Tunable Meta-surfaces for Active Manipulations of Electromagnetic Waves

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Acknowledgements

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• **NSFC Shanghai Sci. Tech. Committee**
Outline

- Backgrounds and recent works in my group
- Complete phase diagram for metal/insulator/metal meta-surfaces (PRL, 2015)
- Graphene meta-surfaces for full-range phase control (PRX, 2015)
- Conclusions
What is Metamaterial?

- **In principle, nothing is homogeneous except vacuum.**
- **However, as structural unit << wavelength, a material is homogenized with effective \( \varepsilon, \mu \); A natural material is homogeneous for visible light**
- **Change natural atom to subwavelength microstructure, a Metamaterial is formed**
Metamaterials $\rightarrow$ Metasurfaces

- Bulk MTM goes to single-layer metasurface
- Inhomogeneity provides more freedom to control EM waves
1) Gradient meta-surfaces to bridge PW and SW

Generalized Snell’s law

\[ k_{\parallel}^r = \xi + k_0 \sin \theta_i \]

PW → SW conversion

S. Sun et al., Nat. Mater. 11, 426 (2012)

S. Sun et al., Nano Lett. 12, 6223 (2012)
Problems of the gradient coupler

- “Driven SW” flows on the “inhomogeneous” meta-surface
- Decouplings due to scatterings are inevitable
- Only works for small beam width

Q. Che et al., EPL 101, 54002 (2013)
New concept: Meta-coupler for high-efficiency SPP conversion

- **Transparent** gradient meta-surface: No reflection
- No x → -x symmetry, decoupling is forbidden
- More efficient to extract SPP

\[
\varepsilon_M(x) = \mu_M(x) = 1 + \frac{\xi x}{k_0 d_M}
\]

\[
k_{\parallel} = \xi + k_0 \sin \theta_i
\]
Meta-coupler is the best, several times higher than others;

Working bandwidth: 8.8-9.5 GHz;
SPP excitation efficiency: Measured vs FDTD

→ 73% efficiency (Expt.)

→ Match well with FDTD (75%).

2) Spin-dependent meta-surfaces for 100%-efficiency PSHE

Case 1: Symmetrical

Case 2: Asymmetrical

\[ r_{uu} + r_{vv} = r_{uv} - r_{vu} = 0 \]

Half-wavelength plate

- Establish a criterion to realize 100%-efficiency PSHE
- Experimentally demonstrated in microwaves

1) Tailor the functionalities of meta-surfaces based on a complete phase diagram

2) Toward full-range phase modulation with gate-controlled graphene meta-surfaces
What is Metal/Insulator/Metal Metasurface?

MIM Meta-surface can control reflectance and phase on resonance.
Applications 1: Reflectance Modulation

Perfect absorption

N. I. Landy, et. al.
PRB 78, 241103(2008)

Perfect absorption

JM Hao et. al.
APL 96 251104 (2010)
Na Liu, et. al.
NL 10, 2342(2010)

Color Printing

Alexander S. Roberts, et. al.
Nano Lett. 14, 783 (2014)

Active modulation

Yu Yao, et. al.
Nano Lett. 14, 6526 (2014)

MIM metasurface triggers many applications through reflectance modulation
Application 2: Phase Modulation

**polarization control**

J.M. Hao, et. al.
PRL. 99, 063908 (2007)

**anomalous reflection**

S.L. Sun, et. al.
Nat Mater 11, 426-431(2012)

**holograms**

Wei Ting Chen, et. al.

**flat-lens focusing**

Anders Pors, et. al.
Nano Lett. 13, 829 (2013)

MIM metasurface triggers many applications through phase control
Motivations

Reflectance modulation

Na Liu, et. al.
*Nano Lett.* 10, 2342(2010)

Phase modulation

S.L. Sun, et. al.
*Nat Mater* 11, 426-431(2012)

- Why and when certain functionality?
- Guidelines for designing MIM metasurfaces with desired functionalities
Coupled-mode theory for MIM metasurface

Coupled mode theory:
\[
\begin{align*}
\frac{\partial}{\partial t} \psi &= (-i \omega_0 - \frac{1}{\tau_a} - \frac{1}{\tau_r}) \psi + \sqrt{\frac{2}{\tau_e}} \cdot 1 \\
r &= \sqrt{\frac{2}{\tau_e}} \cdot \psi + r_0 \cdot 1
\end{align*}
\]

Response:
\[
r = -1 + \frac{1}{Q_r} \left( \frac{1}{i(1 - \omega/\omega_0) + 1/2Q_a + 1/2Q_r} \right)
\]
\[
Q_i = \frac{\tau_i \omega_0}{2}
\]


CMT model describes response through lumped $Q_r$ and $Q_a$. 
Coupled-mode analyses: Generic phase diagram

The competitions between two $Q$ factors generate a variety of physical effects.
Coupled-mode analysis on MIM metasurface

Question: what determines Q factors?

\[ r = -1 + \frac{1/Q_r}{i(1 - \omega/\omega_0) + 1/2Q_a + 1/2Q_r} \]

Perfect absorption

Under-damped \( Q_r < Q_a \)

Over-damped \( Q_r > Q_a \)
Mode-expansion theory: Analytical results

Ma et al, PRB (2016) to appear

Conditions:
- Subwavelength: $d \ll \lambda$
- Thin-slit: $a \ll d$

\[
\begin{align*}
\rho_0 + \delta_{0,0} &= S_0^{(1,2)} [a_0^+ + a_0^-] \\
S_0^{(2,1)} Y_0^{I} &\left[ \rho_0 - \delta_{0,0} \right] = Y_0^{II} [a_0^+ - a_0^-] \\
c_m^+ + c_m^- &= S_m^{(3,2)} [a_0^+ + a_0^-] \\
\sum_m S_m^{(2,3)} Y_m^{III} [c_m^+ - c_m^-] &= Y_0^{II} [a_0^+ - a_0^-] \\
c_m^+ \exp(-ik_{m,z} h) + c_m^- \exp(ik_{m,z} h) &= 0
\end{align*}
\]

Resonance freq. & Q of MIM metasurfaces analytically obtained
Analytical expressions for \( Q \) factors

**\( Q_r \) factor:**

\[
Q_r = \frac{2\pi \omega \langle U \rangle_{cavity}}{\langle P \rangle_{radia}}
\]

\[
Q_r = \frac{1}{k_0 h} \cdot F(a,d)
\]

**\( Q_a \) factor:** (perturbation)

\[
Q_a = \frac{2\pi \omega \langle U \rangle_{cavity}}{\langle P \rangle_{absorb}}
\]

\[
Q_a = \frac{\text{Re}(\varepsilon)hd}{\alpha \text{Im}(\varepsilon)hd + \beta (2d-a) \cdot \delta_{eff}}
\]

Concrete expressions of \( Q \) factors are obtained.
Tailor MIM Metasurface Through Structural/Material Tuning

- **Response:**

\[
    r = -1 + \frac{1}{Q_r} \cdot \frac{1}{i(1 - \omega/\omega_0) + 1/2Q_a + 1/2Q_r}
\]

- **\(Q_r\) factor:**

\[
    Q_r = \frac{1}{k_0h} \cdot F(a,d)
\]

- **\(Q_a\) factor:**

\[
    Q_a = \frac{\text{Re}(\varepsilon)hd}{\alpha \text{Im}(\varepsilon)hd + \beta(2d-a)\delta_{\text{eff}}}
\]
Tailor MIM Metasurfaces via tuning $h$

- $Q_r$ factor:
  \[ Q_r = \frac{1}{k_0 h} \cdot F(a,d) \]

- $Q_a$ factor:
  \[ Q_a = \frac{\text{Re}(\varepsilon) h d}{\alpha \text{Im}(\varepsilon) h d + \beta (2d - a) \cdot \delta_{\text{eff}}} \]

Critical parameter

Tuning $h$ can dramatically change the property of a metasurface.
Tailor MIM metasurfaces via tuning $a$

- $Q_r$ factor:
  \[ Q_r = \frac{1}{k_0 h} \cdot F(a,d) \]
- $Q_a$ factor:
  \[ Q_a = \frac{\text{Re}(\varepsilon)hd}{\alpha \text{Im}(\varepsilon)hd + \beta(2d-a) \cdot \delta_{\text{eff}}} \]

Critical parameter

Tuning $a$ can change the property of a metasurface
Tailor MIM Metasurfaces via tuning material loss

- \( Q_r \) factor:
  \[
  Q_r = \frac{1}{k_d h} \cdot F(a,d)
  \]

- \( Q_a \) factor:
  \[
  Q_a = \frac{\text{Re} (\varepsilon) h d}{\alpha \text{Im} (\varepsilon) h d + \beta (2d - a) \cdot \delta_g}
  \]

Tune dielectric loss:

Gate-controlled graphene:

Tuning material can dramatically change the property of a metasurface
Extension to General Situations

- $Q_r$ factor:
  \[ Q_r = \frac{1}{k_0 h} \cdot R \text{(shape)} \]

- $Q_a$ factor:
  \[ Q_a = \frac{\text{Re}(\varepsilon)hd}{\alpha \text{Im}(\varepsilon)hd + \beta \cdot S_{\text{metal}} \cdot \delta_{\text{eff}}} \]

- $h$ increase: $Q_r \downarrow$, $Q_a \uparrow$
- $l$ increase: $Q_r \sim C$, $Q_a \downarrow$
- $w$ increase: $Q_r \downarrow$, $Q_a \sim C$

THz experiments verification:

Tuning can be extended to a general 2D metasurface
Re-interpreting previous works with our phase diagram

Phase-modulation
Polarization control
Gradient MS

Perfect absorbers
Conclusions

- Response:

\[ r = -1 + \frac{1/Q_r}{i(1 - \omega/\omega_0) + 1/2Q_a + 1/2Q_r} \]

- \( Q_r \) factor:

\[ Q_r = \frac{1}{k_0h} \cdot F(a,d) \]

- \( Q_a \) factor:

\[ Q_a = \frac{\text{Re}(\varepsilon)hd}{\alpha \text{Im}(\varepsilon)hd + \beta (2d - a) \cdot \delta_{\text{eff}}} \]

Guidelines for designing metasurfaces with desired functionalities: Perfect absorption, Phase modulation, Active control …

1) Tailor the functionalities of metasurfaces based on a complete phase diagram

2) Toward full-range phase modulation with gate-controlled graphene metasurfaces
Background: Why need phase control?

Fermat-Huygens law:  
*Phase distribution on a certain plane determines the far-field radiation  
Refraction, polarization control, hologram …*
How to realize phase control?

Conventional techniques: Gradient-index natural materials or MTMs:

*Bulk effect, difficult for photonics integration*


Meta-surfaces: full-range phase control in deep-subwavelength regime

Anomalous refractions
Vortex generations,

All these are passive!

Wide-band, optical regime

High-efficiency meta-holograms
Available active phase modulations

<table>
<thead>
<tr>
<th>Material</th>
<th>Type</th>
<th>Modulation depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs:Si</td>
<td>doped</td>
<td>3%</td>
</tr>
<tr>
<td>Al_{0.3}Ga_{0.7}As:Si</td>
<td>n = 1.4x10^{18} cm^{-3}</td>
<td>3%</td>
</tr>
<tr>
<td>Al_{0.3}Ga_{0.7}As</td>
<td>undoped</td>
<td></td>
</tr>
<tr>
<td>GaAs</td>
<td>undoped</td>
<td></td>
</tr>
<tr>
<td>Si GaAs</td>
<td>undoped</td>
<td></td>
</tr>
</tbody>
</table>


Limited phase modulations far from *full-range control*, even enhanced by MTM.
Using graphene – an atomic-thin material with great tunability?


Great tuning capability, loss --- low Q factor

Far away from full-wave control!


Combined with MTM: Tuning phase with 32.2 degrees
Our motivations

Realize *active* and *full-range* phase control with gate-controlled graphene *meta-surface*
Our structure
Graphene + Meta-surface

- Combining Graphene with reflective meta-surface
- Working at THz domain
- The transmission port is blocked --- crucial!
- Top-gating graphene using Ion-Gel
Graphene identification and TDS-THz measurements
Amplitude/phase modulation (Expt.)
– e-doping

Reference:
Spectrum with highest n
Essentially featureless

±180 degrees of phase modulation

- As voltage increases, reflection amplitudes first decreases to 0, then increases to 1
- Phase behaviors change from a magnetic (~360 variation) to electric (<180) resonance
- Phase modulation covering ±/− 180 degrees
Amplitude/phase modulation (Expt.) -- hole doping

- Symmetrical behaviors compared to e-doping
- Slight asymmetry caused by band-structure deviations
Two slightly different pixels lead to full-range phase modulation at a frequency interval. Previous mechanism can never work, due to intrinsic limitations.
Complete phase diagrams (Expt.) --- different spacers

- Critical point determined by structure geometry
- Some system does not support critical transition
• Why can we achieve full-range phase modulation?

• Why previous system can not?

• What’s the role played by graphene?
The temporal coupled mode theory (Fan, 2003)

\[ \frac{da_m}{dt} = (-if_0 - \Gamma_{mi} - \Gamma_{ms})a_m + \sum_n k_{m,n}S_{m,n}^+ \]

\[ S_{m,n}^- = c_{m,n}^s S_{m,n}^+ + c_{m,n}^a a_m \]

Single resonance

Single port

\[ r = \frac{\Gamma_r - \Gamma_i}{\Gamma_r + \Gamma_i}, \quad f = f_0 \]

- Different damping parameters yield different phase behaviors!
- Whether or not enclosing origin determines the phase variation range!
Generic phase diagram

Typical behaviors in 3 regions (Reference: gold)

• Under-damped resonator: 360 variation
• Over-damped resonator: < 180 variation
• Critical coupling: Perfect absorber

Tuning the ratio $\Gamma_s / \Gamma_i$ tune the system dramatically

Qu, PRL 115 235503 (2015)
Role of graphene upon gating
(Fitting FDTD with CMT)

Effects of gating graphene:
1) increasing $\Gamma_i$
2) has little effect on $\Gamma_r$
3) drives the system to transit from an under-damped to an over-damped resonator

Gating graphene breaks the subtle balance between intrinsic and radiation losses!
Remaining puzzles:

1) Why some of our systems cannot?
2) Why previous systems fail?

Do we have a general design guideline?
1) Why small-spacer one does not work?

- Smaller $d$, stronger near-field coupling, higher Q, smaller $\Gamma_r$
- Already in over-damped region even with graphene
- Graphene can only make it even more over-damped, no critical transition
2) Why previous one cannot cover full range?

- Two-ports system has no critical coupling
- Always E-resonance, can never be M-type!

An application: an active polarizer

Only x polarized wave are modulated strongly
Tuning the polarization actively

Polarization state strongly tuned by gate voltage

Conclusions

• Based on a complete phase diagram, we can easily tailor the functionalities of MIM metasurfaces.

• Combining graphene with meta-surface, we can realize active full-range phase modulation in deep-subwavelength regime

W. Sun et al., Light: Science & Applications 5, 16003 (2016)
Thanks & Questions?