements and modeling
- Optimization
- Conclusions

Motivation

Graphene based photodectors:

- Absorbs from UV to THz
- High carrier mobility

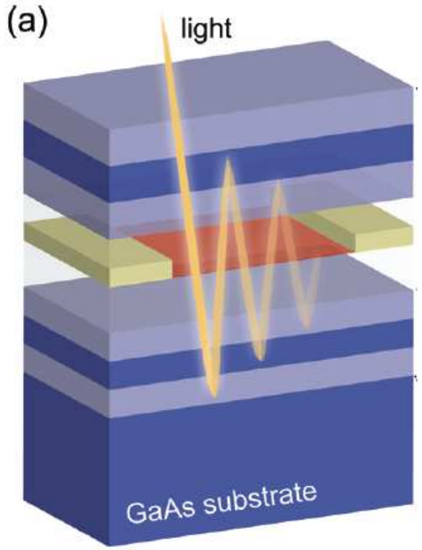


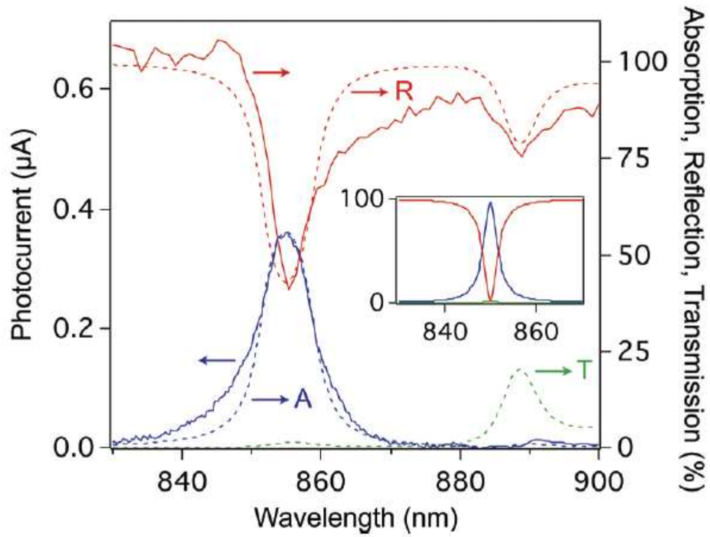


Problem: the low absolute value of the absorption of graphene (2.3% of the incident light) limits the photocurrent efficiency

F. Xia, T. Mueller, Yu. Li, A. Valdes-Garcia and P. Avouris, Nat. Nanotech. 2009, 4, 839.
F. Bonaccorso, Z. Sun, T. Hasan and A. C. Ferrari, Nat. Photon., 2010, 4, 611.

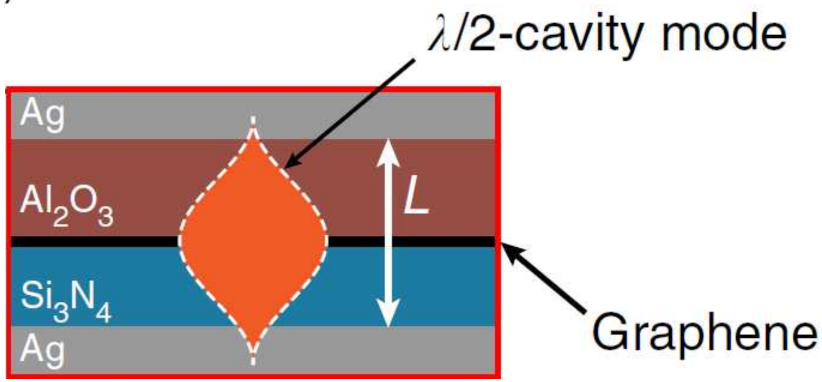
Enhanced photodetection





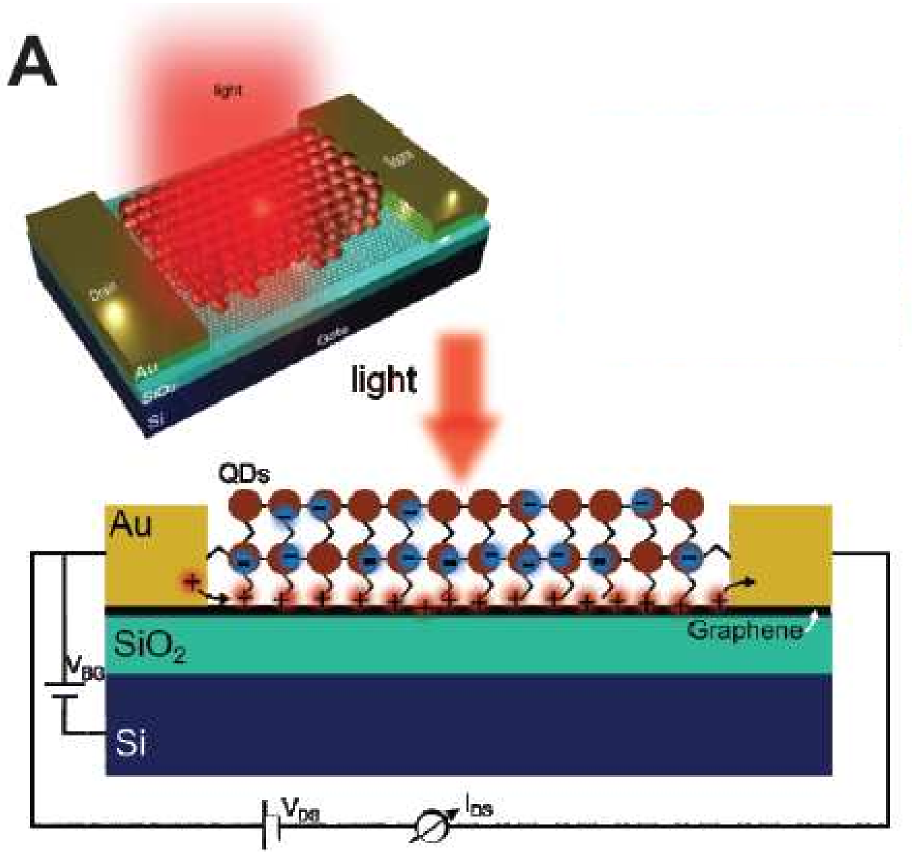
Not ideal for broadband absorption

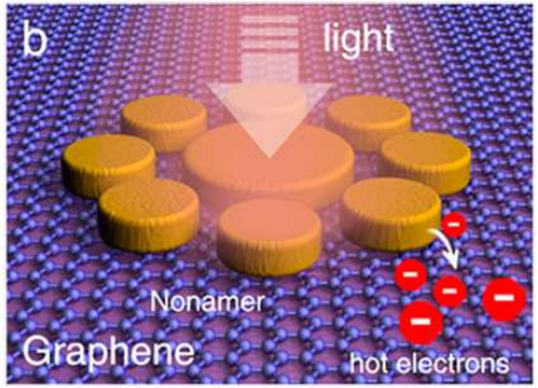
Microcavity realized
through Bragg mirrors
(optimized for narrow wavelength
- angular window)

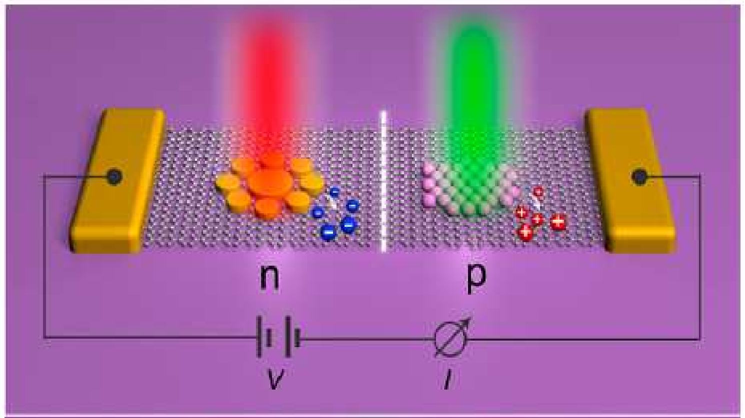


M. Furchi, et al., Nano Lett., 2012, 12, 2773
M. Engel, M. Steiner, A. Lombardo, A. C. Ferrari, H. v. Lohneysen, P. Avouris and R. Krupke,
Nat. Commun., 2012, 3, 906.

Hybrid devices



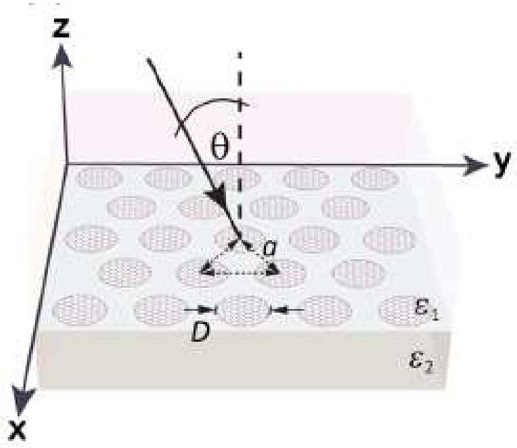


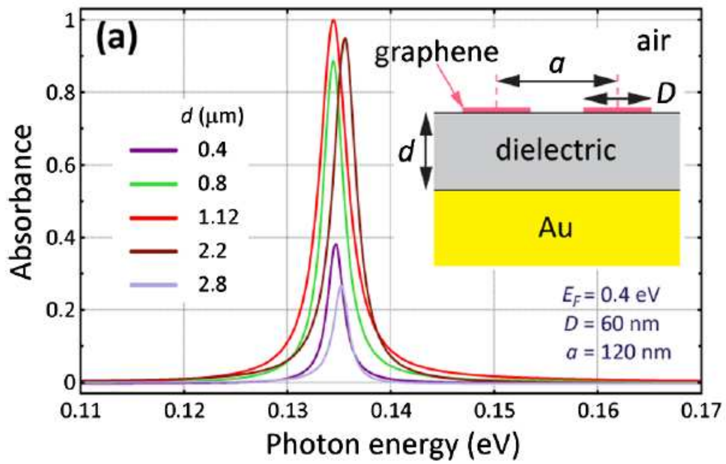


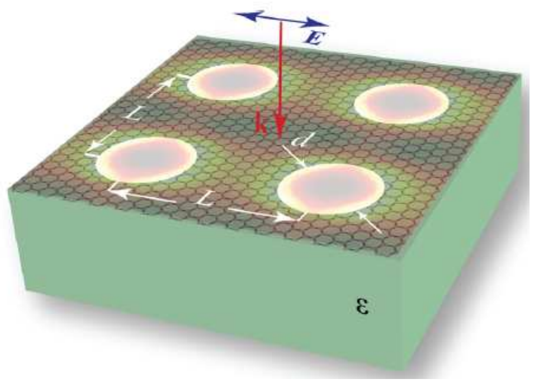
G. Konstantatos, M. Badioli, L. Gaudreau, , J. Osmond, M. Bernechea, F. P. Garcia de Arquer, F. Gatti and F. H. L. Koppens, Nat. Nanotech., 2012, 7, 363.

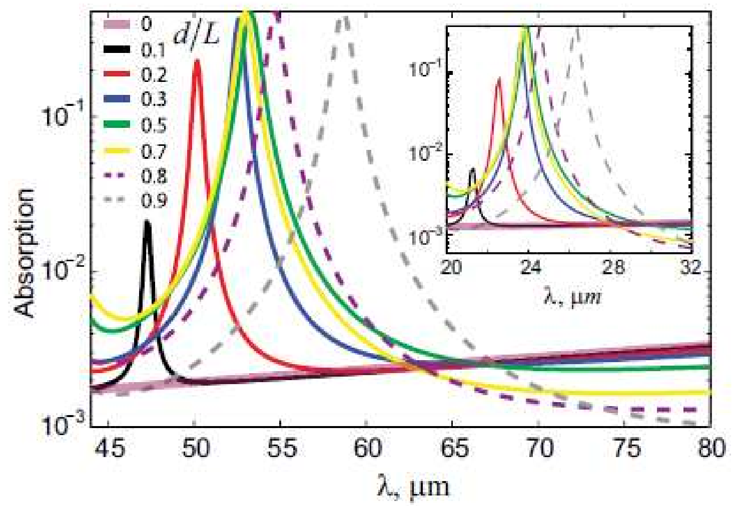
Z. Fang, Y. Wang, Z. Liu, A. Schlather, P. M. Ajayan, F. H. L. Koppens, P. Nordlander and N. J. Halas, ACS Nano, 2012, 6, 10222

Plasmonics to enhance absorption









S. Thongrattanasiri, F. H. L. Koppens and J. Garcia de Abajo, Phys. Rev. Lett., 2012, 108, 047401.
Y. Nikitin, F. Guinea and L. Martin Moreno, Appl. Phys. Lett., 2012, 101, 151119.

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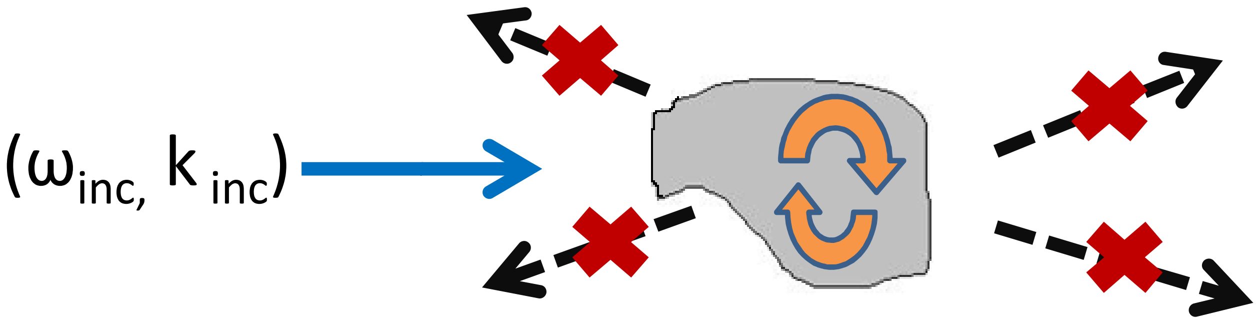
Scattering problem

Perfect energy transfer between incoming channels (optical modes) and the structure.

↔

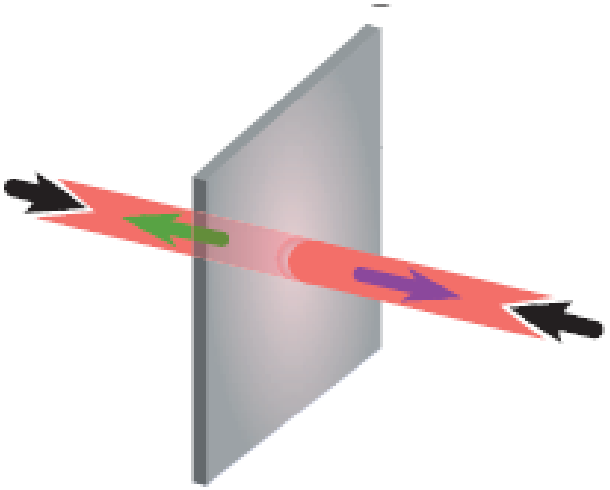
Building a destructive interference pattern in the far-field will cause the light to be trapped in the structure. The material losses will eventually dissipate the energy.



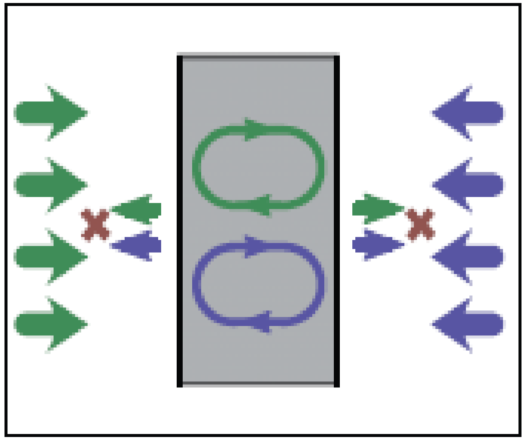
Weakly absorbing material

Coherent Perfect Absorption

2 channels CPA



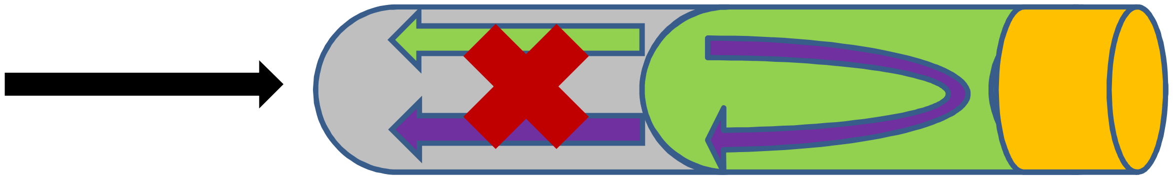
Weakly absorbing material

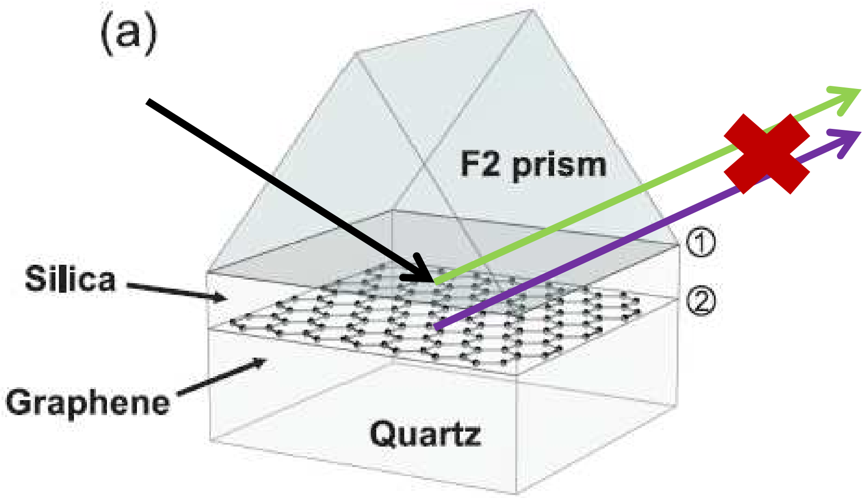


W. Wan, Y. Chong, L.Ge, H. Noh, A. Douglas Stone and H. Cao, Science, 2011, 331, 889.

From 2 to 1 channel

1 channel CPA (single port reflector)





$\varepsilon_p \sim 2.59$ $\varepsilon_{silica} = 2.12$

$\varepsilon_{subs} = 2.08$

Mirror → Total internal reflection

Absorbing cavity → Graphene (multi)layer

W. Wan, Y. Chong, L. Ge, H. Noh, A. Douglas Stone and H. Cao, Science, 2011, 331, 889.

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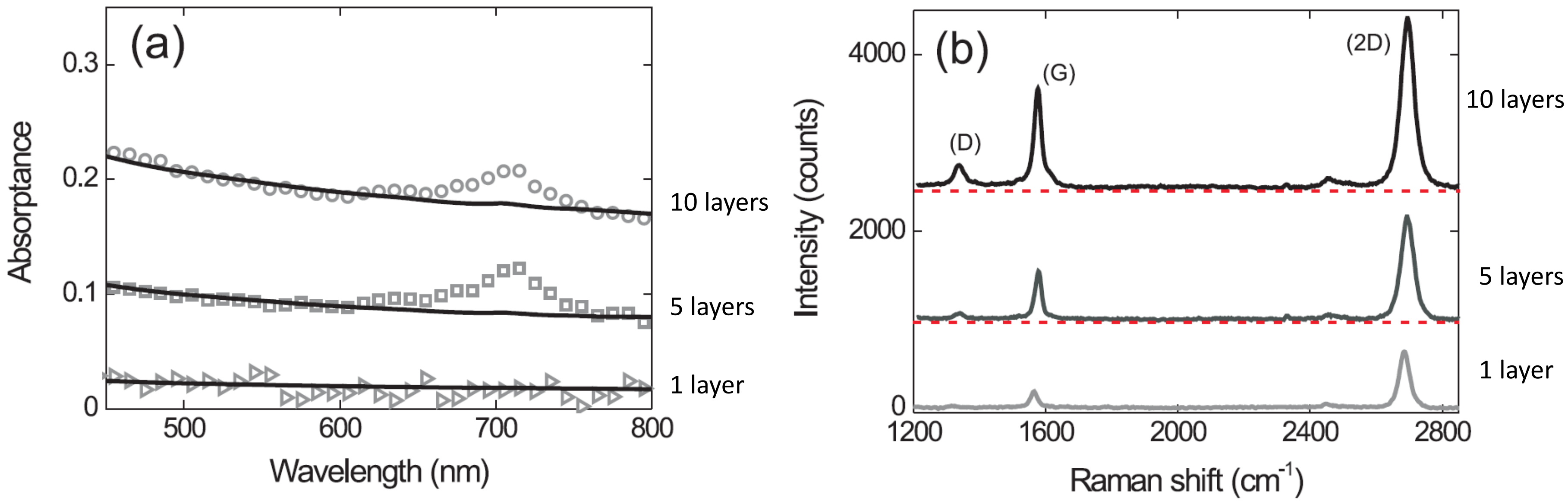
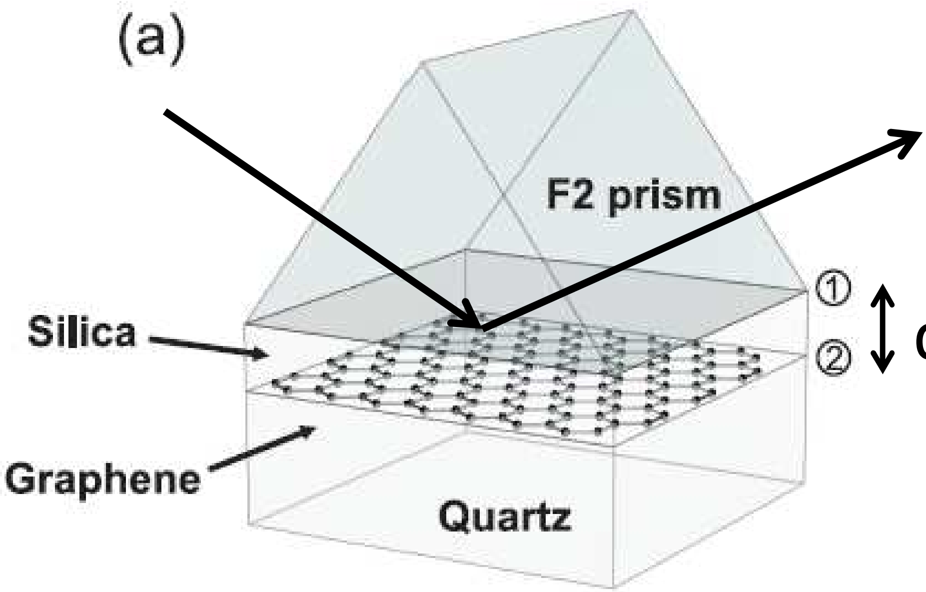
Graphene characterization



CVD deposition of graphene on copper foils.
PMMA transfer onto silica substrates (turbostratic deposition)

G. Pirruccio, G. Lozano, L. Martin Moreno and J. Gomez Rivas, submitted.
V. G. Kravets, A.N. Grigorenko, R. R. Nair, P. Blake, S. Anissimova, K. S. Novoselov and A.K. Geim, Phys. Rev. B, 2010, 81, 155413

Sample



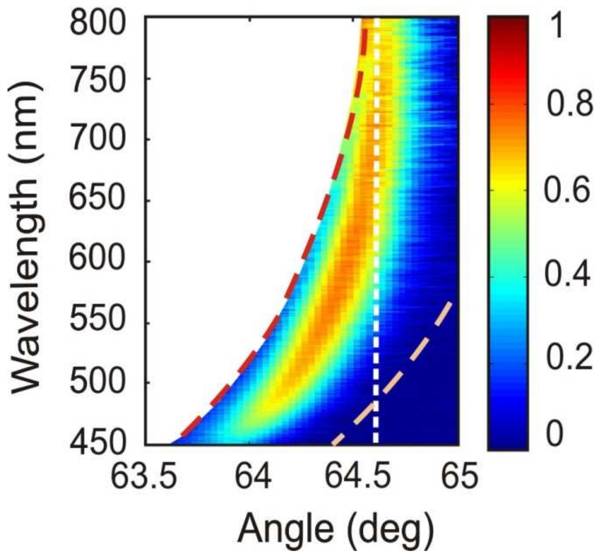
d_{silica} = 590 – 1300 nm

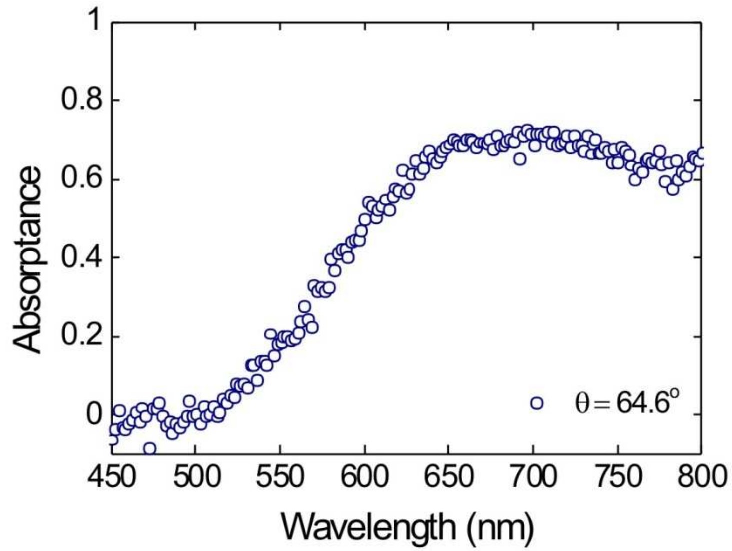
Magnetron-sputtering
in steps (low temperature on
graphene)

$$\theta_{c,2} < \theta_{c,1}$$

Absorptance measurements

Absorptance (5 layers)

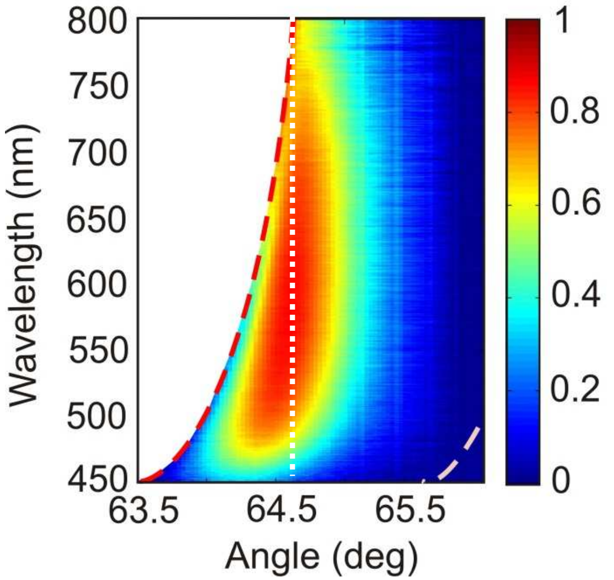


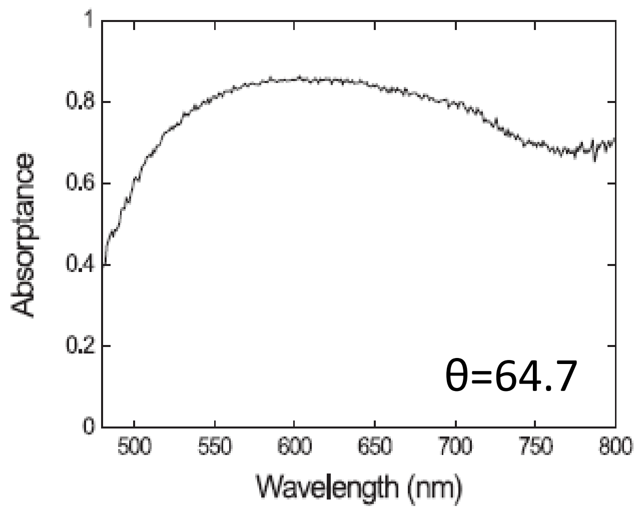


When $\theta^{*}<\theta<\theta_{c,1}$ the incident wave is transmitted through the prism-silica layer interface and undergoes total internal reflection at the silica-substrate interface. → T=0

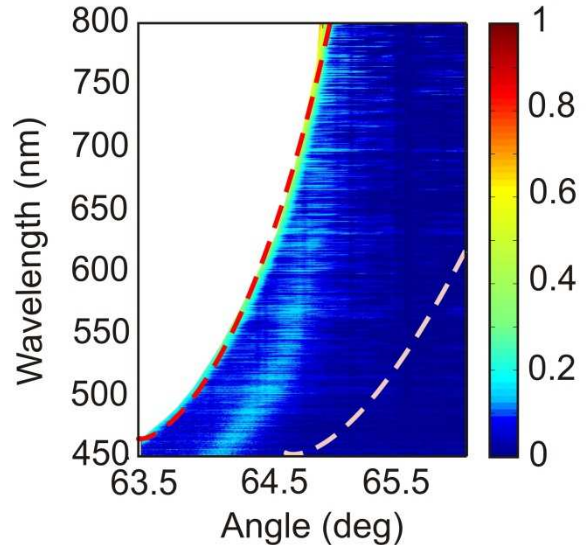
Broadband absorption

Absorptance (10 layers)





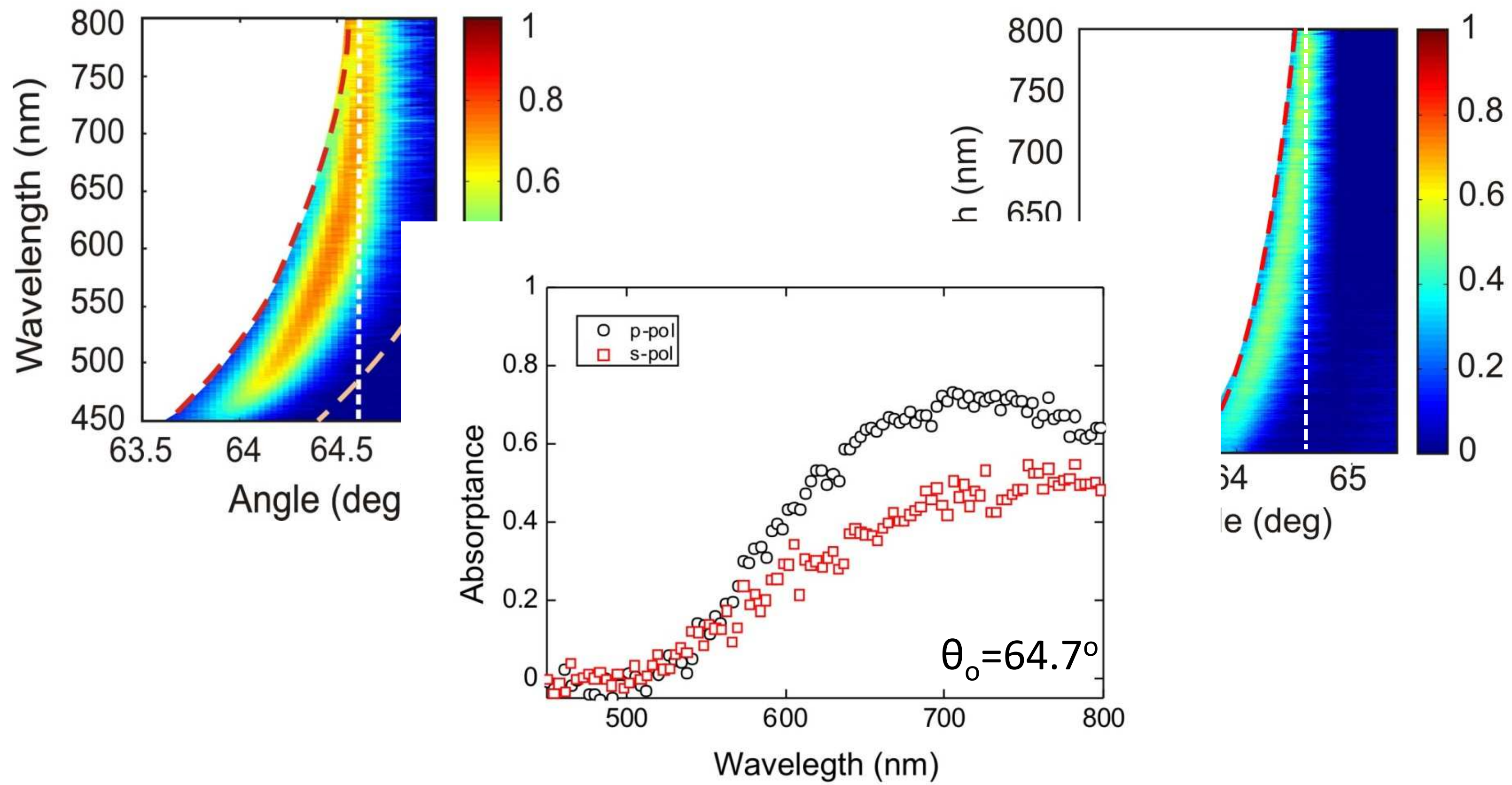
Absorptance (1 layer)



Polarization independence (5 layers)

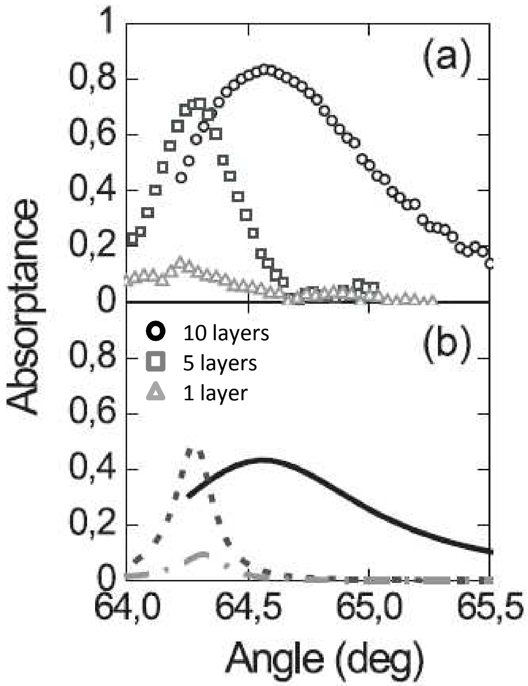
p-polarized absorptance

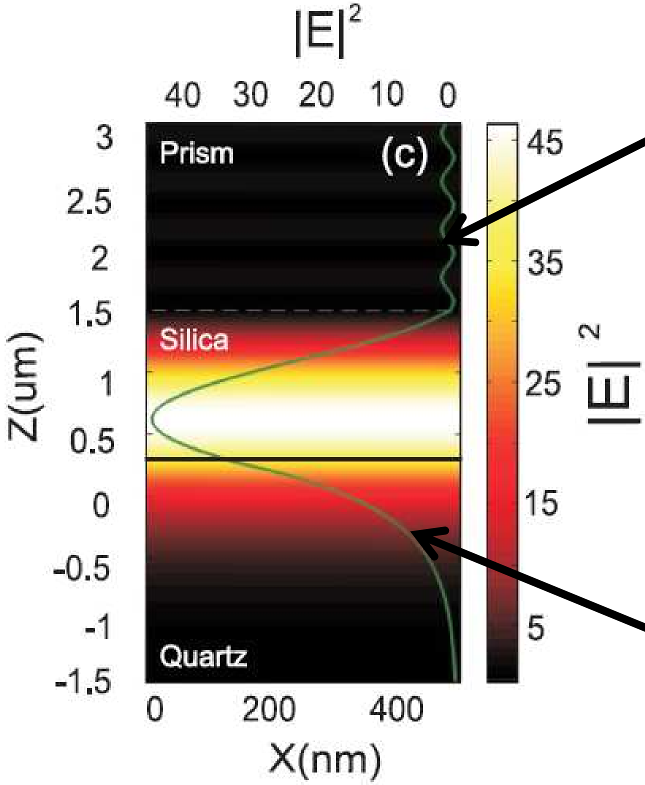
s-polarized absorptance



Transfer matrix calculation

λ_0=540 nm





Residual reflection

Evanescent decay

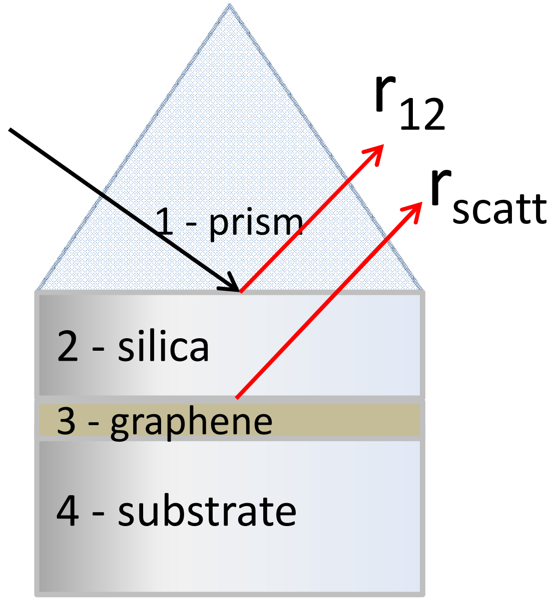
$$\varepsilon_g(\lambda,\theta) = \varepsilon_o(\lambda) + \frac{\varepsilon_o(\lambda)-\varepsilon_e(\lambda)}{\varepsilon_e(\lambda)} sin^2\theta$$

V. G. Kravets, A.N. Grigorenko, R. R. Nair, P. Blake, S. Anissimova, K. S. Novoselov and A.K. Geim, Phys. Rev. B, 2010, 81, 155413

Interpretation

$$S = \begin{pmatrix} t_{1234} & r_{4321} \\ r_{1234} & t_{4321} \end{pmatrix}$$

$$r_{1234} = r_{12} + r_{scatt}$$



$$\begin{cases} |S_{21}|^2 = |r_{1234}|^2 = R \\ |S_{11}|^2 = |t_{1234}|^2 \propto T \\ A = 1 - R - T \end{cases}$$

$$R = \left| \, |r_{12}| e^{i\varphi_{12}} + |r_{scatt}| e^{i\varphi_{scatt}} \right|^2 \longrightarrow R = 0 \Leftrightarrow \begin{cases} |r_{12}| = |r_{scatt}| \\ \varphi_{12} - \varphi_{scatt} = \pi \end{cases}$$

$$T = 0$$

Total internal reflection

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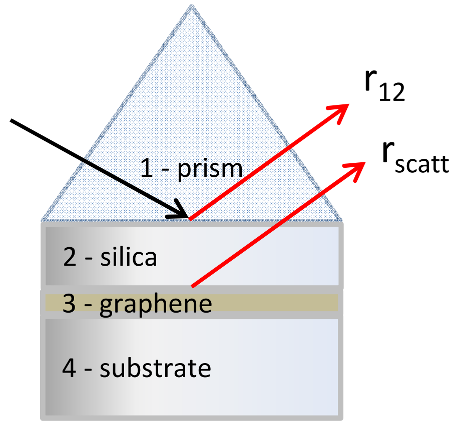
Optimized structure

$$\min_{d_{silica}}(R) =$$

$$\min_{d_{silica}}\left(\left|\frac{r_{12}^{p}(\lambda_0,\theta)+r_{234}^{p}(\lambda_0,\theta)e^{-2ik_{x2}d_{silica}}}{1+r_{12}^{p}(\lambda_0,\theta)r_{234}^{p}(\lambda_0,\theta)e^{-2ik_{x2}d_{silica}}}\right|^{2}\right)$$



$$r_{1234}^{p} = r_{12}^{p} + r_{scatt}^{p}(d_{silica}, N)$$

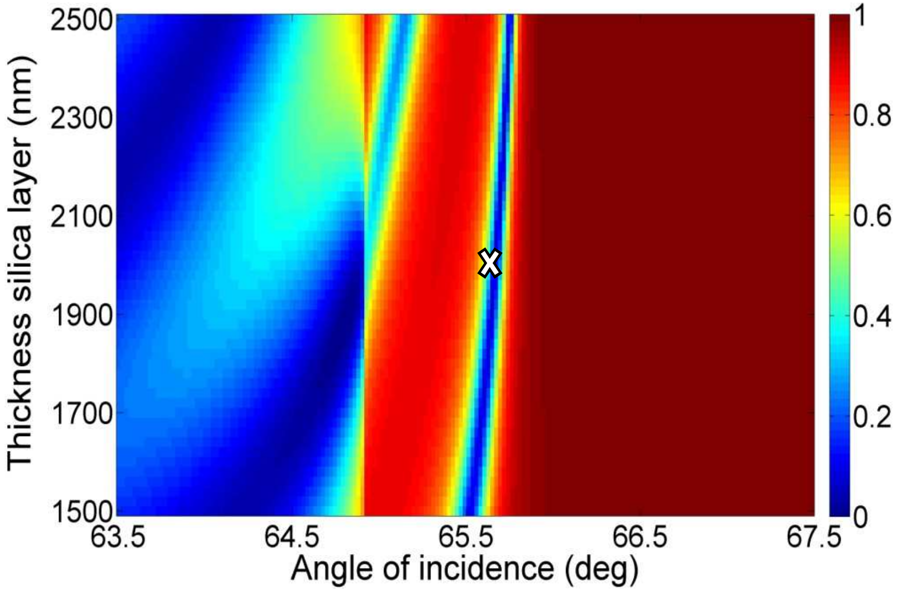
Full control on $\varphi_{12} - \varphi_{scatt}$

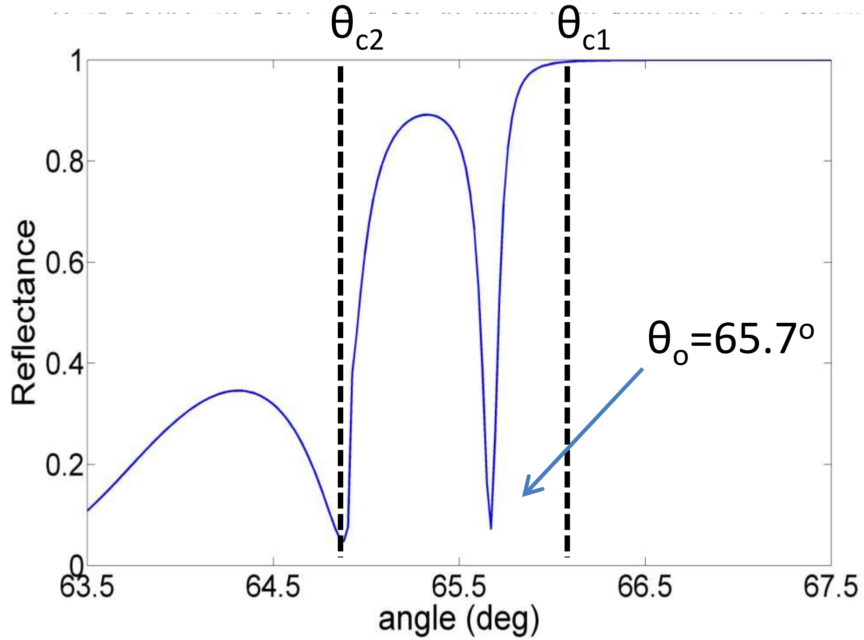
- Total Internal Reflection
- Graphene is the only absorbing material

→ N controls $|r_{scatt}|$

Optimized structure

Reflectance

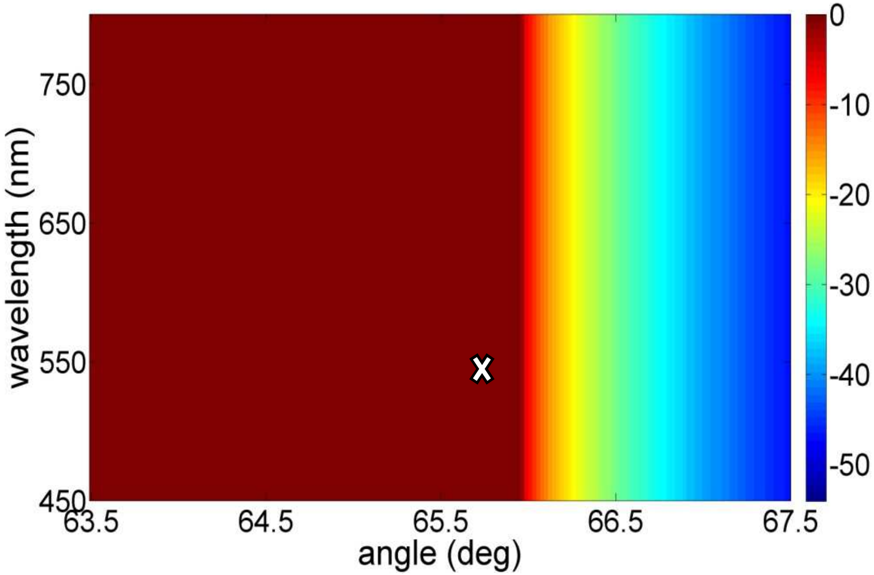




λ_0=540 nm

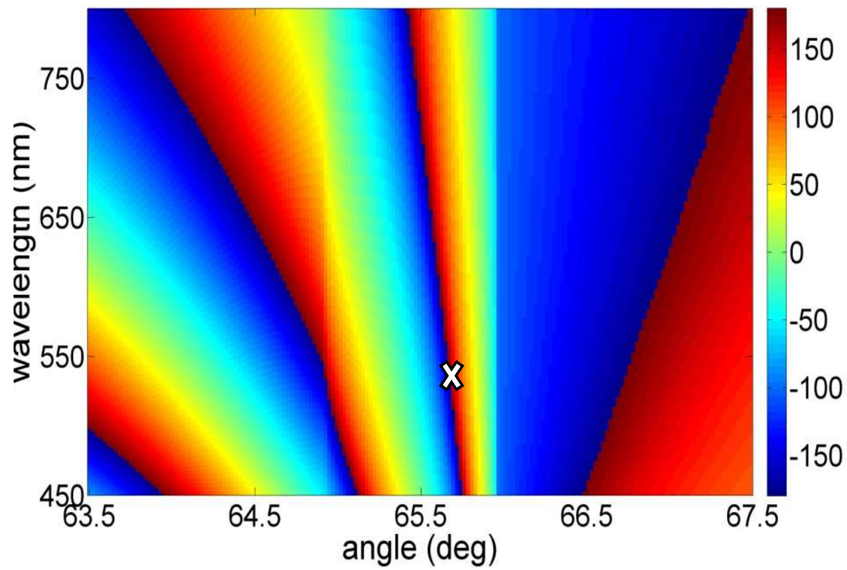
Optimized structure

φ_{12}



$$\varphi_{12}(\lambda_0, \theta_0) = 0^o$$

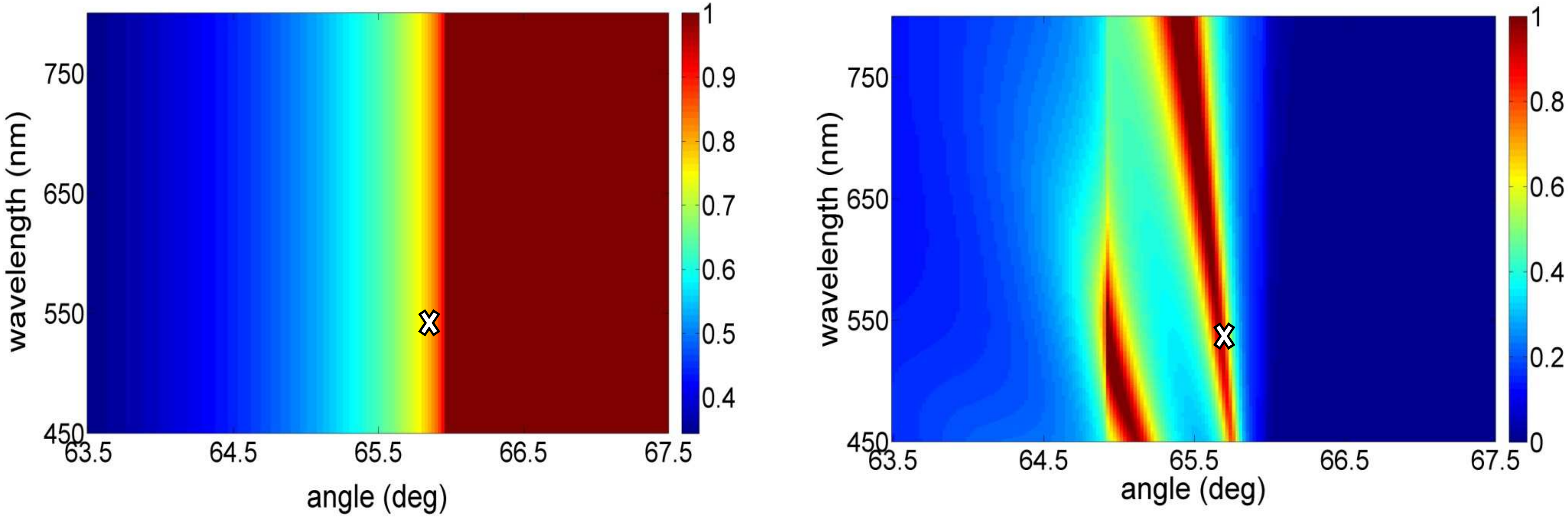
φ_{scatt}



$$\varphi_{scatt}(\lambda_0, \theta_0) = 174^0$$

Optimized structure

$$|r_{12}| \qquad\qquad |r_{scatt}|$$

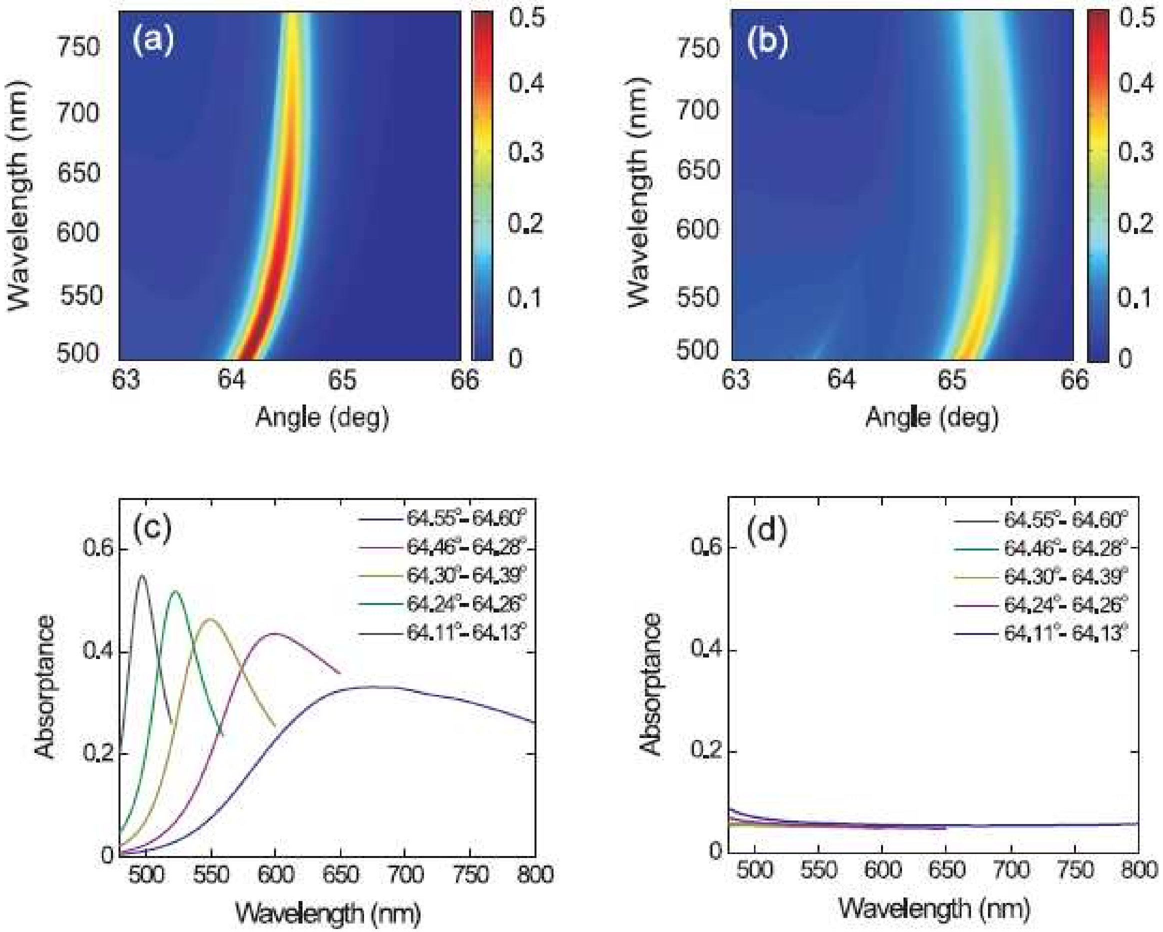


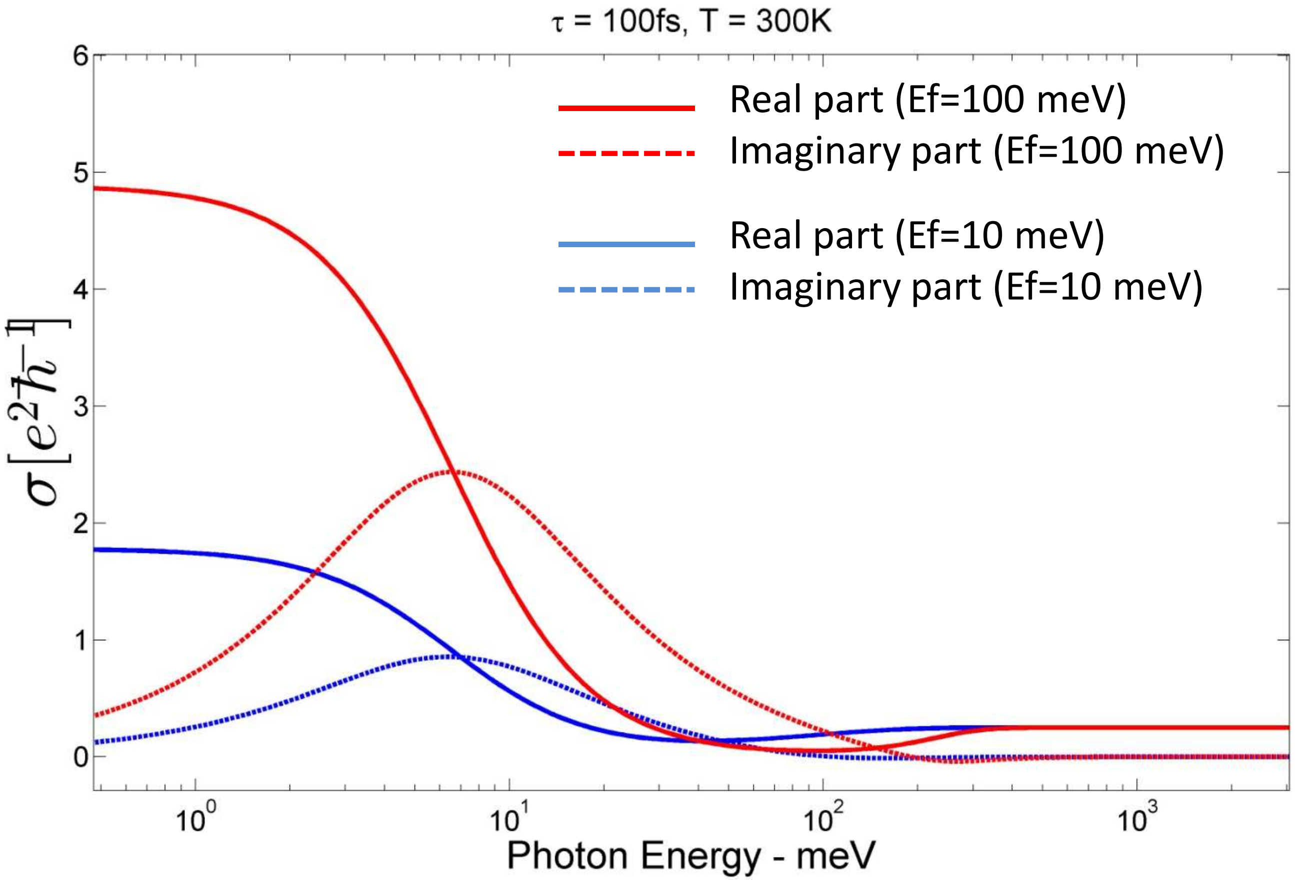
$$|r_{12}(\lambda_0, \theta_0)| = 0.7 \qquad\qquad |r_{scatt}(\lambda_0, \theta_0)| = 0.9$$

Conclusions

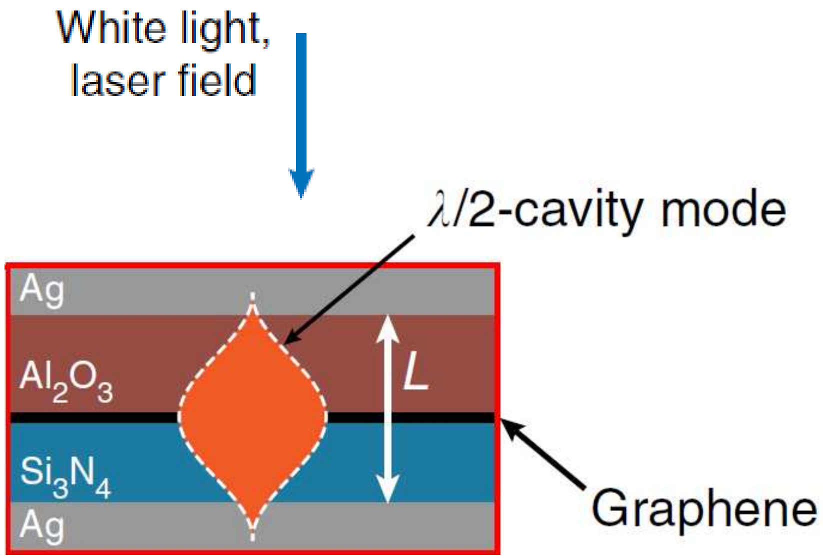
- We have experimentally demonstrated broadband and enhanced absorption in graphene
- This enhancement is explained in terms of coherent absorption arising from interference and dissipation in a multilayer structure.
- For 10 layers of graphene it is possible to enhance the absorptance over 91%. For the 5 layer and monolayer sample a similar analysis leads to a maximum absorption of 76% and 15%.

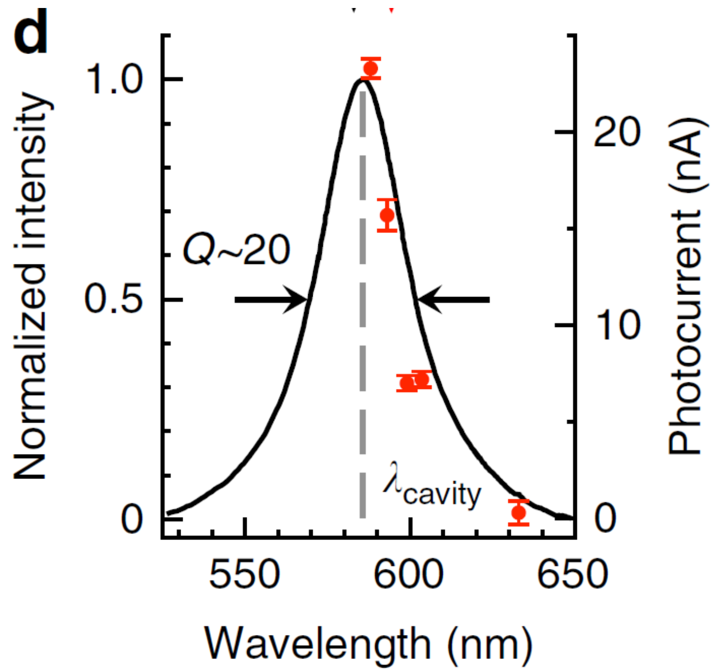
Controlling the absorption




τ = 100fs, T = 300K
Real part (Ef=100 meV)
Imaginary part (Ef=100 meV)
Real part (Ef=10 meV)
Imaginary part (Ef=10 meV)
$\sigma[e^2\hbar^{-1}]$
Photon Energy - meV

Microcavity control

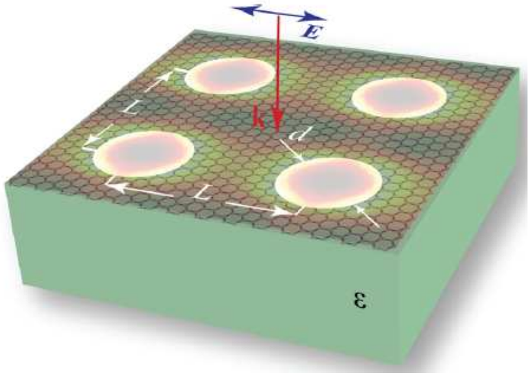


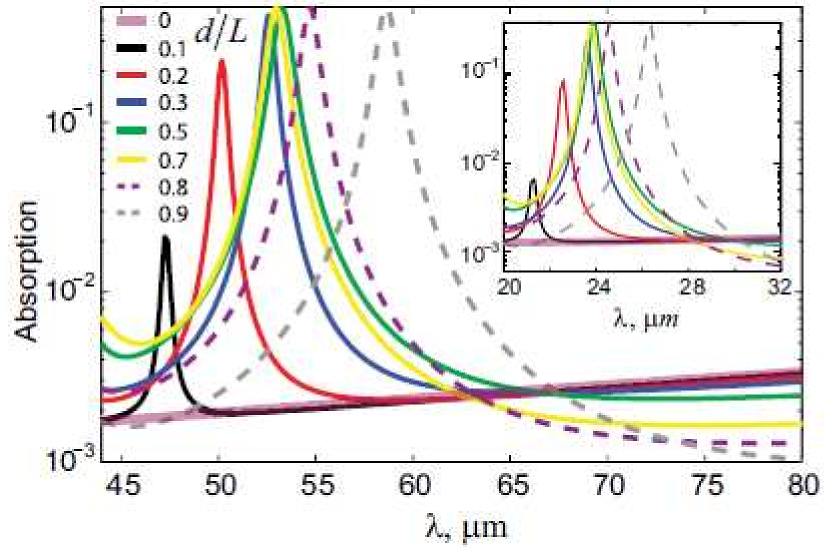


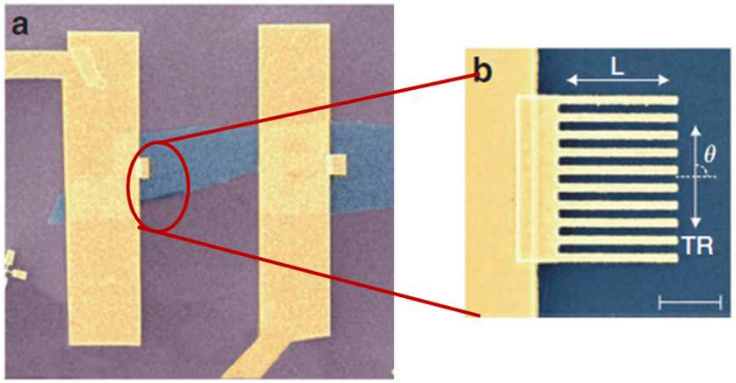
Not ideal for broadband illumination

M. Engel, M. Steiner, A. Lombardo, A. C. Ferrari, H. v. Lohneysen, P. Avouris and R. Krupke, Nat. Commun., 2012, 3, 906.

Plasmonics to enhance absorption





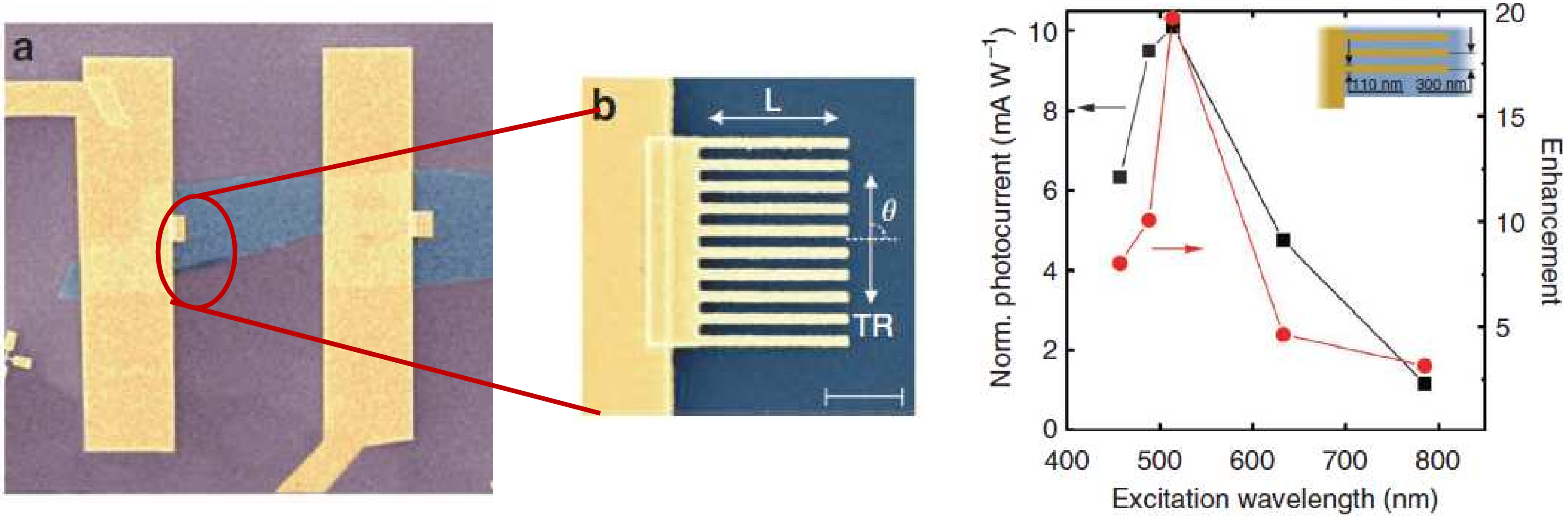


Graphene plasmons resonance:

- up to 50% absorption
- electrically continuous system
- highly wavelength dependent

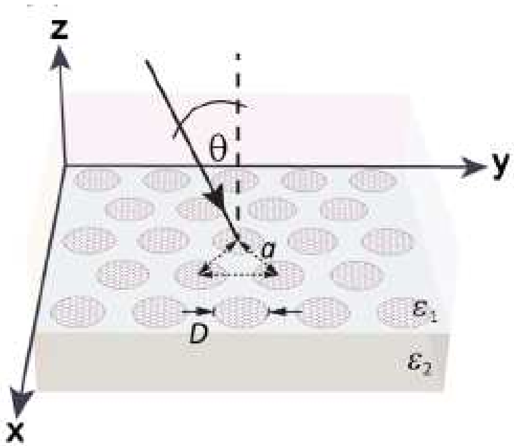
Y. Nikitin, F. Guinea and L. Martin Moreno, Appl. Phys. Lett., 2012, 101, 151119.
T. J. Echtermeyer, L. Britnell, P. K. Jasnos, A. Lombardo, R. V. Gorbachev, A. N. Grigorenko, A. K. Geim, A. C. Ferrari and K. S. Novoselov, Nat. Commun., 2001, 2, 458.

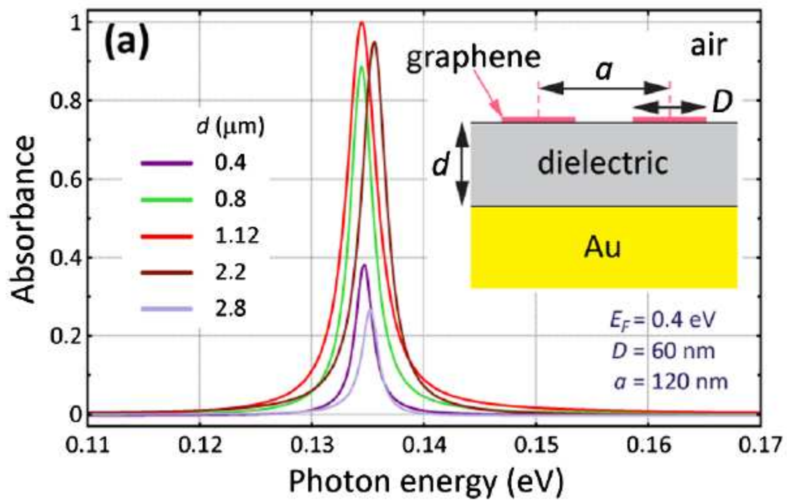
Plasmonics to enhance absorption

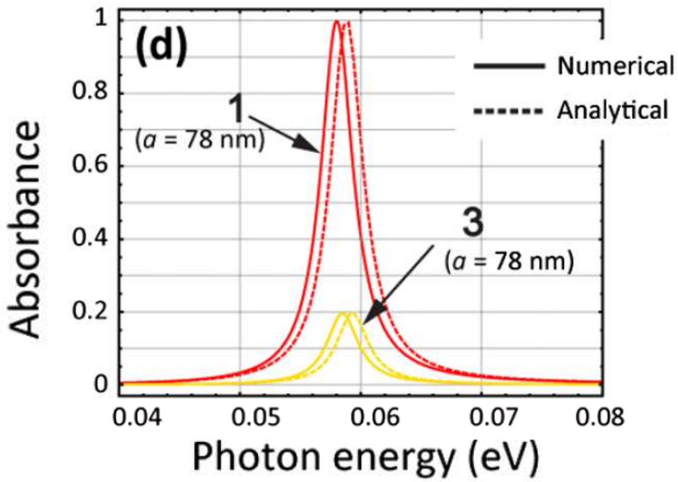


T. J. Echtermeyer, L. Britnell, P. K. Jasnos, A. Lombardo, R. V. Gorbachev, A. N. Grigorenko, A. K. Geim, A. C. Ferrari and K. S. Novoselov, Nat. Commun., 2001, 2, 458.

Total absorption



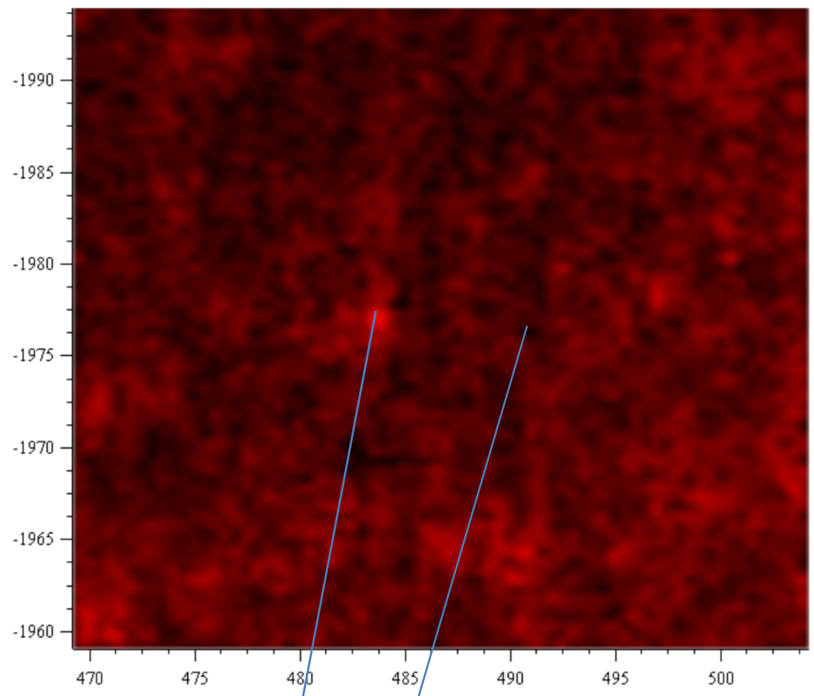


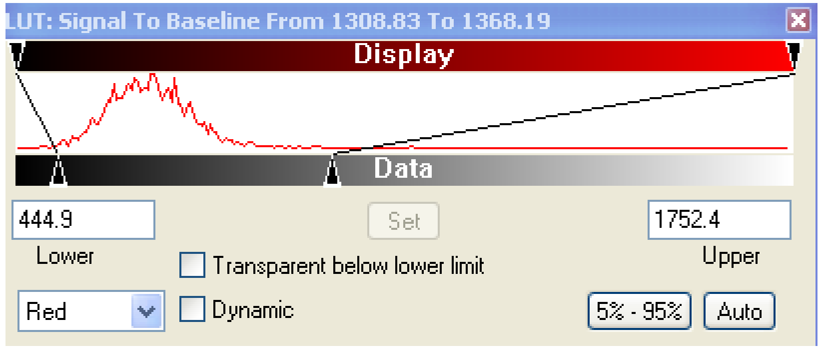


Localized resonance:

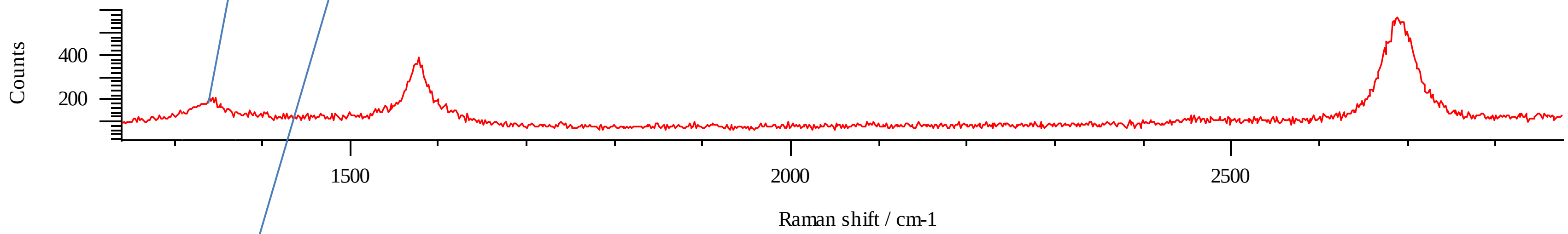
- nearly omnidirectional absorption
- polarization independent
- strongly limited in energy
- challenging to fabricate
- electrically discontinuous

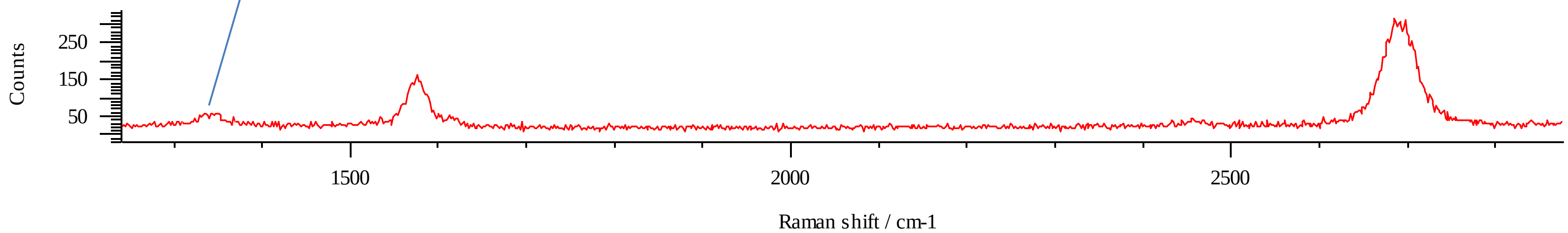
S. Thongrattanasiri, F. H. L. Koppens and J. Garcia de Abajo, Phys. Rev. Lett., 2012, 108, 047401.

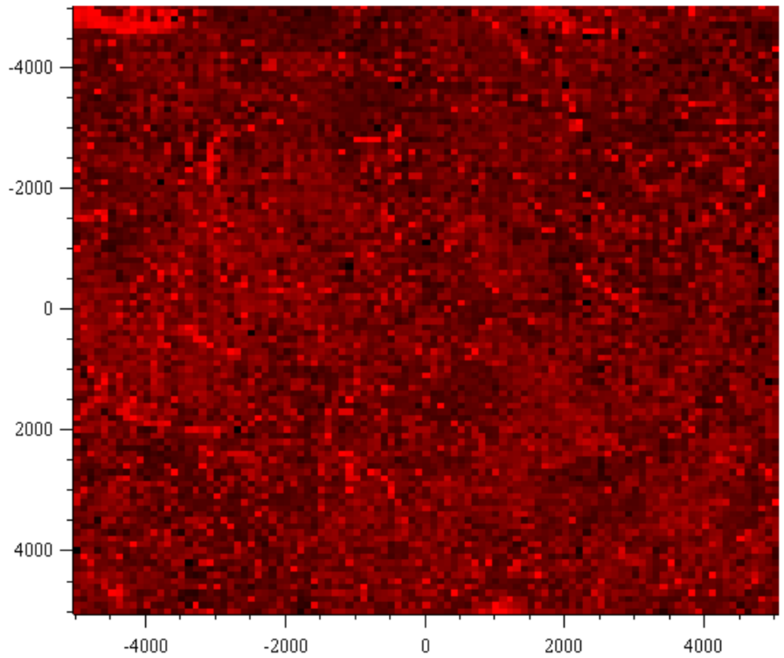

-1990
-1985
-1980
-1975
-1970
-1965
-1960
470
475
480
485
490
495
500

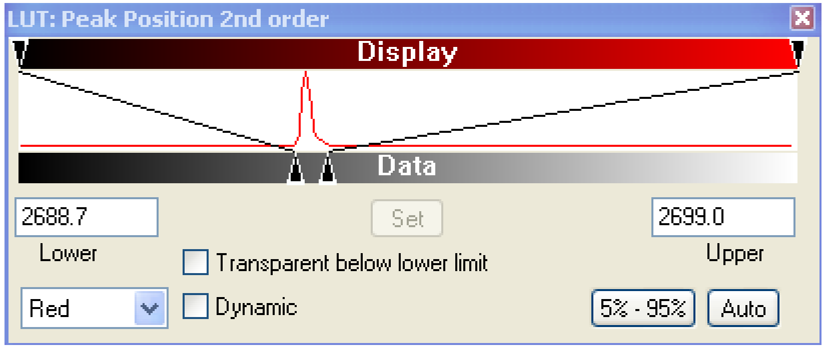

LUT: Signal To Baseline From 1308.83 To 1368.19
Display
Data
444.9
Set
1752.4
Lower
Transparent below lower limit
Upper
Red
Dynamic
5% - 95%
Auto

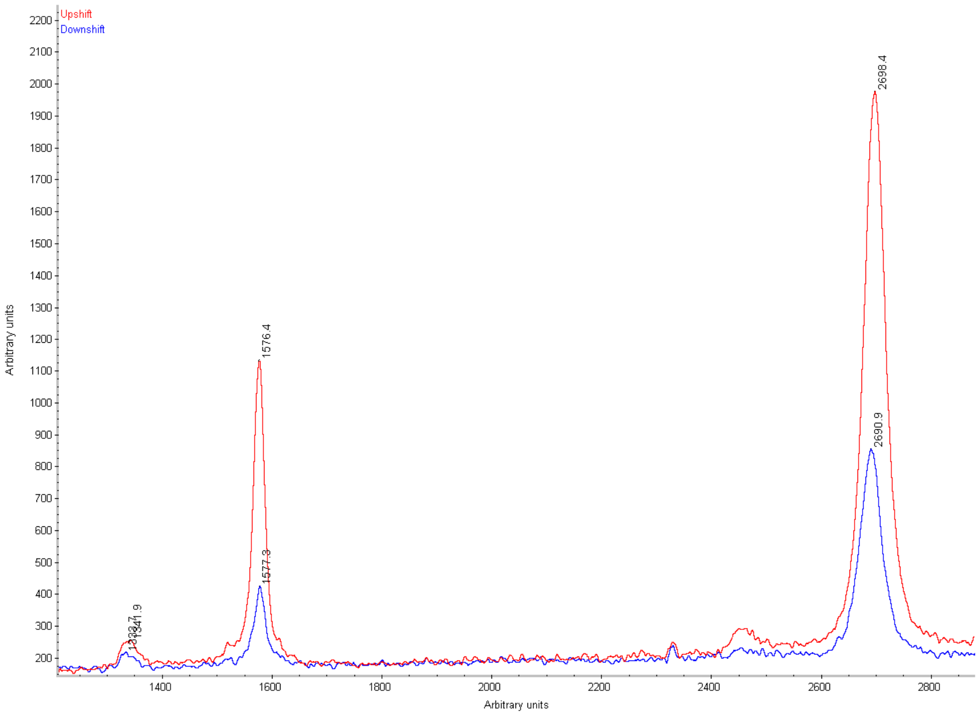
10 layers


Counts
400
200
1500
2000
2500
Raman shift / cm-1


Counts
250
150
50
1500
2000
2500
Raman shift / cm-1

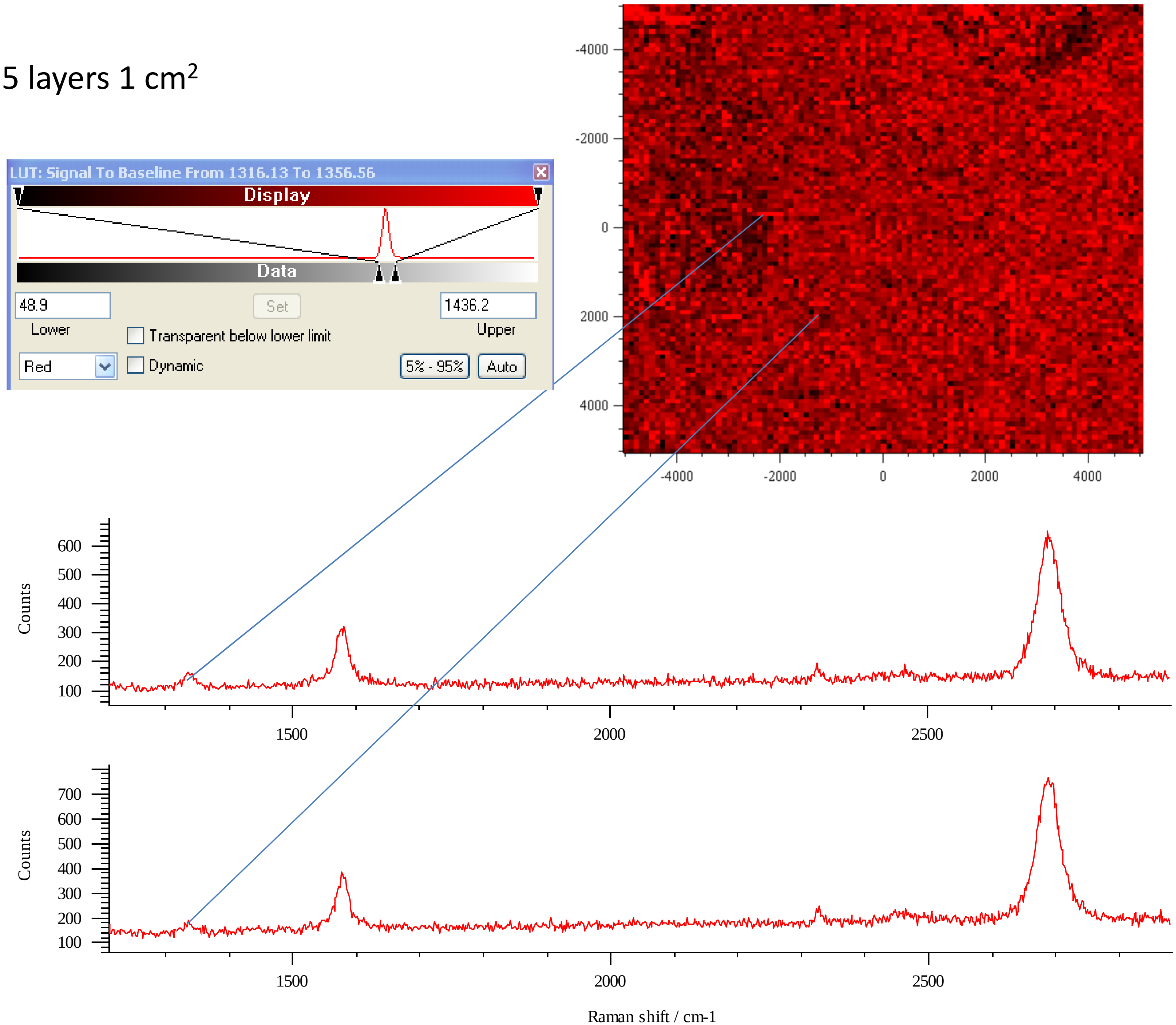


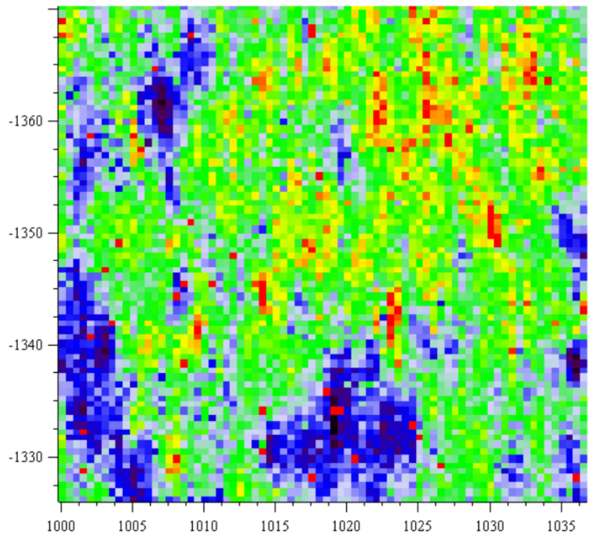


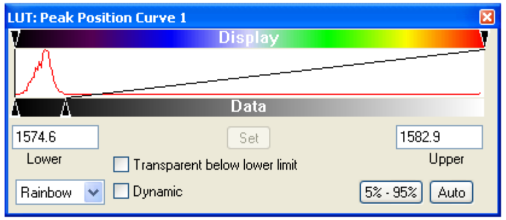


Position G-line
5 layers 1 cm2

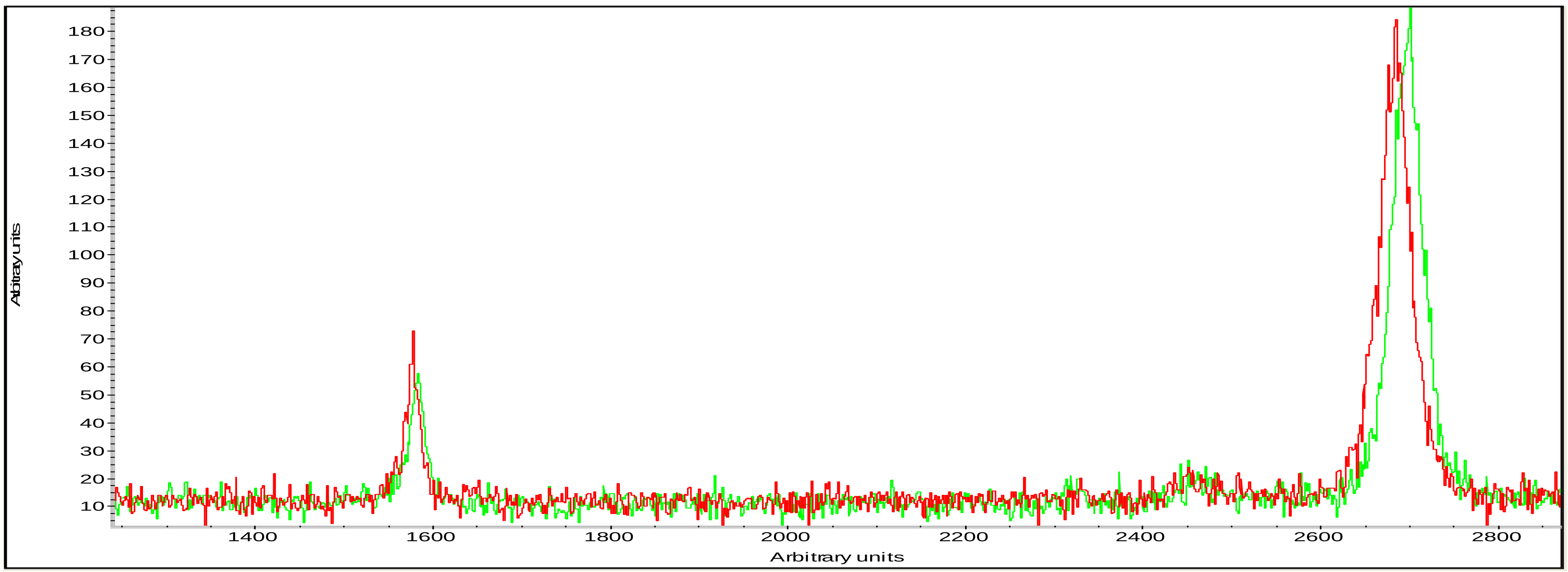
5 layers 1 cm^2

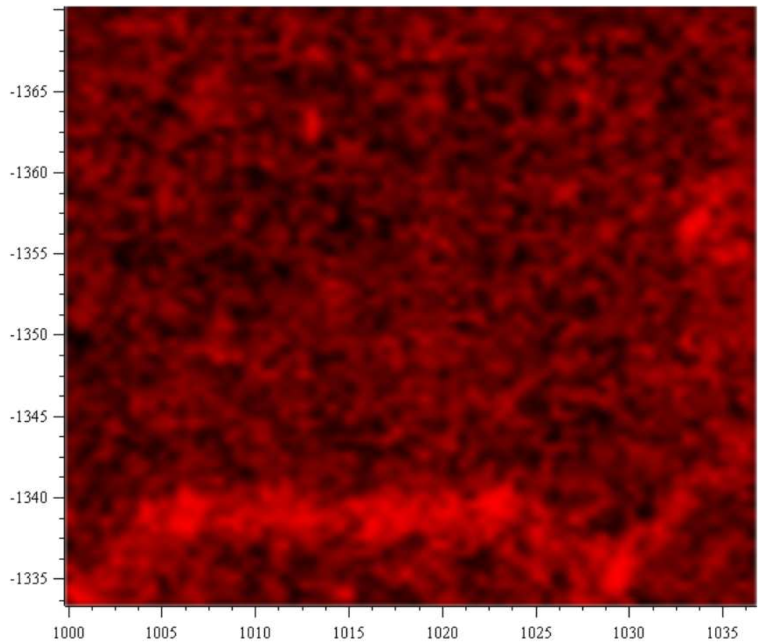


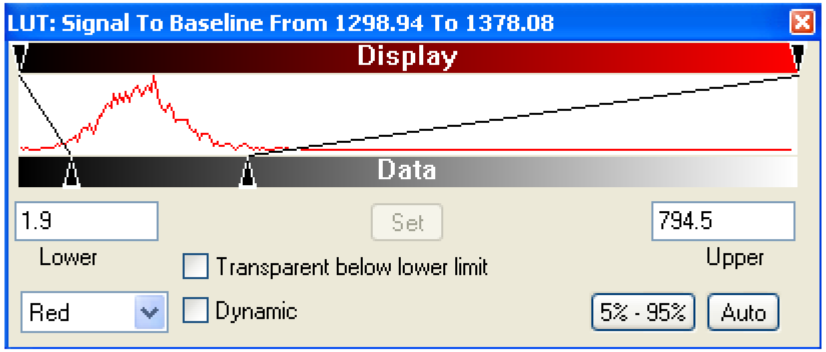




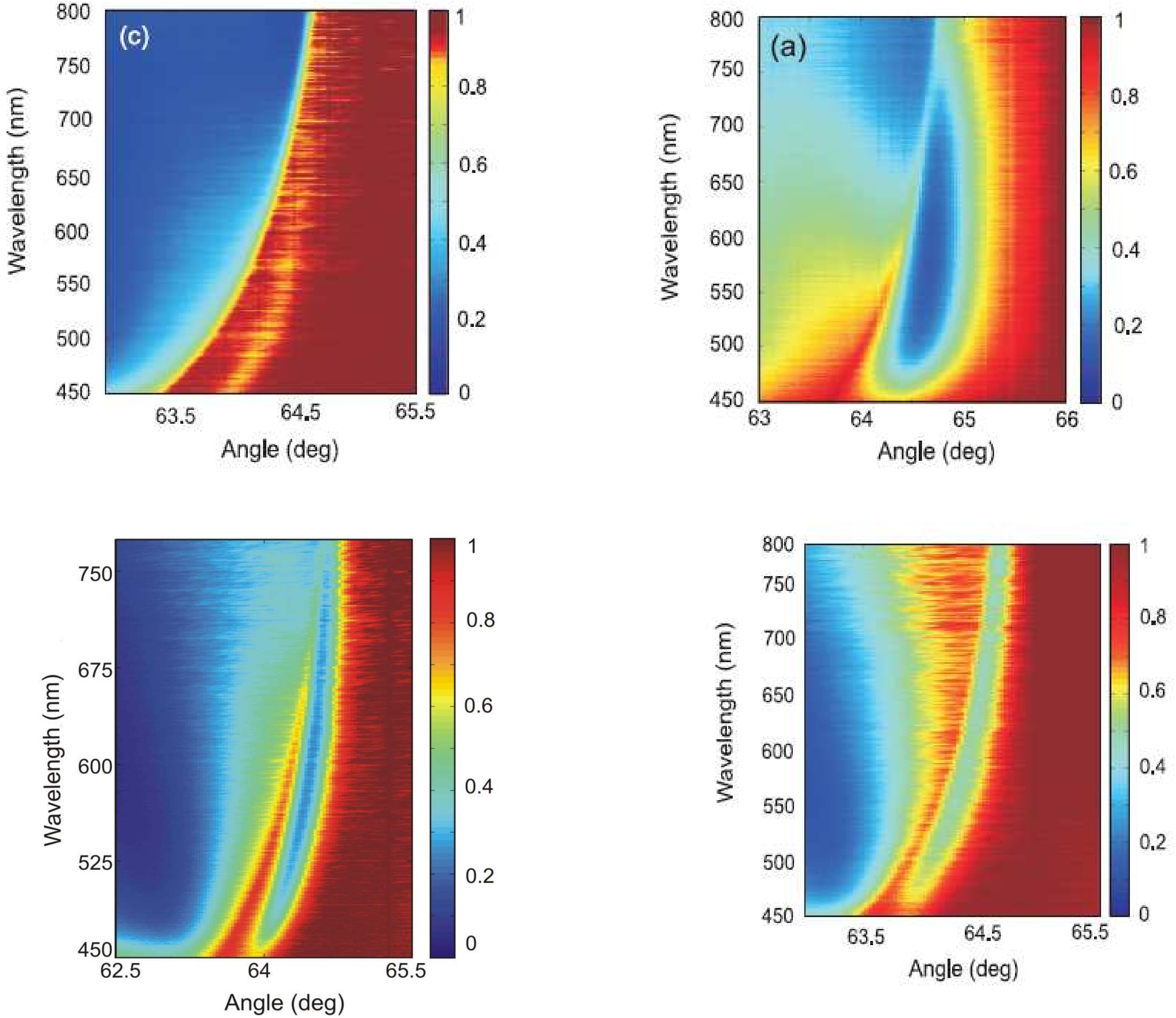
1 layer G-line position







1 layer intensity of D-line



(c)
Wavelength (nm)
800
750
700
650
600
550
500
450
63.5
64.5
65.5
Angle (deg)
1
0.8
0.6
0.4
0.2
0
(a)
Wavelength (nm)
800
750
700
650
600
550
500
450
63
64
65
66
Angle (deg)
1
0.8
0.6
0.4
0.2
0
Wavelength (nm)
750
675
600
525
450
62.5
64
65.5
Angle (deg)
1
0.8
0.6
0.4
0.2
0
Wavelength (nm)
800
750
700
650
600
550
500
450
63.5
64.5
65.5
Angle (deg)
1
0.8
0.6
0.4
0.2
0

Coherent absorption

$$S = \begin{pmatrix} t_{1234}^{p} & r_{4321}^{p} \\ r_{1234}^{p} & t_{4321}^{p} \end{pmatrix}$$

$$\begin{cases} |S_{21}|^2 = |r_{1234}^{p}|^2 = R = 0 \\ |S_{11}|^2 = |t_{1234}^{p}|^2 \propto T = 0 \end{cases}$$

$$A = 1 - R - T$$