Tutorial 3

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Photonics-2018

Tamm plasmons and Bloch surface waves

Quantum plasmonics:

Two photon interference:

Photon coalescence and anticoalescence

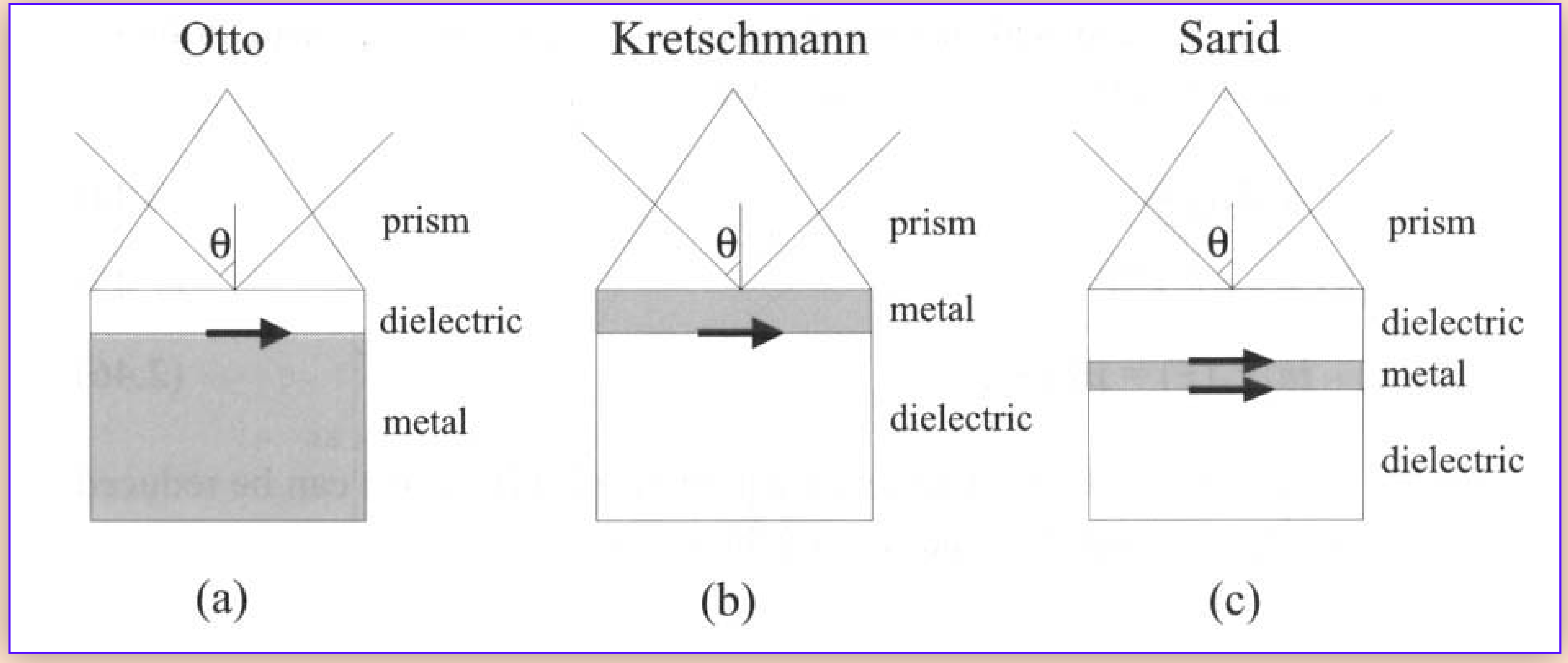
Bloch surface waves and Tamm states

BSW and Surface Plasmons	Tamm States and Tamm Plasmons
• Finite surface component of wave vector • Surface resonance	• Zero or finite surface component • Surface States • With TE and TM

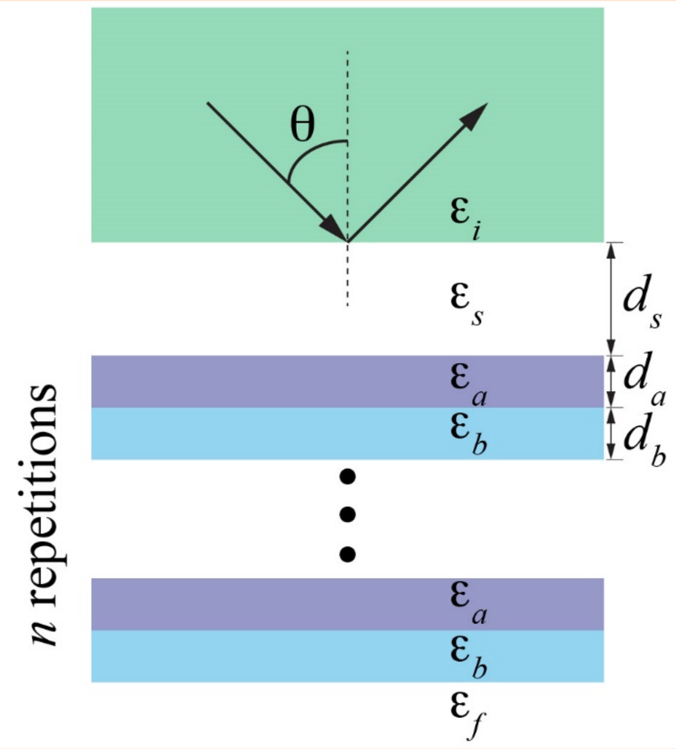
Large local field enhancement (PRB 96, 045308, 2017)
low mode volume

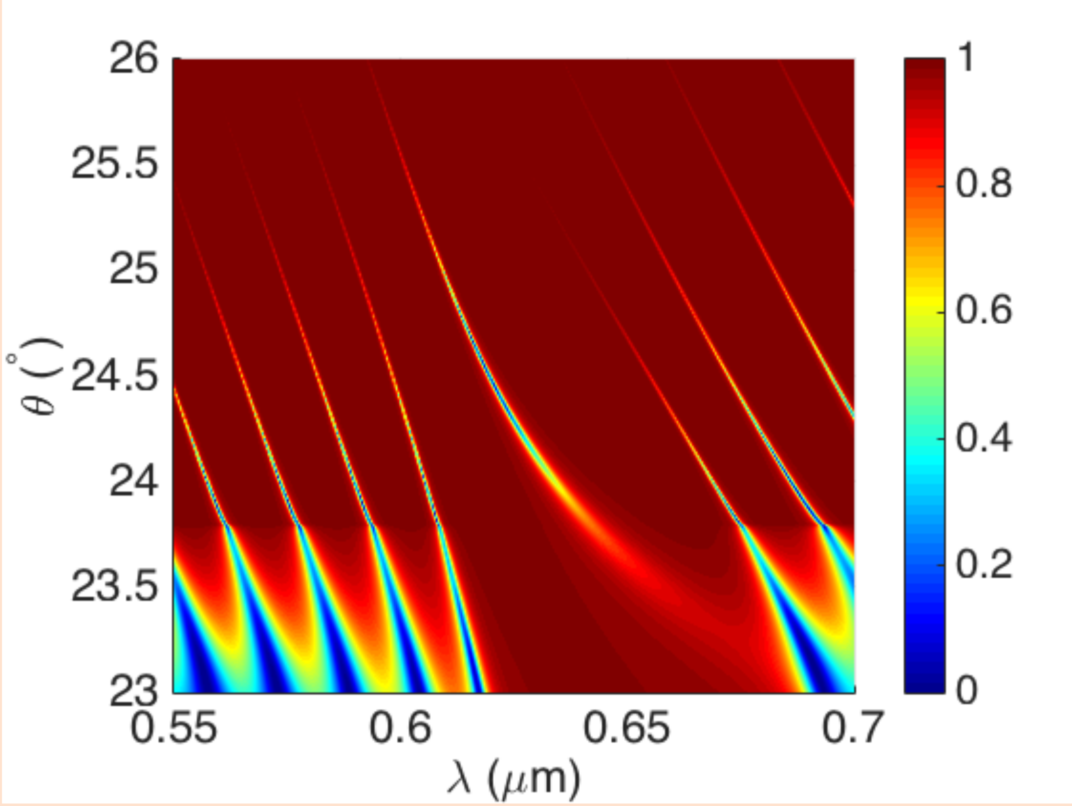
suitable for
CQED, NLO, SERS, Sensing

Surface plasmons



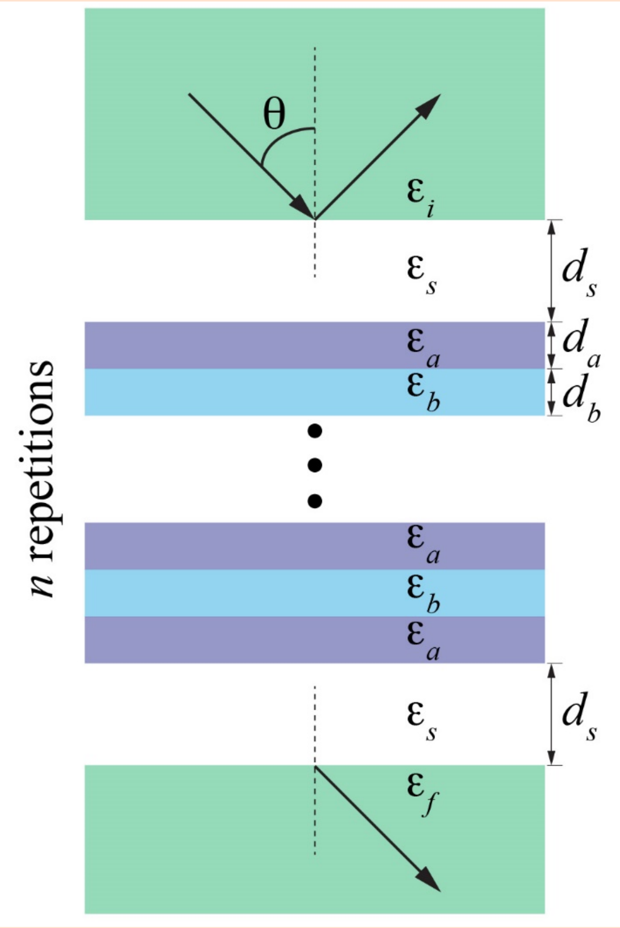
Bloch surface waves

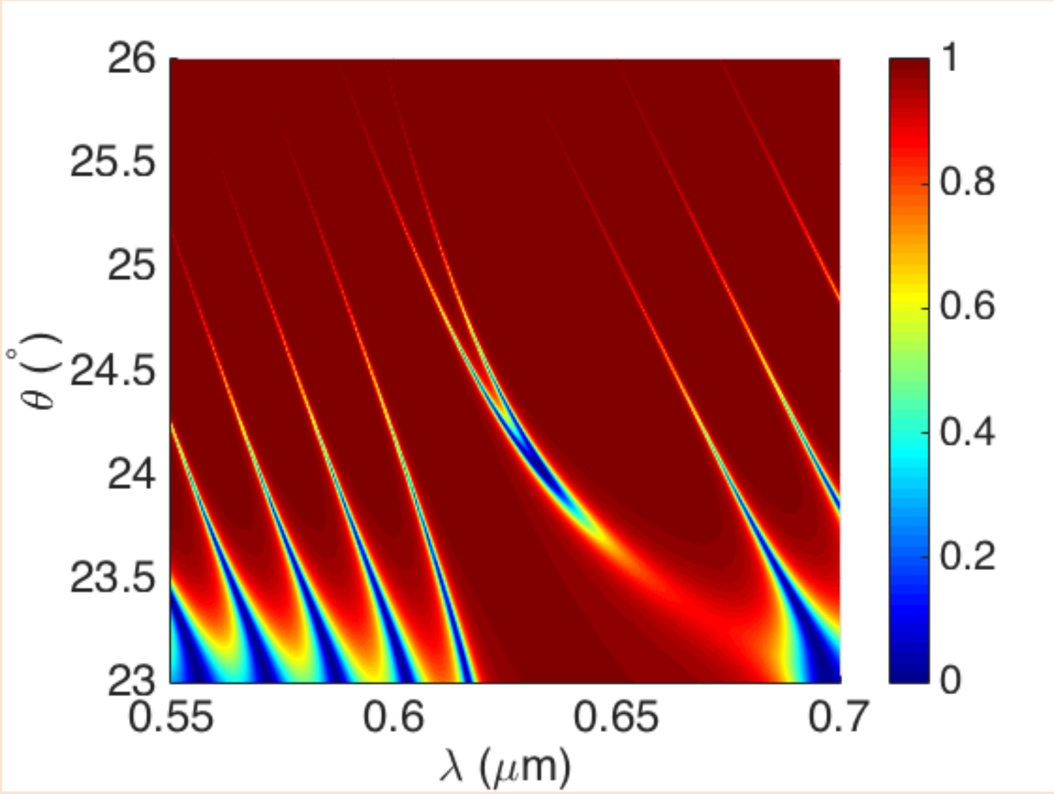




ε_i=6.145, ε_f=1,
Spacer layer: d_s=1μm, ε_s=1
DBR parameters: ε_a=4+0.001i (ZnO), ε_b=1.88+0.001i (MgF_2),
d_a=d_b=120nm, periodicity n=30

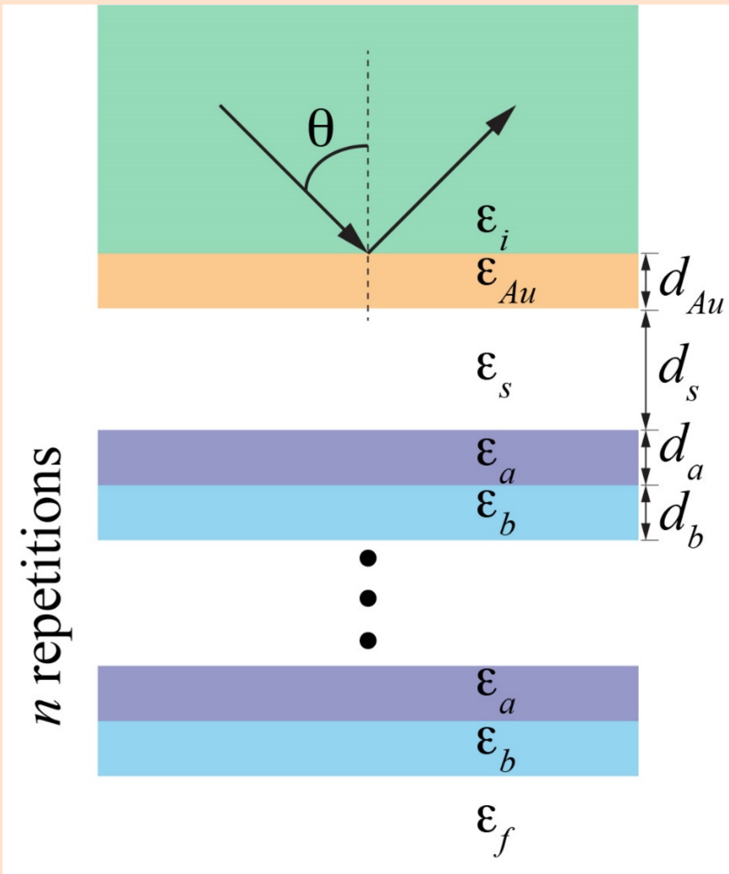
Coupled BSW

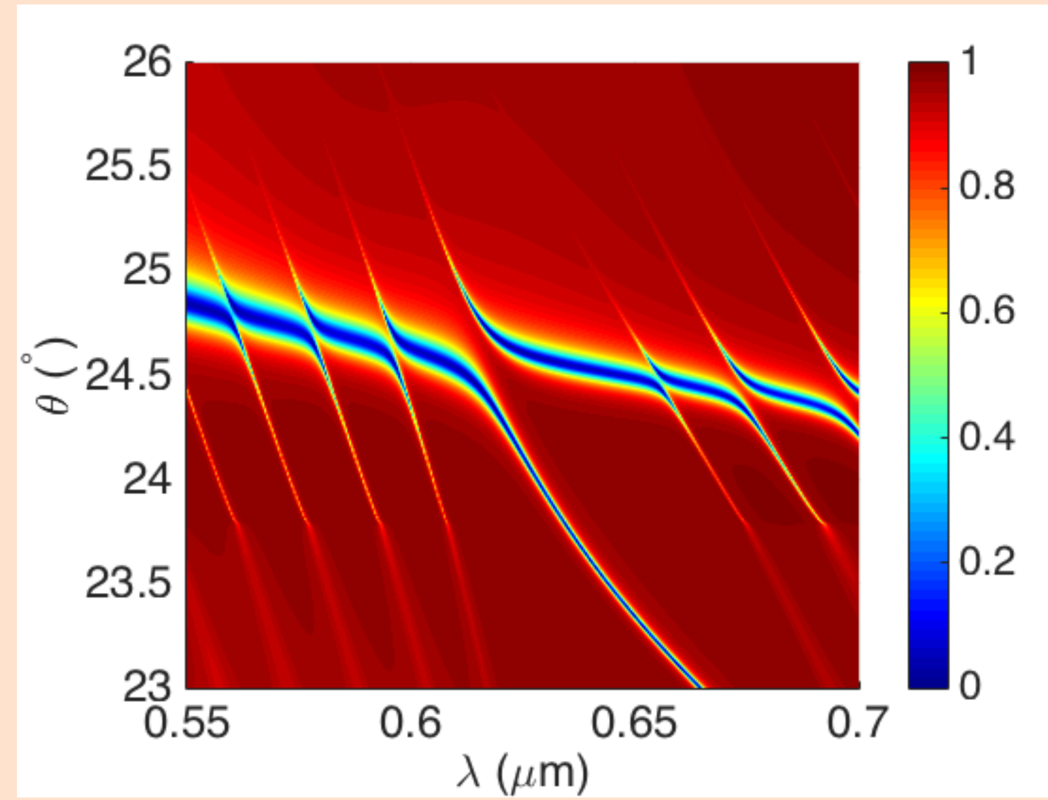




ε_i=6.145, ε_f=1
Spacer layer: d_s=1μm, ε_s=1
DBR parameters: ε_a=4+0.001i (ZnO), ε_b=1.88+0.001i (MgF_2),
d_a=d_b=120nm, periodicity n=30

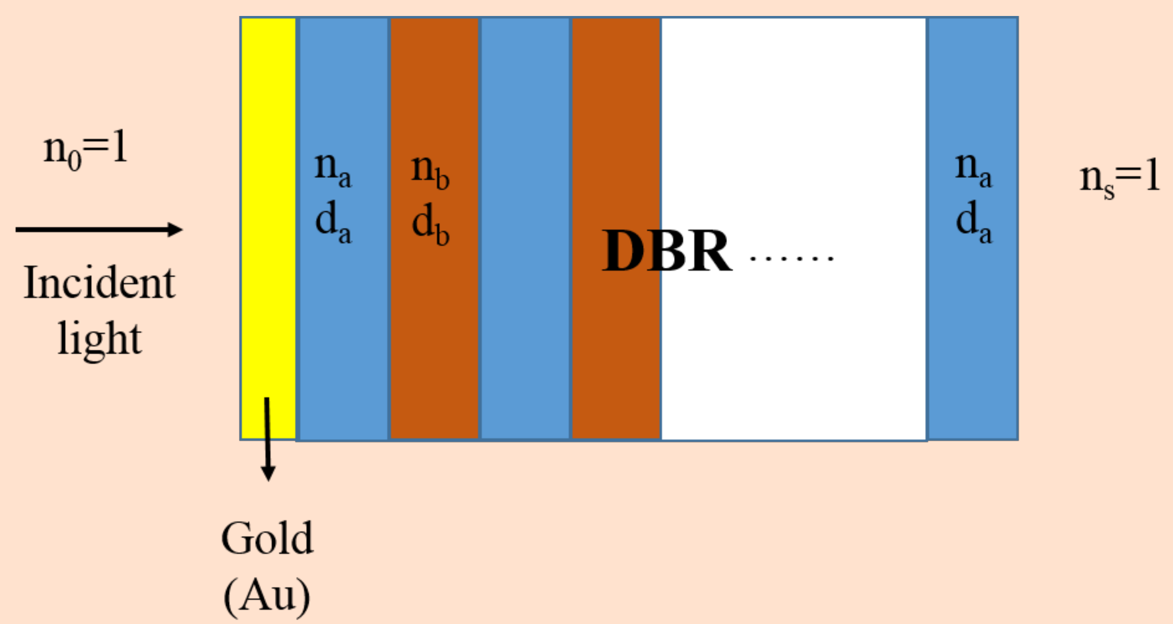
Coupled BSW-Plasmon

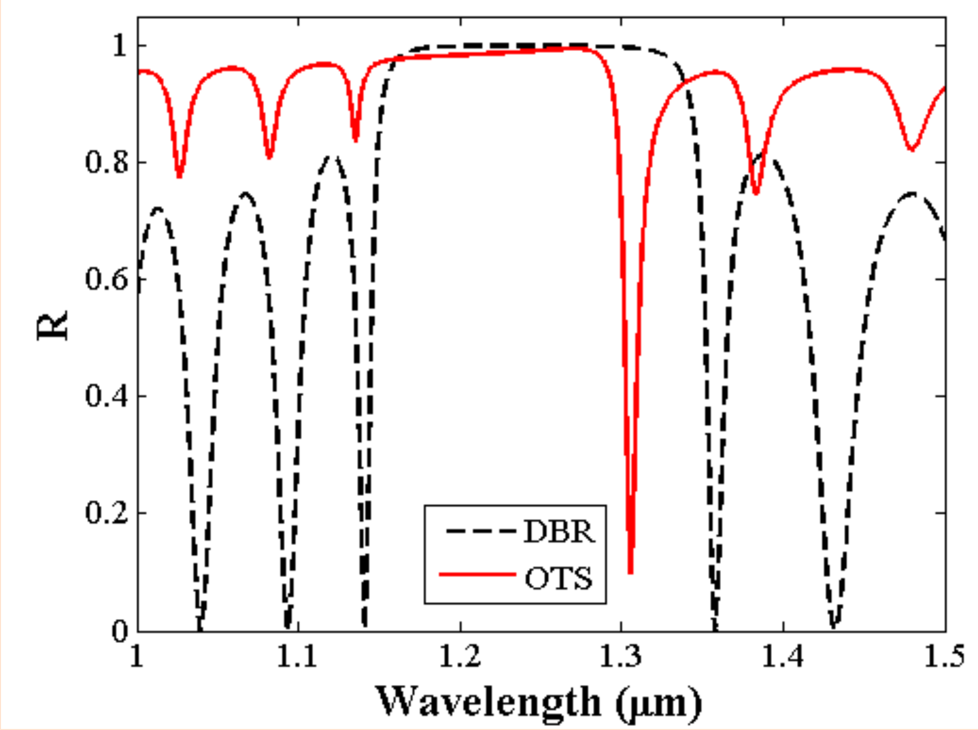




ε_i=6.145, ε_f=1
Thickness of Gold d_{Au}=50nm
Spacer layer: d_s=1μm, ε_s=1
DBR parameters: ε_a=4+0.001i (ZnO), ε_b=1.88+0.001i (MgF_2),
d_a=d_b=120nm, periodicity n=30

Tamm Plasmons



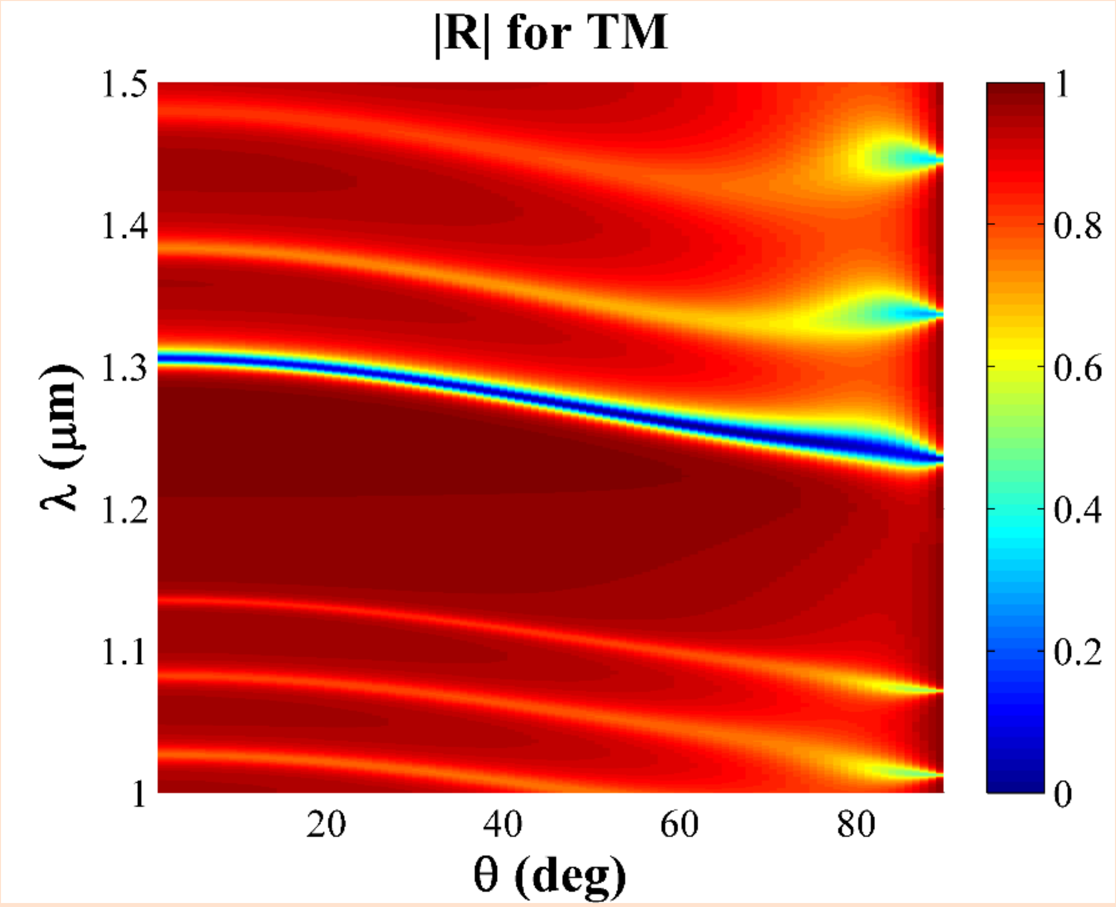


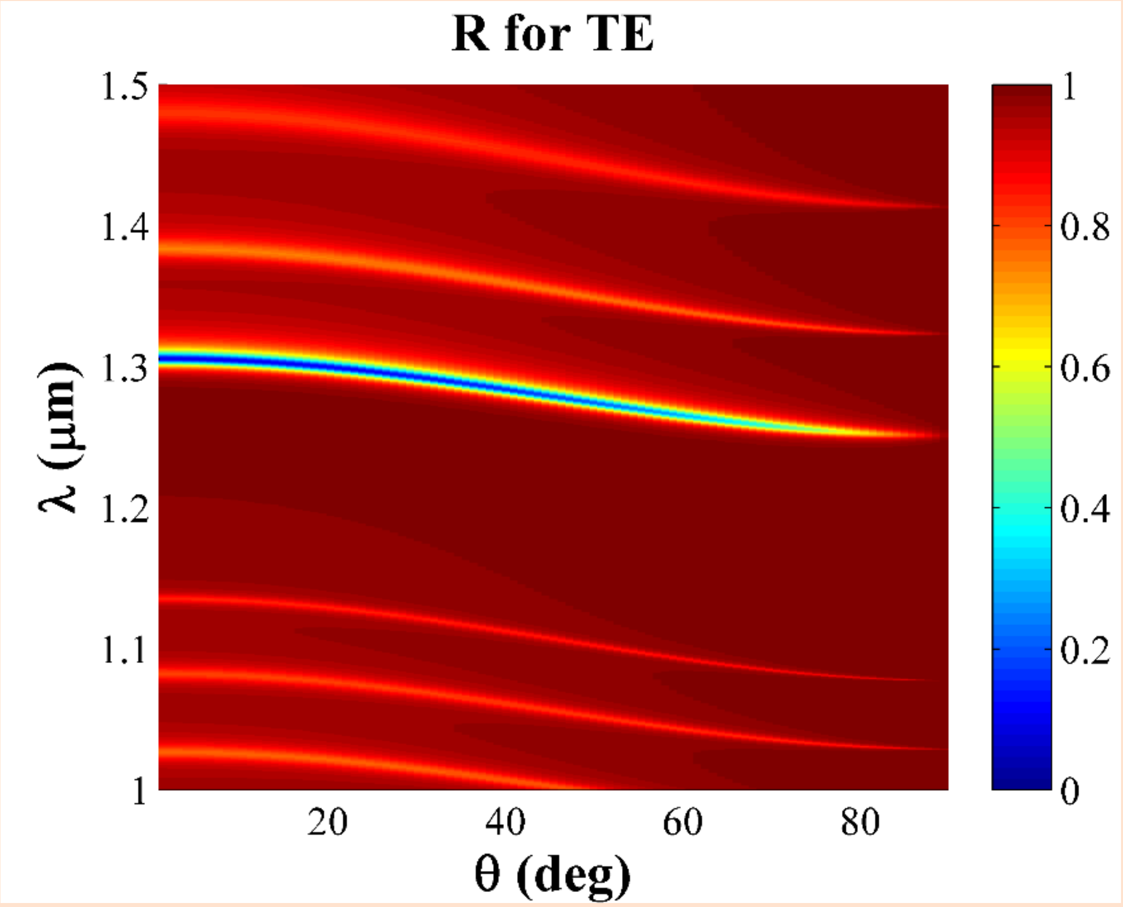
DBR Parameters: n_a=3.7 , n_b=3, periodicity=14

Bragg frequency $\hbar\omega_0$= 1 eV, corresponding wavelength being λ_c=1.24μm.

Thickness of gold layer=0.03μm;

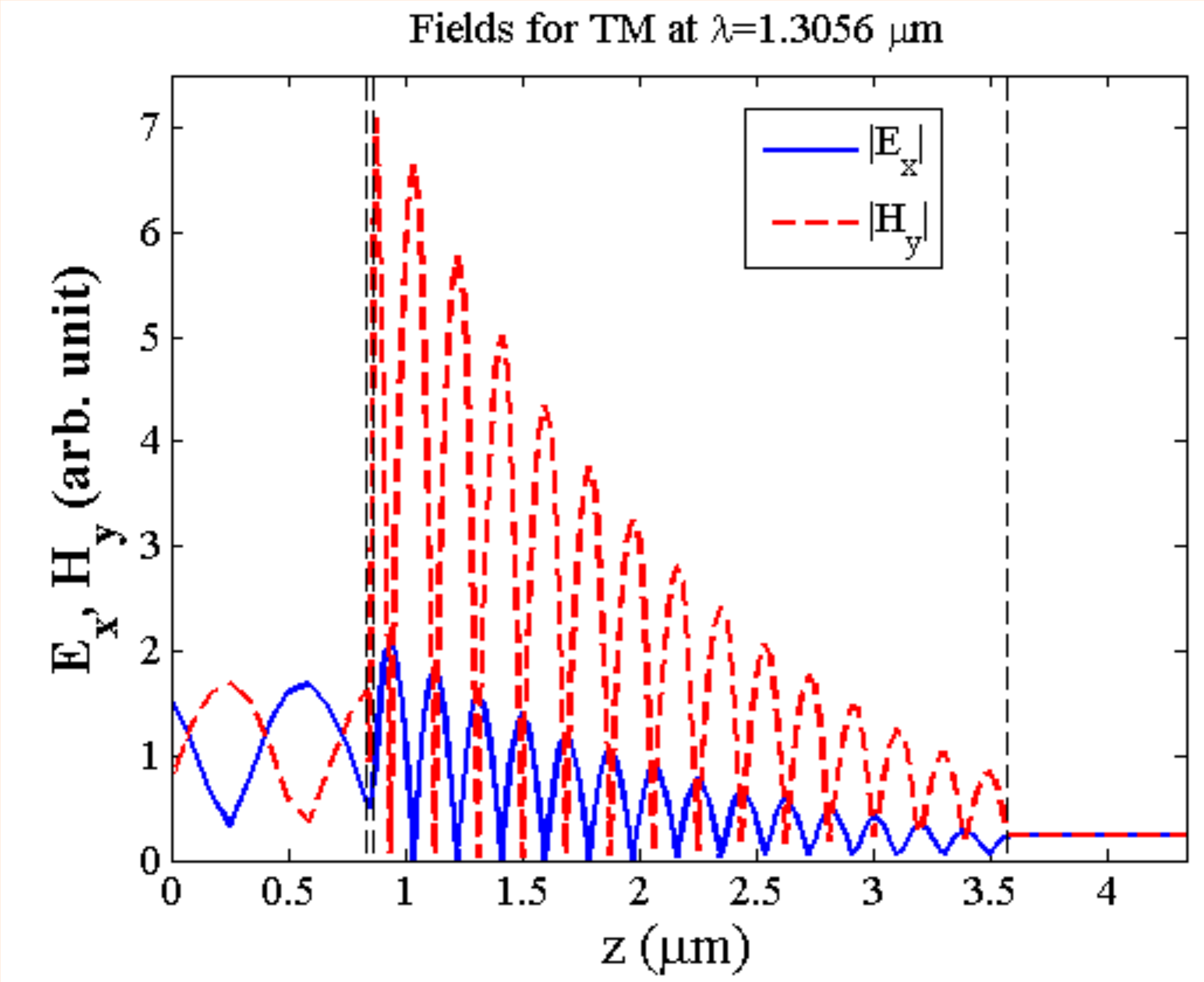
Intensity reflection for TE and TM



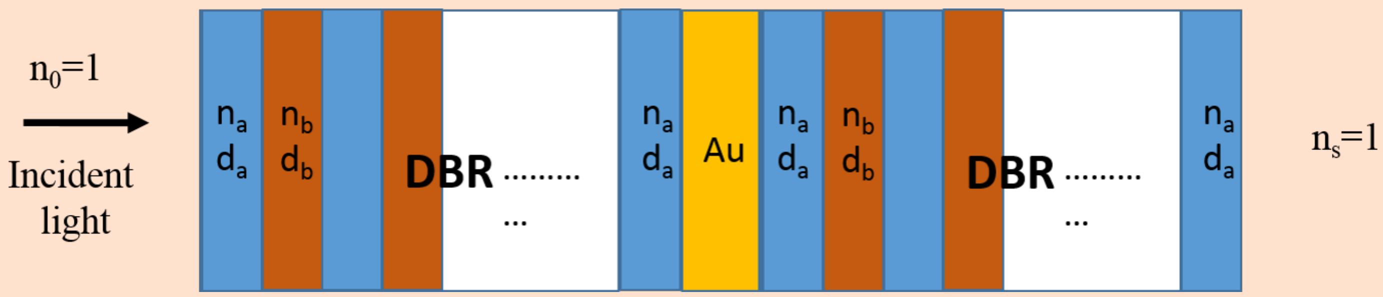


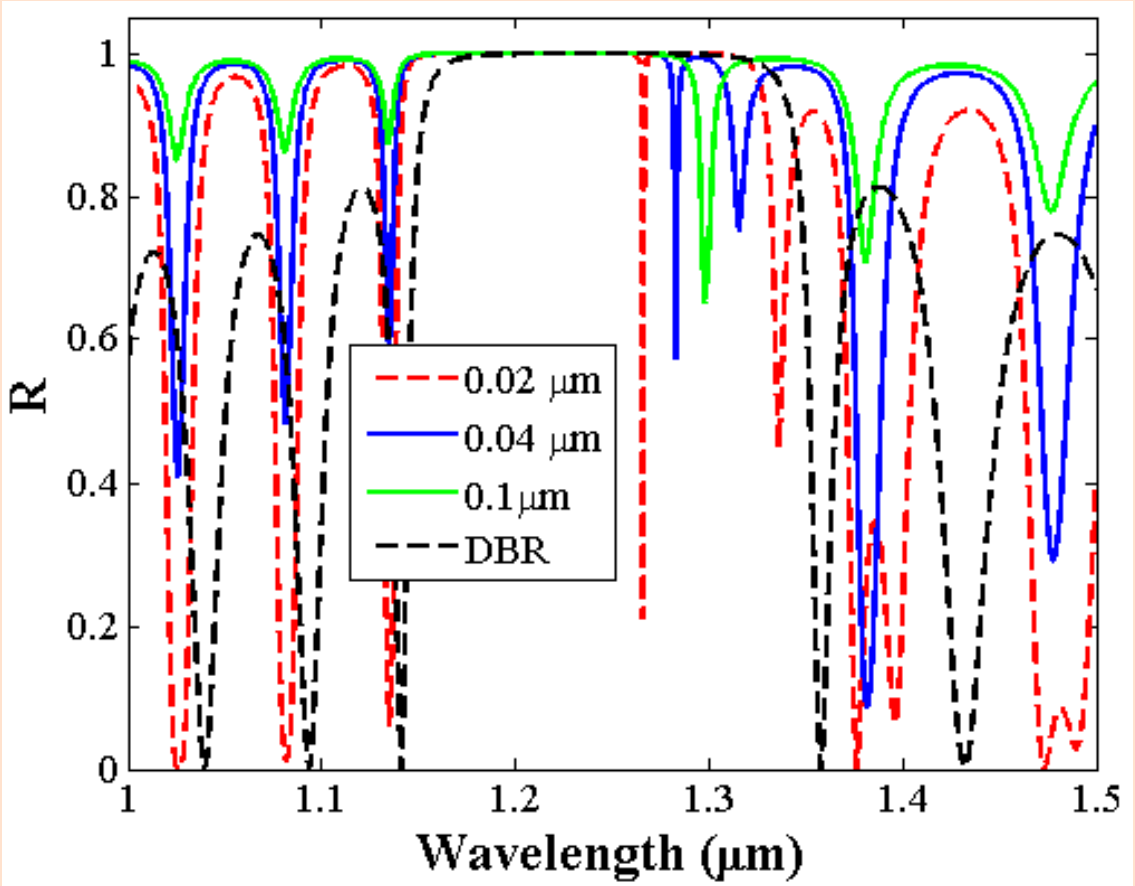
Fields under normal incidence inside

(Air-Au-DBR-Air)



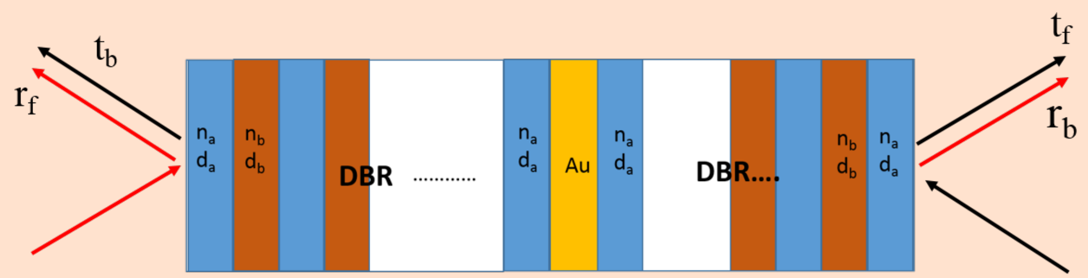
Coupled Tamm plasmons

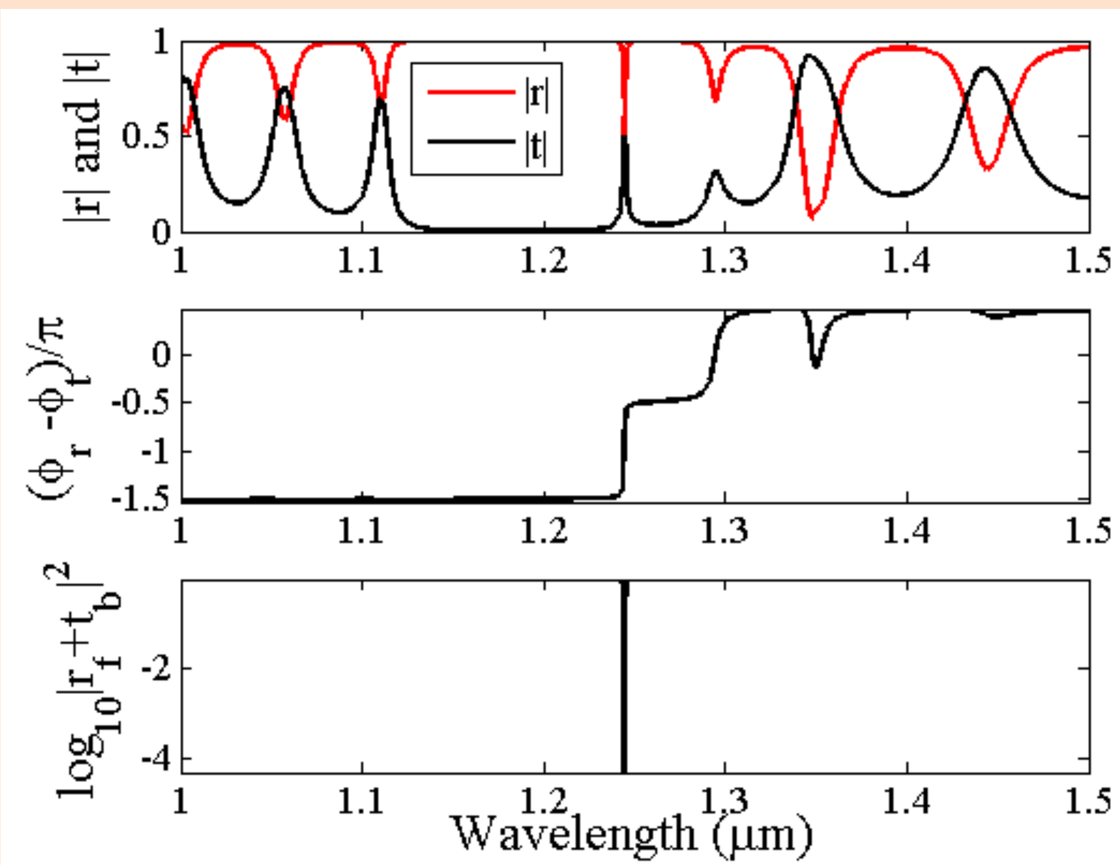




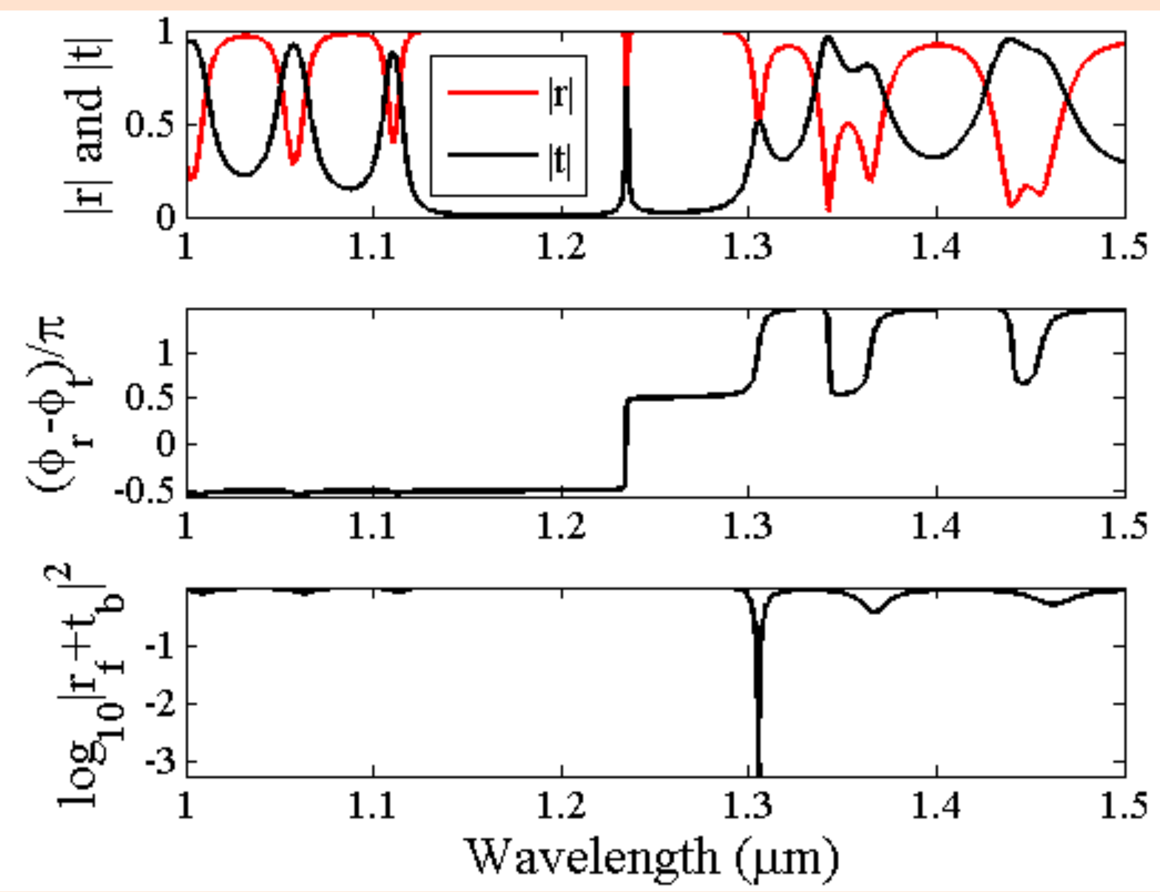
Coupling of Tamm plasmons is controlled by the thickness of the gold layer.

CPA with coupled Tamm plasmons



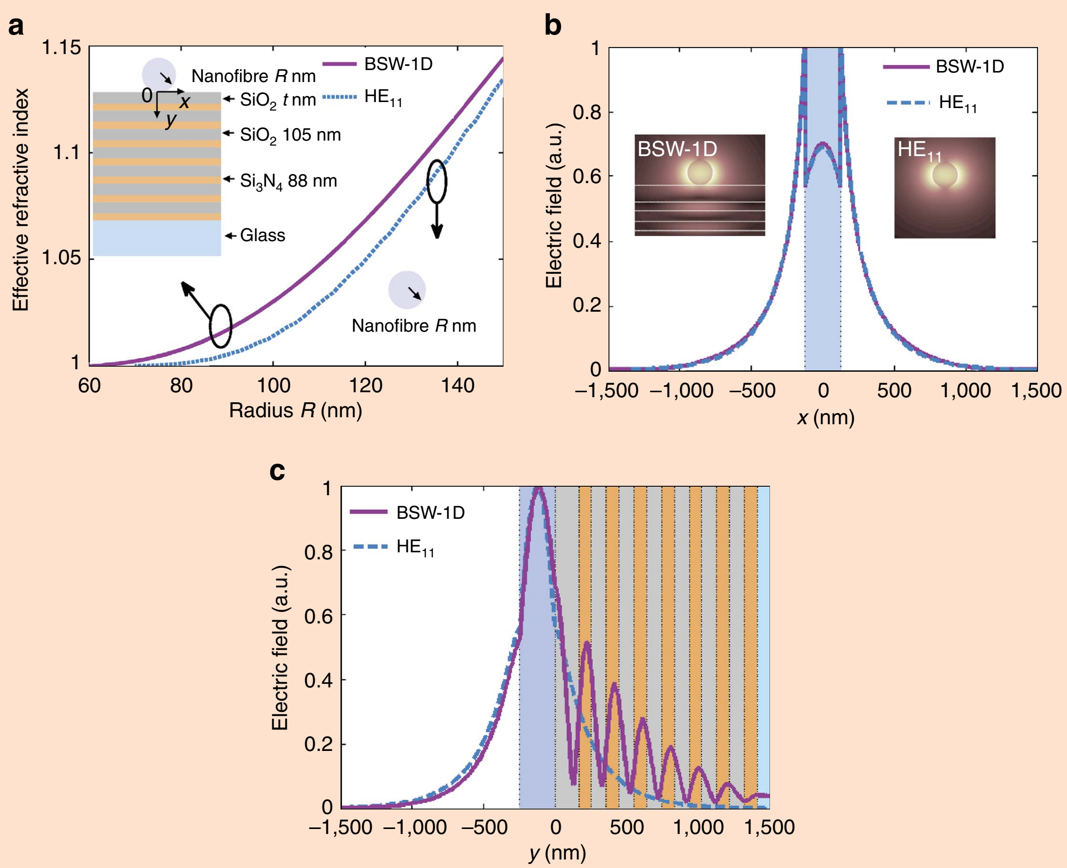


d_{au}=0.0275μm, θ=45deg, TM pol



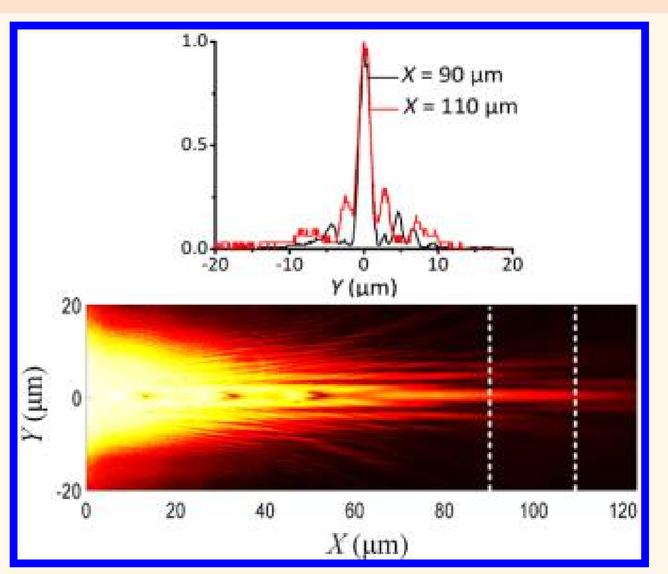
d_{au}=0.018μm, θ=45deg, TM pol
with phase delay of π

Recent literature on BSW & Tamm plasmons



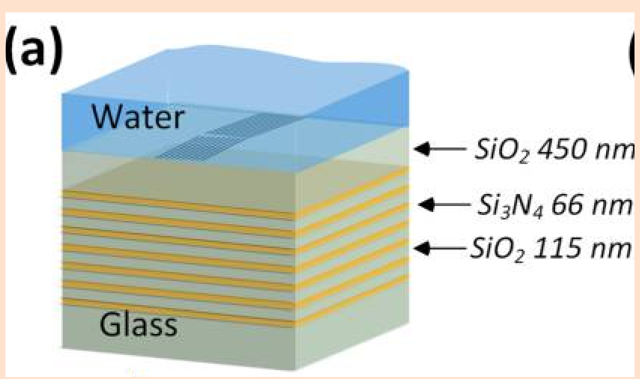
Wang et al, Nat. Com. 8:14330 (2017)

Bloch surface waves confined in one dimension with a single polymeric nanofibre



Wang et al, ACS Nano, 11, 5383 (2017)

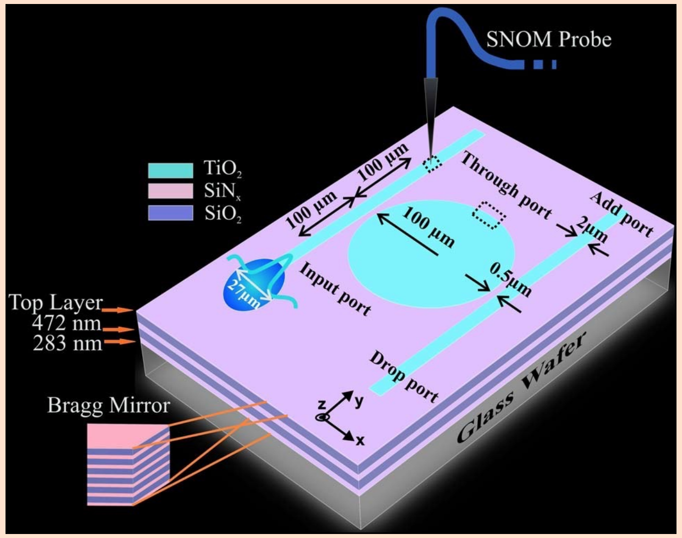
Diffraction-Free Bloch Surface Waves

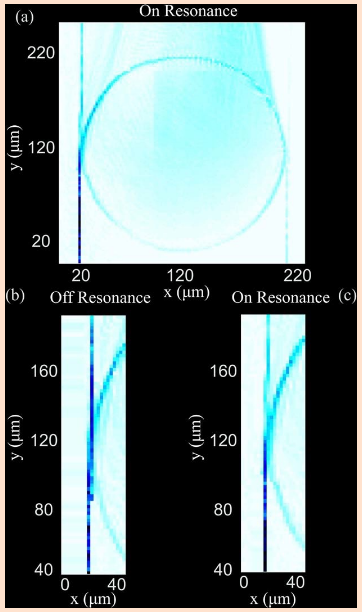


BSW-based optical chip

EPFL group
Probe with SNOM tip

DBR: SiN-SiO_2
guide and disk: TiO_2
radius: 100 micron





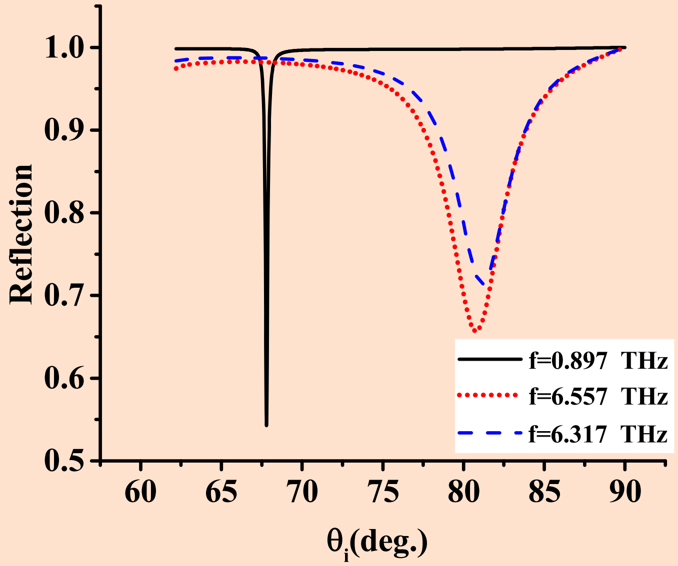
Dubey et al, Opt Lett. 41, 4867 (2017)

Near field characterisation of a BSW-based 2D disk resonator

Graphene-BSW-based biosensors

Baghbadorani et al, Appl. Opt. 56, 462 (2017)

Biosensors based on Bloch surface waves in one-dimensional photonic crystal with graphene nanolayers

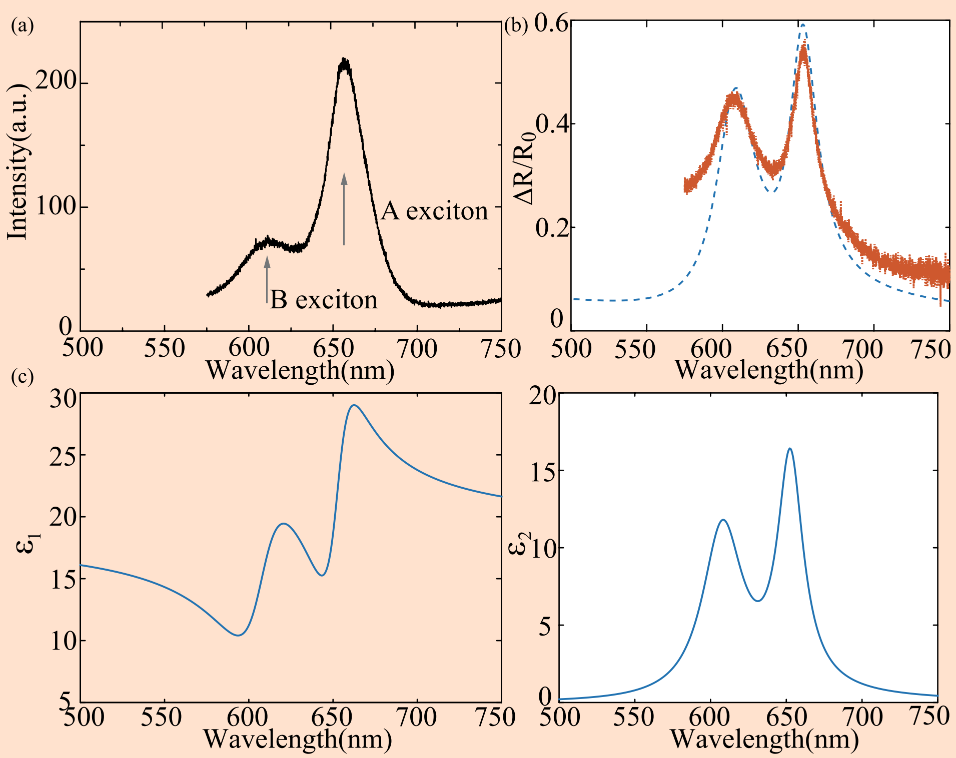


Exciton-TP coupling

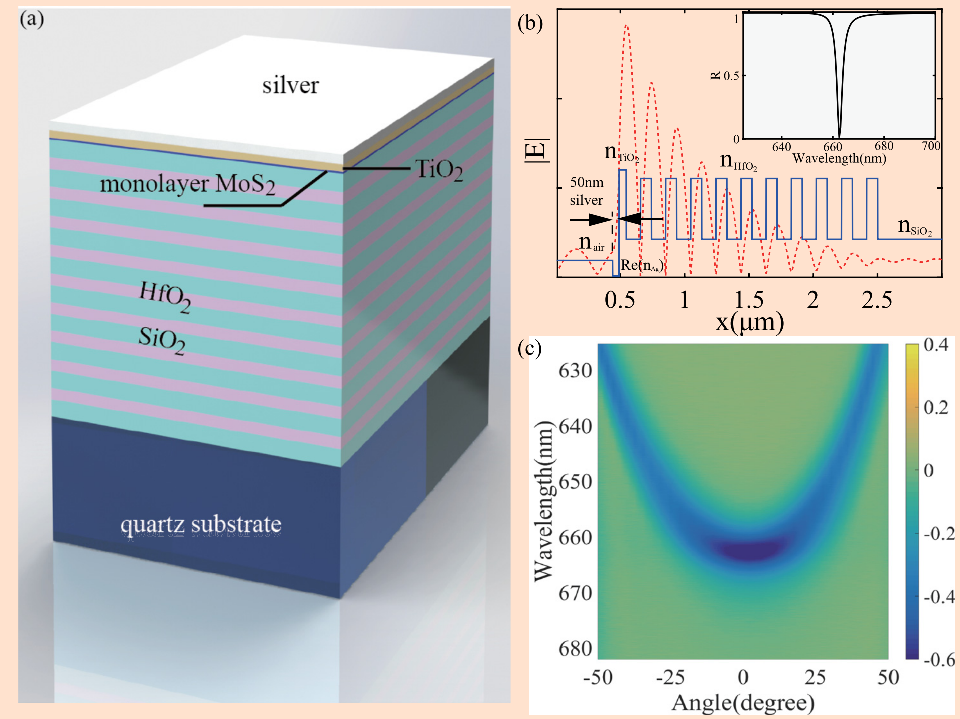
Hu et al, Appl. Phys. Lett. 110, 051101 (2017)

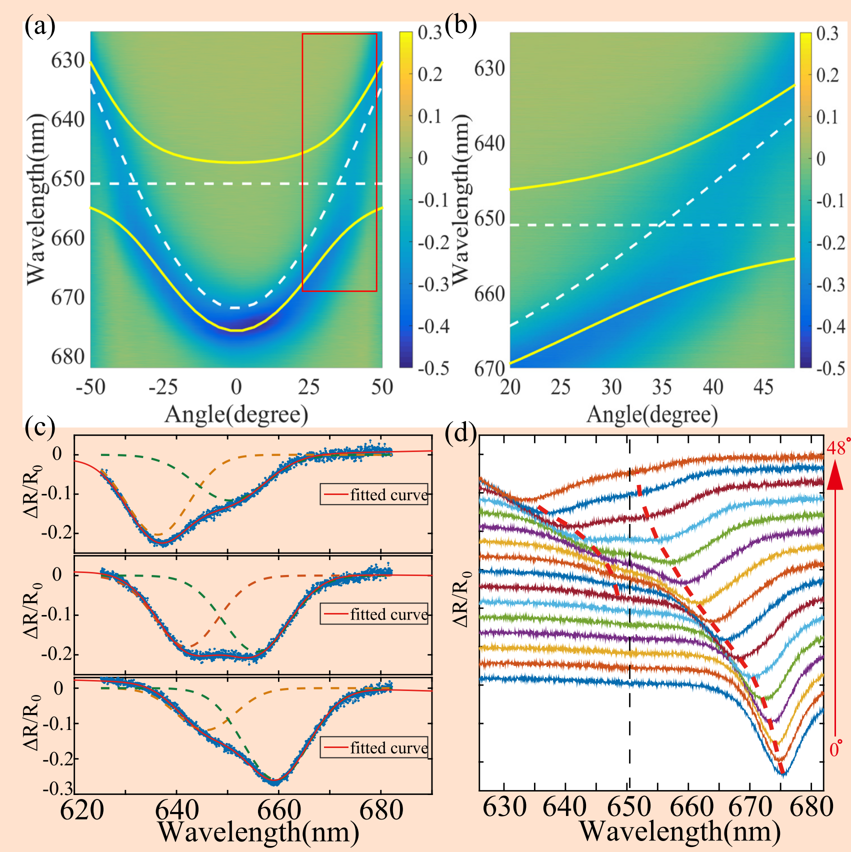
Strong coupling between Tamm plasmon polariton and two dimensional semiconductor excitons

$$\varepsilon(\omega) = \varepsilon_b + \sum_{i=A,B} \frac{f_i}{\omega_i^2 - \omega^2 - i\Gamma_i\omega} = \varepsilon_1 + i\varepsilon_2,$$



MoS2 A & B excitons

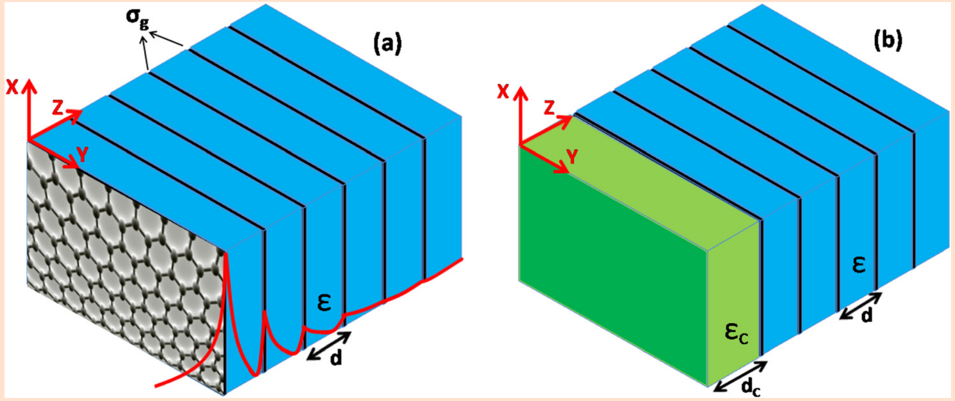




Graphene-dielectric metamaterials

Hajian et al, J. Appl. Phys. 121, 033101 (2017)

Long-range Tamm surface plasmons supported by graphene-dielectric metamaterials



$$\cos(K_B d) = \cosh(qd) - \frac{\alpha q}{2\varepsilon}\sinh(qd).$$

$$H_y(z) = \left\{ \begin{array}{ll} A[\sinh(qz) + \gamma\cosh(qz)] & z \geq 0 \\ B\ \exp(q_s z), & z < 0 \end{array} \right\},$$

without and with a cap layer

$$q = \sqrt{\beta^2 - k_0^2\epsilon}, \quad q_s = \sqrt{\beta^2 - k_0^2\epsilon_s}, \quad \alpha = \sigma_g/(i\omega\epsilon_0)$$

BSW and Tamm plasmons for quantum optics

Anti-coalescence of bosons on a lossy beam splitter

B. Vest,[1] M.-C. Dheur,[1] E. Devaux,[2] A. Baron,[3] E. Rousseau,[4] J.-P. Hugonin,[1] J.-J. Greffet,[1] G. Messin,[1] F. Marquier[1]*

June 2017 Science article

Quantum plasmonics

nature physics

REVIEW ARTICLE

PUBLISHED ONLINE: 3 JUNE 2013 | DOI: 10.1038/NPHYS2615

Quantum plasmonics

M. S. Tame[1]*, K. R. McEnery[1,2], Ş. K. Özdemir[3], J. Lee[4], S. A. Maier[1]* and M. S. Kim[2]

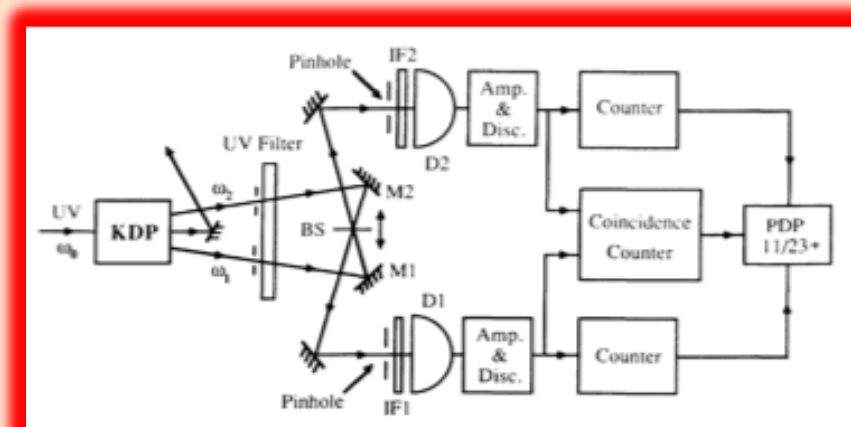
VOLUME 59, NUMBER 18 PHYSICAL REVIEW LETTERS 2 NOVEMBER 1987

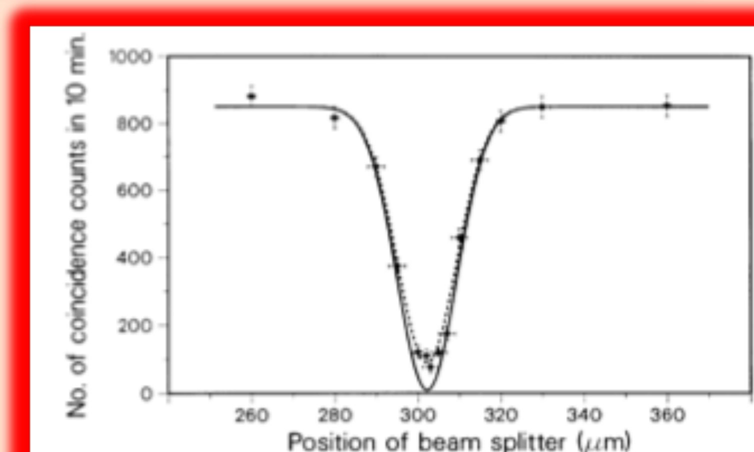
Measurement of Subpicosecond Time Intervals between Two Photons by Interference

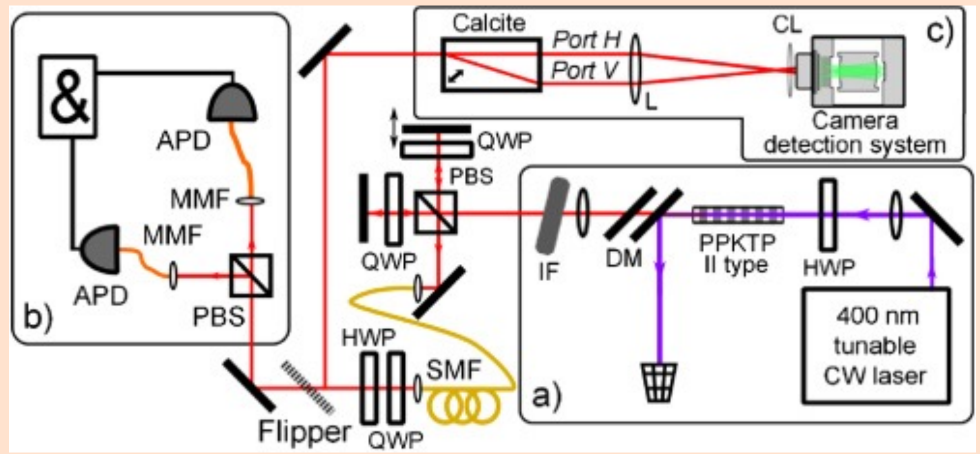
C. K. Hong, Z. Y. Ou, and L. Mandel

Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627

(Received 10 July 1987)







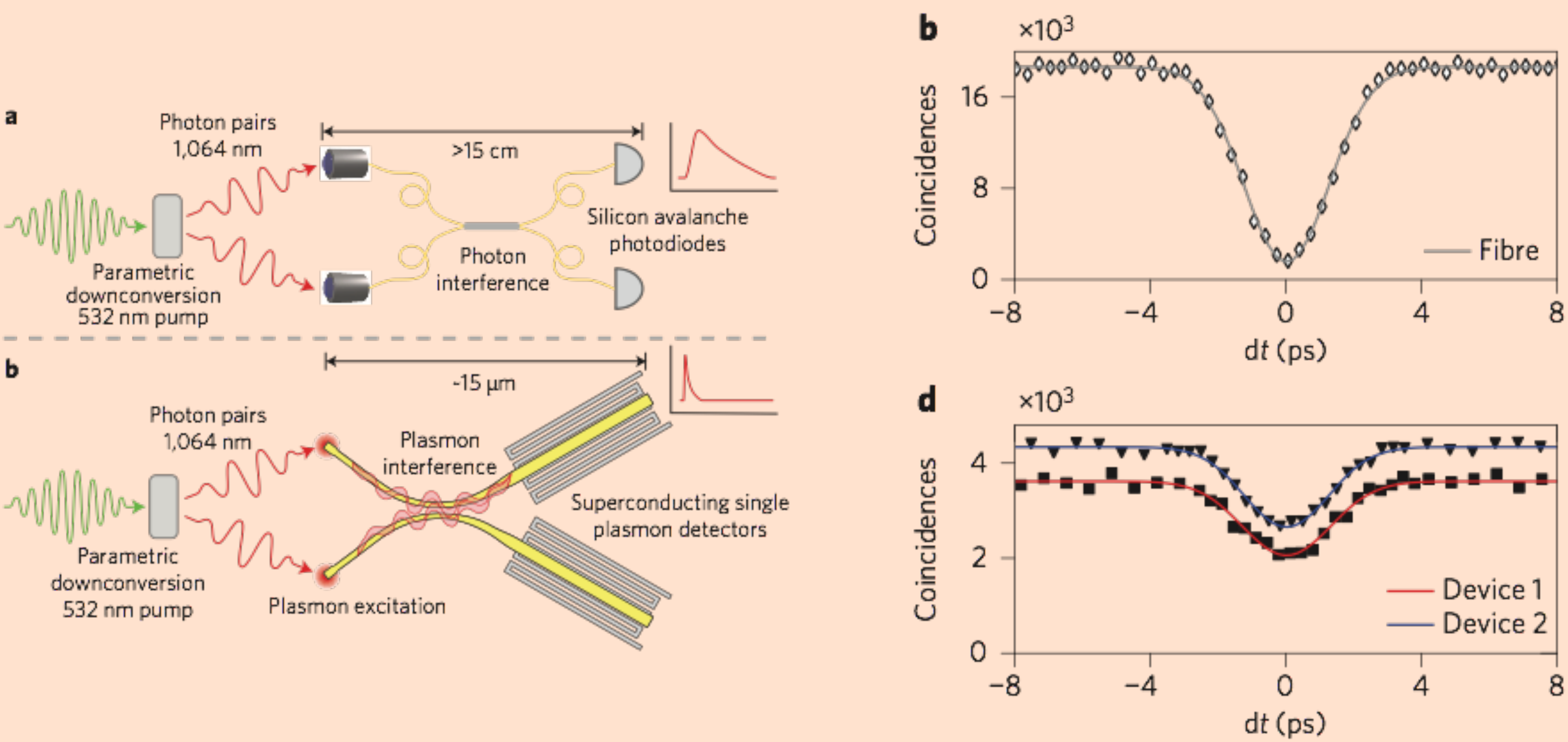
Jachura et al, OL 2015

Plasmonic circuit

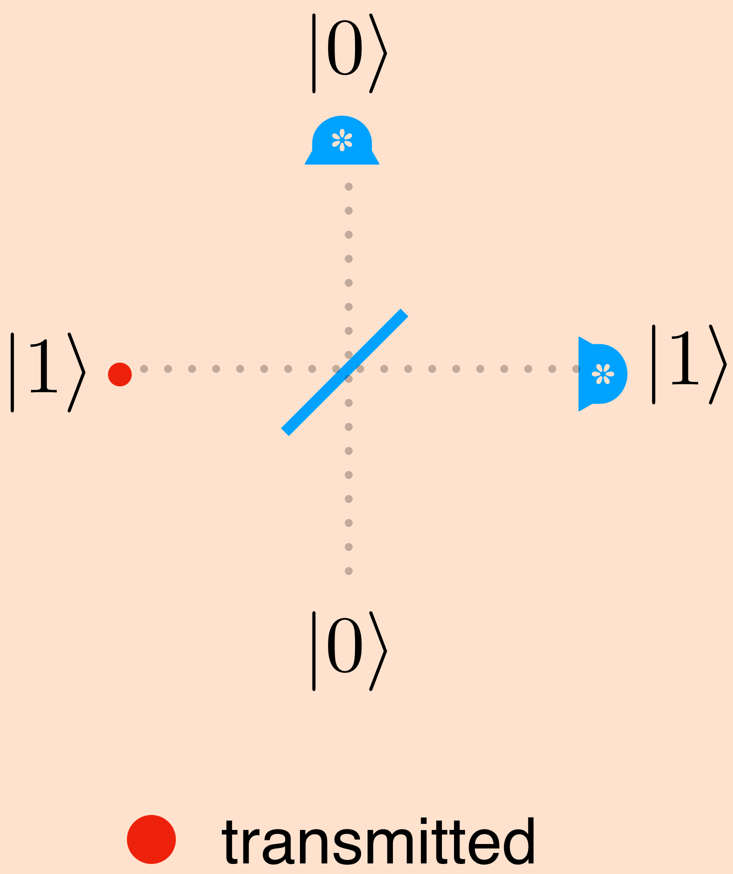
nature nanotechnology
LETTERS
PUBLISHED ONLINE: 11 AUGUST 2013 | DOI: 10.1038/NNANO.2013.150

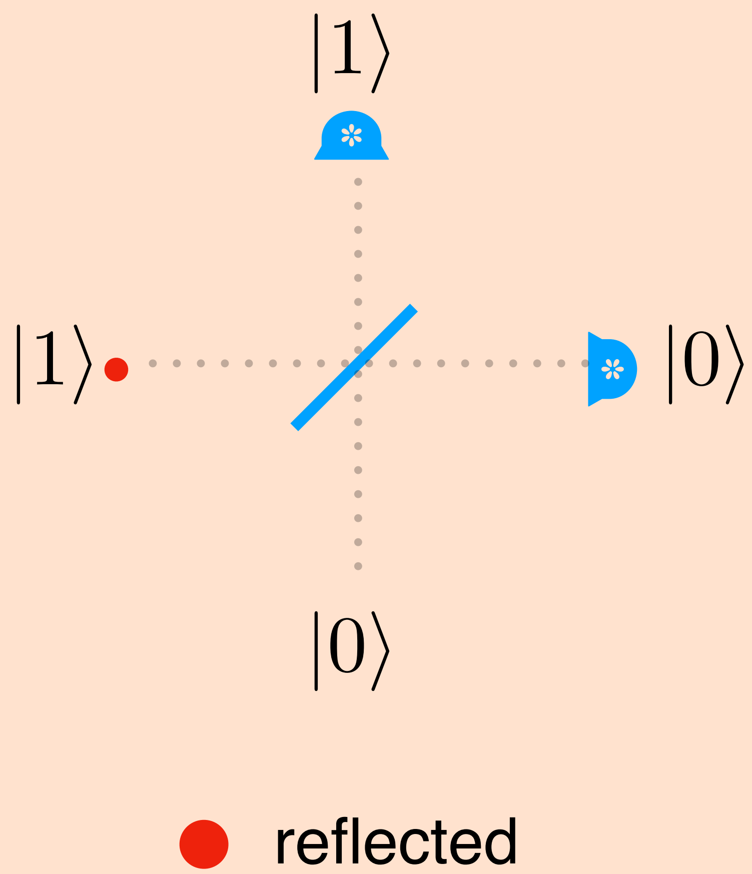
Quantum interference in plasmonic circuits

Reinier W. Heeres*, Leo P. Kouwenhoven and Valery Zwiller



Single photon at a beam splitter



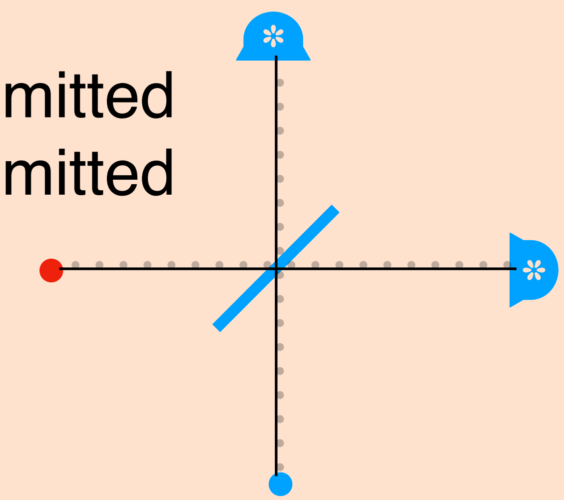


$$|1,0\rangle_{out} = \cos\theta\,|1,0\rangle + i\sin\theta\,|0,1\rangle$$

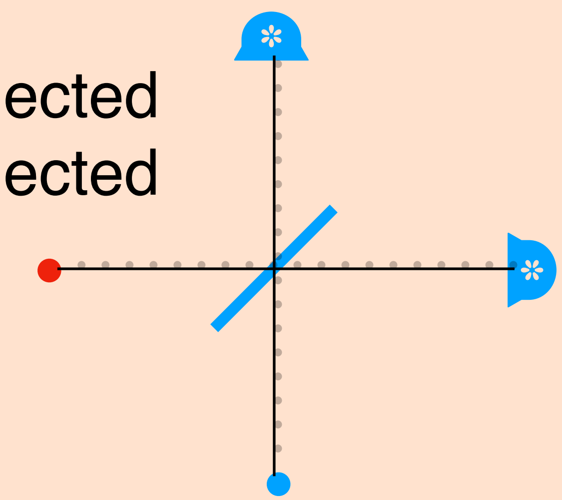
Two single photons at a beam splitter

signal ● idler ●

● transmitted
● transmitted

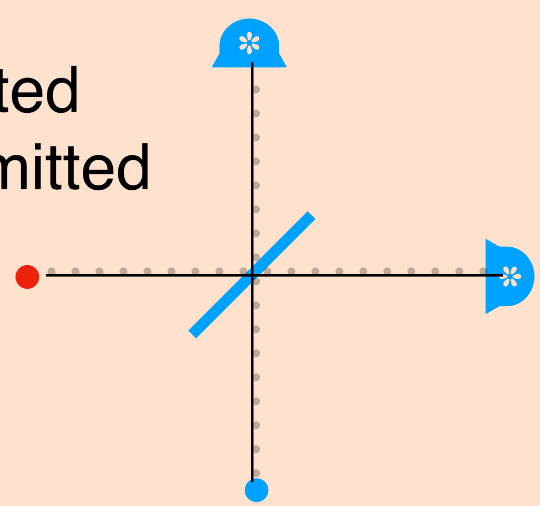


● reflected
● reflected

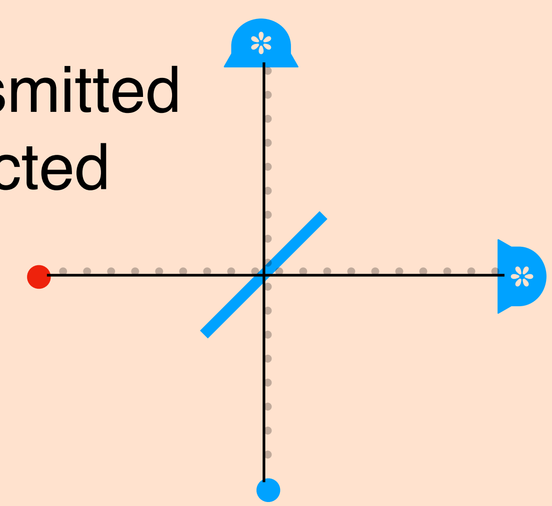


$$|1,1\rangle_{out} = (\cos^2\theta - \sin^2\theta)\,|1,1\rangle + \sqrt{2}i\cos\theta\sin\theta(|2,0\rangle + |0,2\rangle)$$

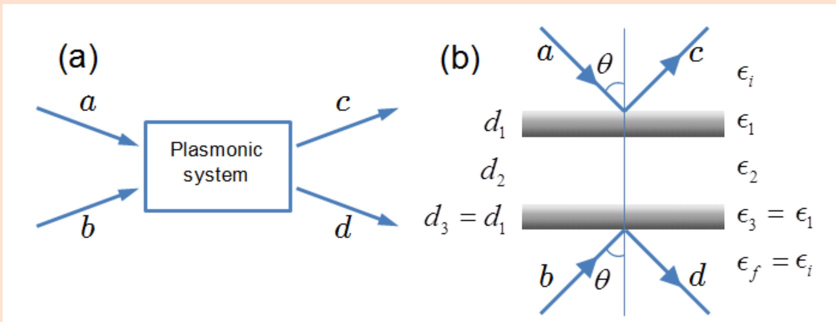
● reflected
● transmitted

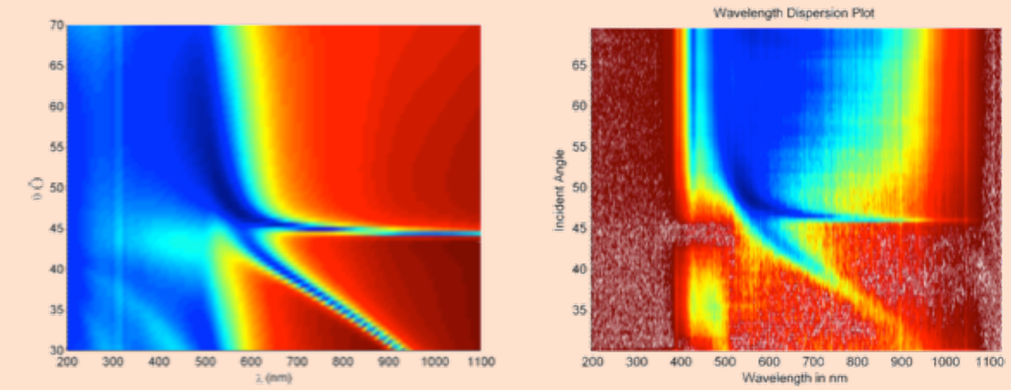


● transmitted
● reflected



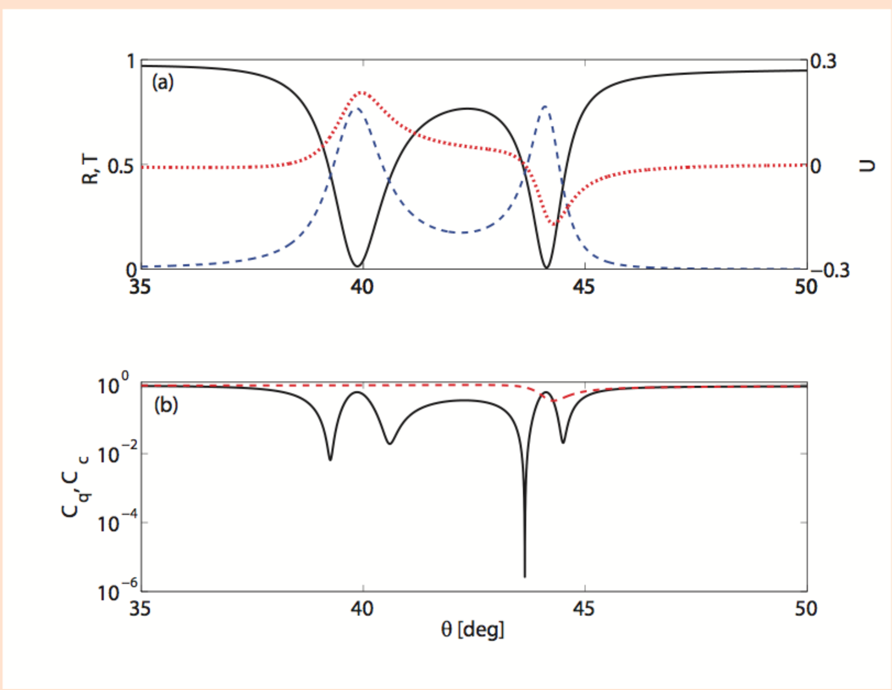
HOM setup with gap plasmons





theory Experiment

Expt: EPFL Lausanne

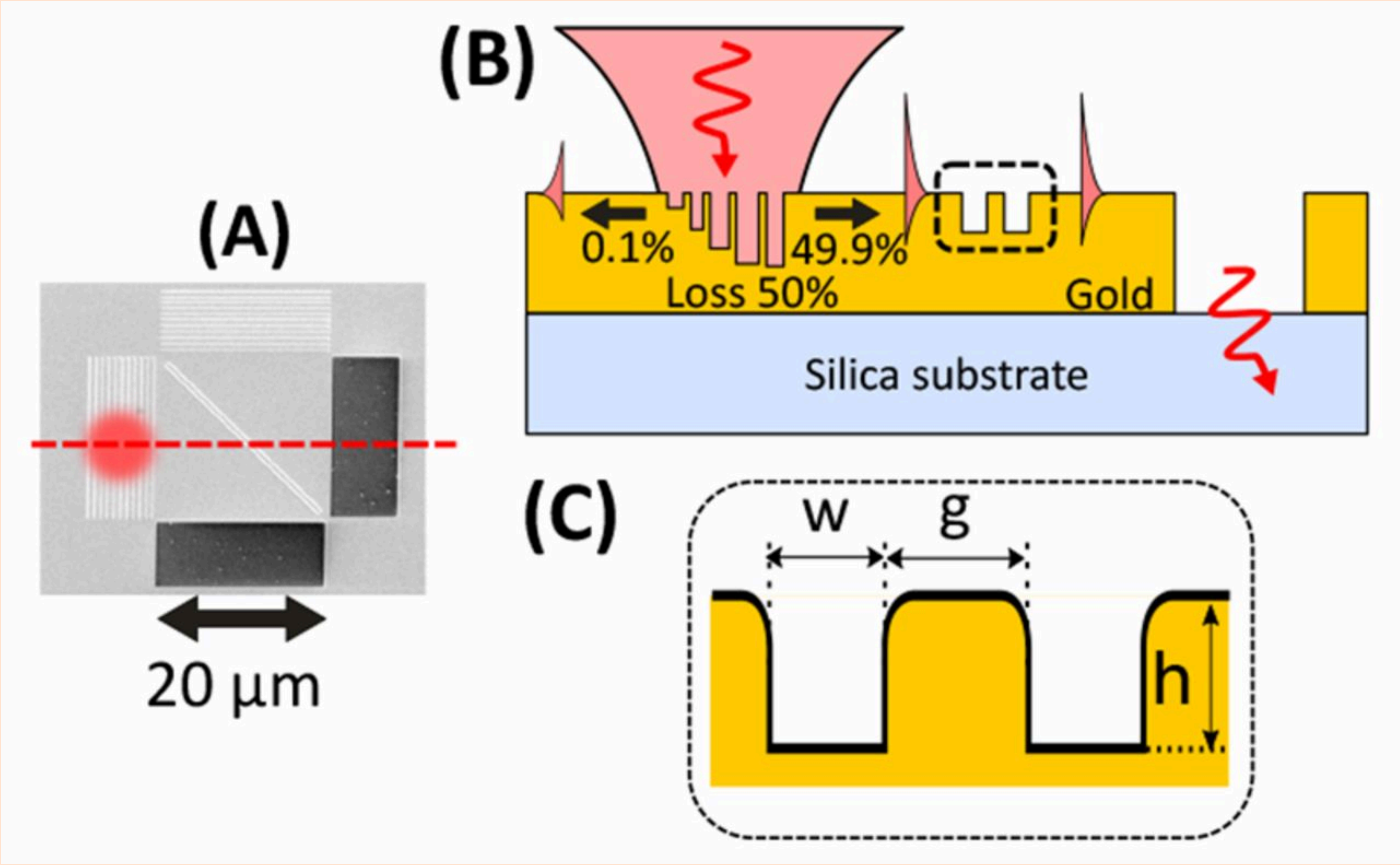


Perfect Interference with Visibility=1

SDG & GSA, Opt. Lett. 39, 390 (2014)

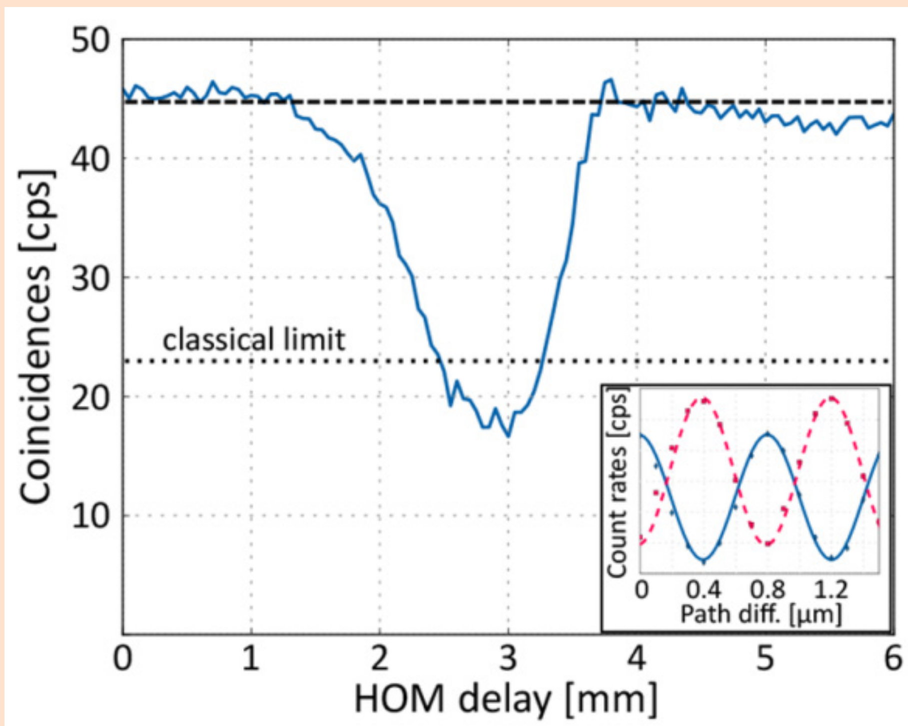
Two-photon quantum interference in plasmonics: theory and applications

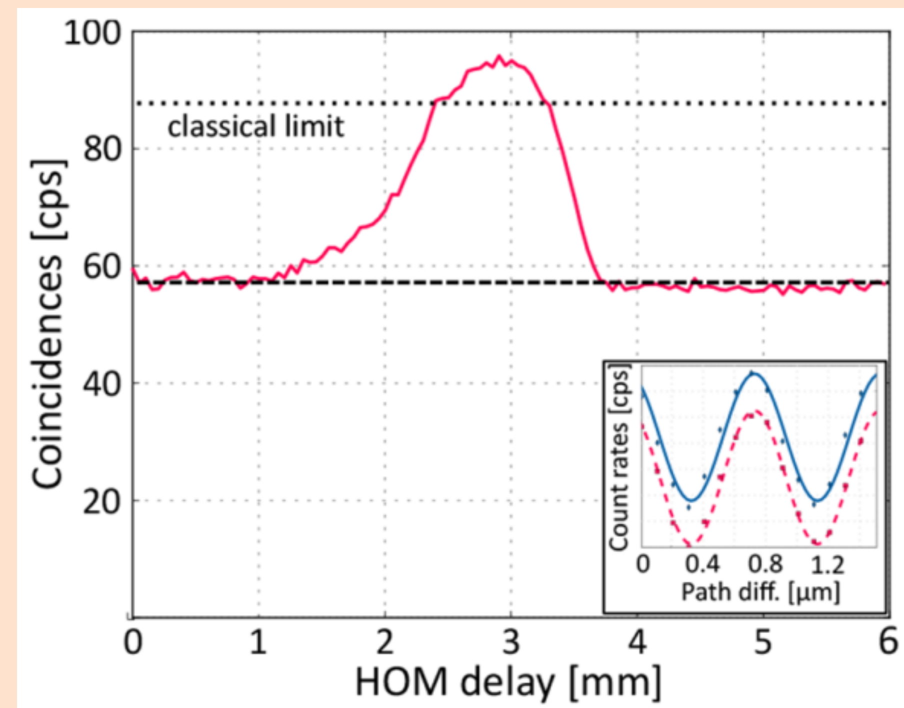
French expt: plasmonic chip



Photon coalescence and anti-coalescence

with two different beam splitters



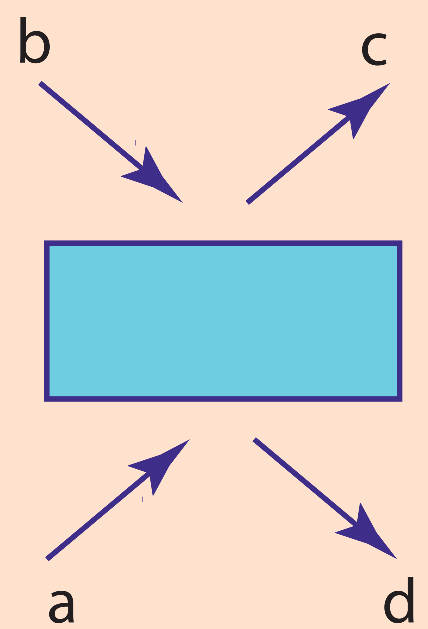


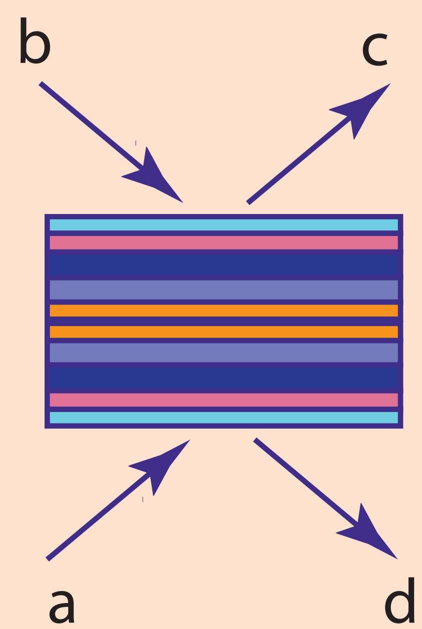
Important papers

Loudon, Fermion and boson BS statistics, Phys. Rev A58, 4904 (1998)

Barnett et al, Quantum optics of lossy BS, Phys. Rev A57, 2134 (1997)

Generalized beam-splitter as a 4-port system





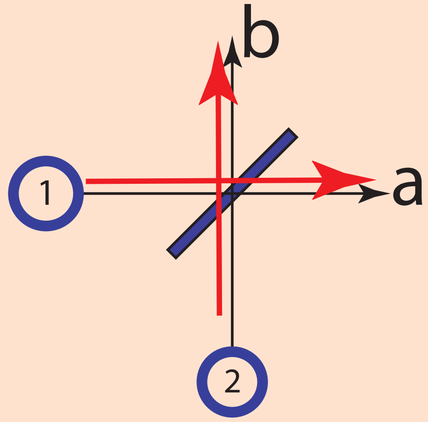
$$\begin{pmatrix} c \\ d \end{pmatrix} = \begin{pmatrix} t & r \\ r & t \end{pmatrix} \begin{pmatrix} a \\ b \end{pmatrix}$$

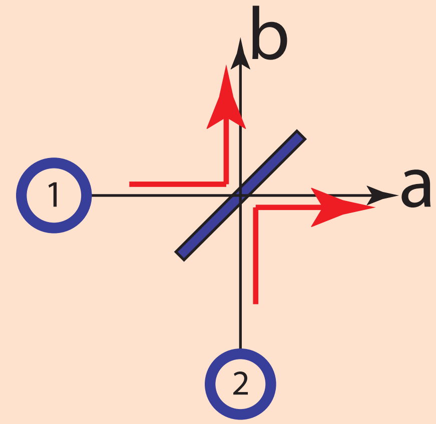
$$[c, c^\dagger] = [d, d^\dagger] = 1, \quad [c, d^\dagger] = 0$$

lossless: unitary $$|r|^2 + |t|^2 = 1, \quad rt^* + r^*t = 0$$

Symmetry and anti-coalescence

$|a\rangle_1\,|b\rangle_2$





$|b\rangle_1\,|a\rangle_2$

$$|\Psi_{spatial}\rangle = (1/\sqrt{2})(|a\rangle_1\,|b\rangle_2 \pm |b\rangle_1\,|a\rangle_2$$

Add polarization degrees of freedom

$$|\Psi_{pol}\rangle = (1/\sqrt{2})(|H\rangle_1\,|V\rangle_2 \pm |V\rangle_1\,|H\rangle_2)$$

$$|\Psi_{total}\rangle = |\Psi_{pol}\rangle \otimes |\Psi_{spatial}\rangle$$

$|\Psi_{total}\rangle$ symmetric for both $|\Psi_{pol}\rangle$ and $|\Psi_{spatial}\rangle$ antisymmetric

Symmetry and anti-coalescence - contd

Assume

1. nonpolarizing BS
2. detectors not sensitive to polarization

Consequence: Setup operates only on the spatial part

Output correlation can reveal anti-coalescence

Bosons can mimic Fermions

Criticality of phase relations

Lossless BS $$|r|^2 + |t|^2 = 1, \quad rt^* + r^*t = 0$$

$$t = \pm ir, \; \Delta\phi = \phi_r - \phi_t = \pm\pi/2$$

Lossy BS $$|t \pm r|^2 \leq 1$$

$$|t|^2 + |r|^2 \pm (rt^* + r^*t) \leq 1$$

$$\text{Absorption} = 1 - |\text{t}|^2 - |\text{r}|^2$$

Correlations: quantum vs classical

$$P(1_a, 1_b) = |t|^4 + |r|^4 + ((rt^*)^2 + (tr^*)^2)I$$

I overlap integral of individual wavepackets

$I = 0$ Classical $\qquad P_{cl}(1_a, 1_b) = |t|^4 + |r|^4$

$$I = 1$$

Coalescence

$t = \pm ir, \quad P(1_a, 1_b) = 0$

$\Delta\phi = \pm\pi/2$

HOM dip

Anti-coalescence

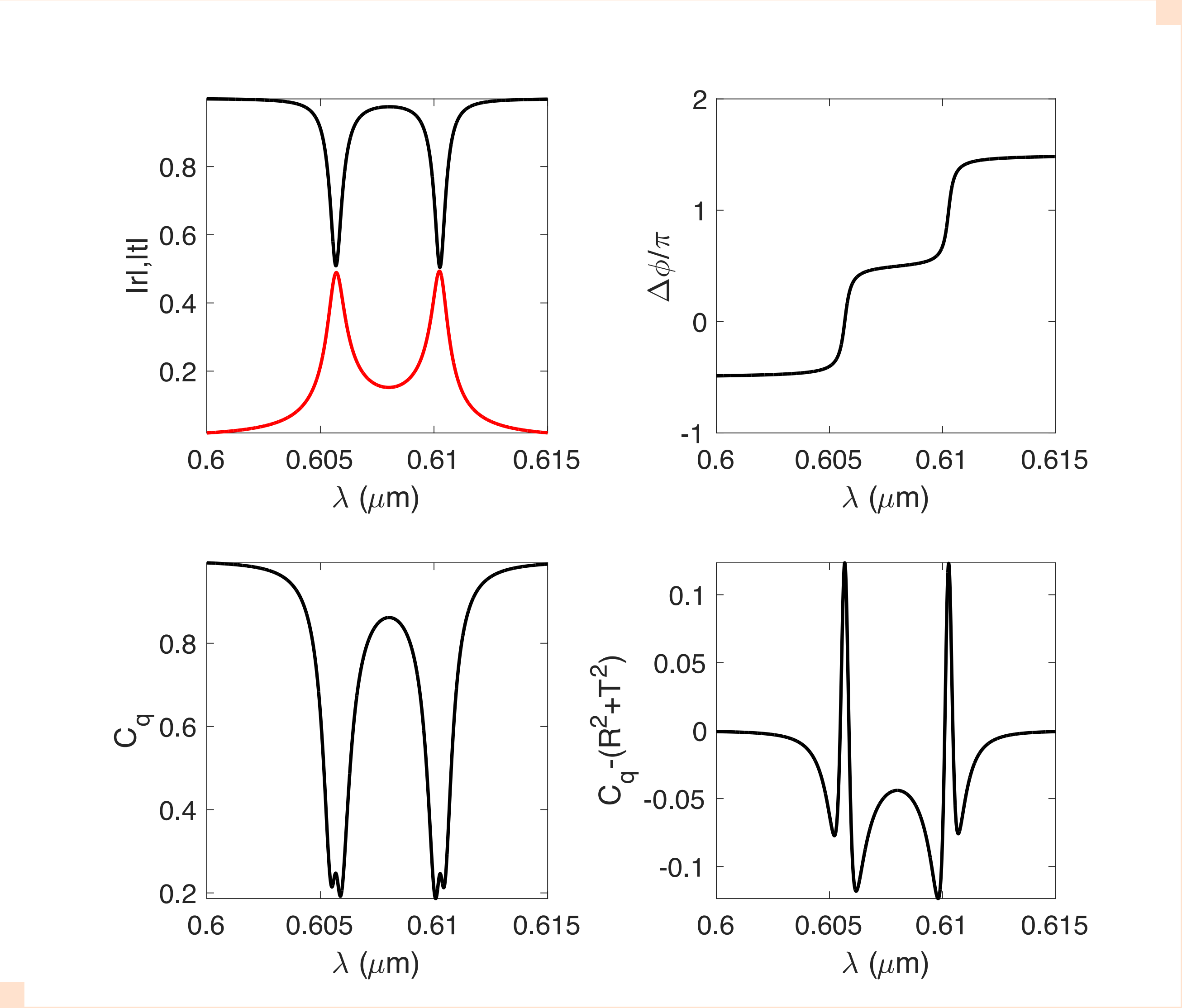
$t = \pm r \quad P(1_a, 1_b) = 2P_{cl}$

$\Delta\phi = 0, \ \pi$

HOM peak

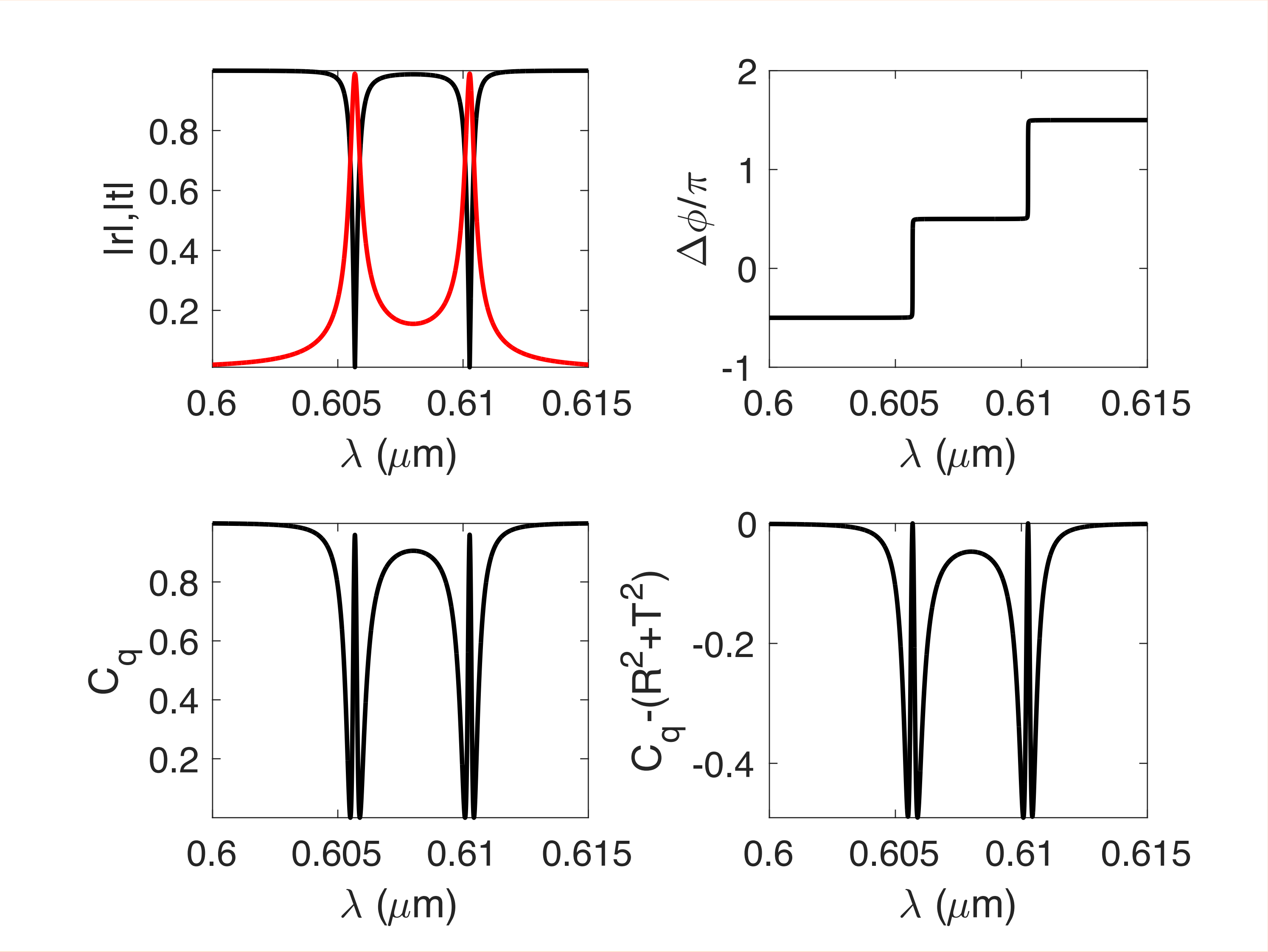
Coupled BSW

Higher losses: 0.001 i

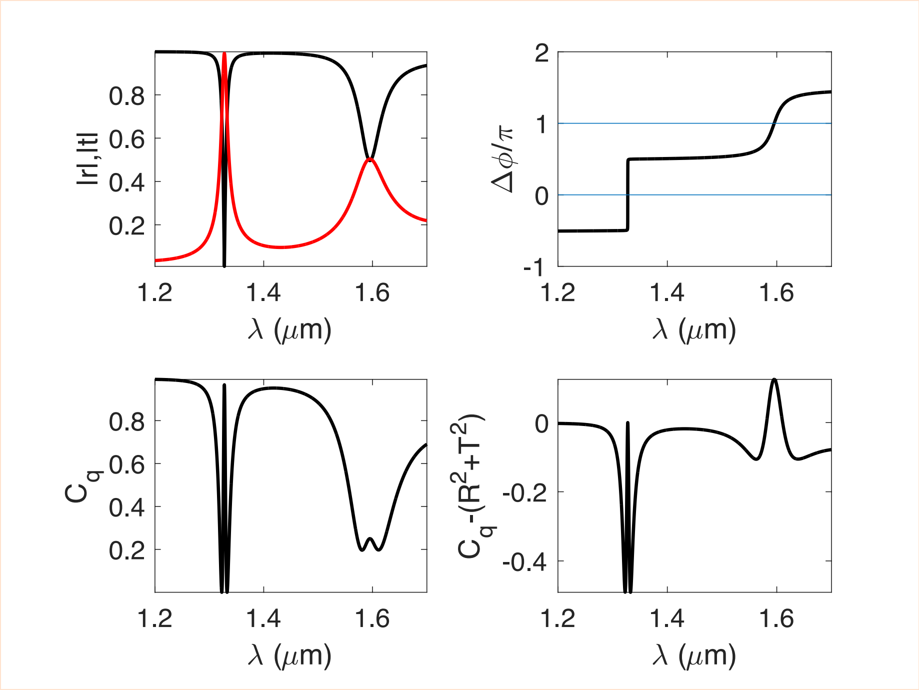


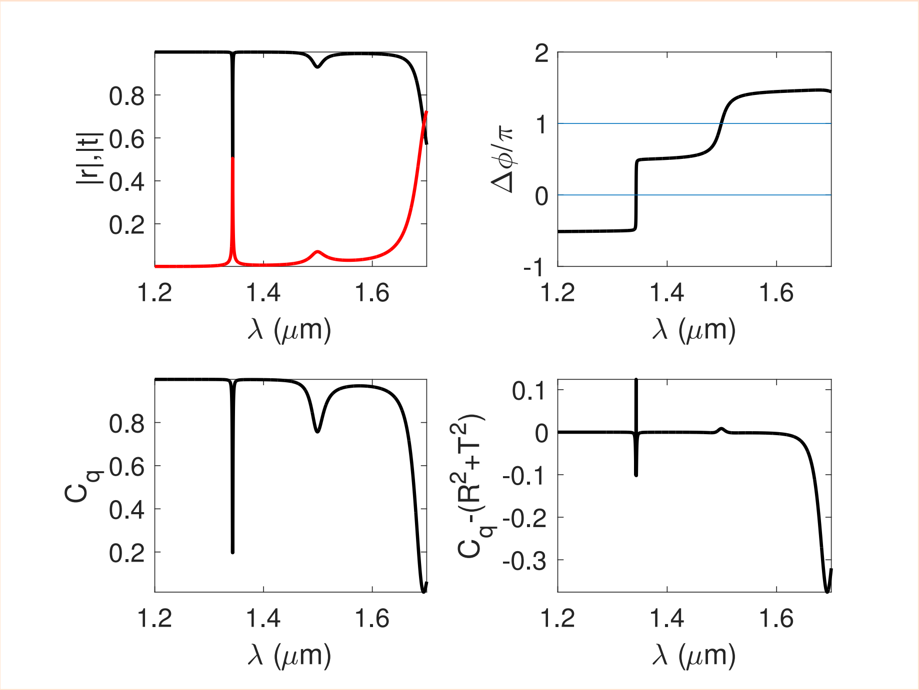
Coupled BSW

Lower losses: 0.00001 i



Coupled Tamm plasmons





Anti-coalescence
at the short range mode

Anti-coalescence
at the long range mode

Conclusions

- Highly dispersive plasmonic systems for quantum optics
- Novel plasmonic structures
- Flexibility with the Bloch surface waves and Tamm plasmons
- Ability to explore both photon coalescence and anti-coalescence in the same structure

Thank You