Higher-order resonances in single-arm nanoantennas: Evidence of Fano-like interference

FANO PLASMONICS MADE SIMPLE

F. López-Tejeira, R. Paniagua-Domínguez, R. Rodríguez-Oliveros

José A. Sánchez-Gil,
Instituto de Estructura de la Materia (CSIC), Madrid (Spain)
Email: j.sanchez@csic.es
Motivation: Fano in Plasmonics

Fano-like plasmon resonances on a variety of complex nanostructures

Nano-disk-rings, nanodolmens, nanoclusters, ...

Luk’yanchuk, Zheludev, Maier, Halas, Nordlander, Giessen, Chong, Nat. Mater. 2010

(Q_{sca}) SINGLE NANO PARTICLES

TNT 2011, Tenerife (Spain)
Outline

• Introduction: Plasmon Fano reso/single-NP
• Nano-Spheroid
  – Quasi-analytical approach: Mode interference
• Nano-rods & nano-wires
  – Numerical calcs
  – 1st-3rd mode: Spatial interference
• Conclusions:
  Spectral & spatial overlap
Outline

• Introduction: Plasmon Fano reso/single-NP Why not?
• Nano-Spheroids
  – Quasi-analytical approach: Mode interference
• Nano-rods & nano-wires
  – Numerical calcs
  – 1st-3rd mode: Spatial interference
• Conclusions:
Spectral & spatial overlap
Introduction: Fano resonances

A Fano resonance exhibits a distinctly asymmetric shape with the following functional form:

$$\frac{(F\gamma + \omega - \omega_0)^2}{(\omega - \omega_0)^2 + \gamma^2}$$

where $\omega_0$ and $\gamma$ are standard parameters that denote the position and width of the resonance, respectively; $F$ is the so-called Fano parameter, which describes the degree of asymmetry. The microscopic origin of the Fano resonance arises from the constructive and destructive interference of a narrow discrete resonance with a broad spectral line or continuum.


Miroshnichenko, Flach, Kivshar, Rev. Mod. Phys. 2010
**Introduction: Fano resonances**

Plasmon-Fano model

Giannini, Francescato, Amrania, Phillips, Maier, Nano Lett. 2011

![Plasmon-Fano model diagram](image-url)
Introduction: Fano resonances

**PLASMONICS: SPHERE ➔ Mie scattering**

**Figure 2**

BROAD mode (Lowest-order, E-Dipole)
DARK mode (Higher-order, EM Multipole)

\[
Q_{sca} = \frac{2}{q^2} \sum_{n} (2n + 1) |a_n|^2 + |b_n|^2
\]

\[Q_{sca} \text{ Mie ➔ NO INTERFERENCE!!} \]

Luk’yanchuk, Zheludev, Maier, Halas, Nordlander, Giessen, Chong, Nat. Mater. 2010

TNT 2011, Tenerife (Spain)
Outline

• Introduction: Plasmon Fano reso/single-NP
• Nano-Spheroids
  – Quasi-analytical approach: Mode interference
• Nano-rods & nano-wires
  – Numerical calcs
  – 1\textsuperscript{st}-3\textsuperscript{rd} mode: Spatial interference
• Conclusions:
  Spectral & spatial overlap
**Fano LSPR/Nanospheroid**

Longitudinal plasmon resonances  
Normal incidence: odd-symmetry modes

**Modified Fano line shape**

\[ Q_{\text{ sca}}(\omega) \propto A(\omega) + B \left[ \frac{b_1}{(\omega - \omega_1) + i b_1} + \frac{Fb_3}{(\omega - \omega_3) + i b_3} \right]^2 \]

López-Tejeira, Rodriguez-Oliveros, Paniagua-Domínguez, Sánchez-Gil, preprint

TNT 2011, Tenerife (Spain)
Fano resonances/Nanospheroid

Longitudinal plasmon resonances
Oblique incidence: all modes n=1,2,3,...

Fano line-shape + Lorentzian
N=1,3 + N=2

\[ Q_{sc}(\omega, \alpha \neq 90^\circ) \approx |f(\omega)|^2 + \frac{|B_2|^2 b_2^2}{b_2^2 + (\omega - \omega_2)^2} \]

López-Tejeira, Rodríguez-Oliveros, Paniagua-Domínguez, Sánchez-Gil, preprint

TNT 2011, Tenerife (Spain)
Longitudinal plasmon resonances

Oblique incidence: all modes n=1,2,3,...

\[ 2_{sca} = \frac{4}{LDk_d^2} \left\{ 2 \sum_l \sqrt{l(l+1)} |b_l^{(1)}|^2 N_l^2(c_d) + \text{Re} \sum_{l=1}^{\infty} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} i^{n-l} \left[ k_d a_{ml}^{(d)} (a_{mn}^{(d)})^* (c_d, c_d) + ik_d \left( b_{ml}^{(d)} (b_{mn}^{(d)})^* (c_d, c_d) - a_{ml}^{(d)} (b_{mn}^{(d)})^* (c_d, c_d) \right) + b_{ml}^{(d)} (b_{mn}^{(d)})^* (c_d, c_d) N_{ml} (c_d) N_{mn} (c_d) \right] \right\} \]

Mie-like: NO INTERFERENCE

Ext-Mie: INTERFERENCE

López-Tejeira, Rodríguez-Oliveros, Paniagua-Domínguez, Sánchez-Gil, preprint

TNT 2011, Tenerife (Spain)
Fano resonances/Nanospheroid

- Plasmon Fano reso/single-Nano-Spheroids
- Quasi-analytical approach: Mode interference
  - Odd modes: 1\textsuperscript{st}-3\textsuperscript{rd} interference
  - Even-odd modes: 1\textsuperscript{st}-2\textsuperscript{nd} NO interference
- Explore other single NP geometries
Outline

• Introduction: Plasmon Fano reso/single-NP
• Nano-Spheroids
  – Quasi-analytical approach: Mode interference
• Nano-rods & nano-wires
  – Numerical calcs
  – 1\textsuperscript{st}-3\textsuperscript{rd} mode: Spatial interference
• Conclusions:
  Spectral & spatial overlap

TNT 2011, Tenerife (Spain)
**Fano resonances/Nanorod**

**Longitudinal L-pλ/2 resonances**

Oblique incidence: all modes n=1,2,3,...

\[ \omega_{\text{res}}^{(1)} = 0.45563 \text{ eV} \]

\[ \omega_{\text{min}} = 1.12139 \text{ eV} \]

\[ \omega_{\text{res}}^{(2)} = 1.19918 \text{ eV} \]

FEM-COMSOL

López-Tejeira, Rodríguez-Oliveros, Paniagua-Domínguez, Sánchez-Gil, preprint

TNT 2011, Tenerife (Spain)
Fano-like LSPR/Nanowire

Nanowire (~2D Nanorods)
Longitudinal $L=n\lambda_{\text{eff}}/2[1-R]$ resonances
Normal incidence: odd modes

$n=1$ (HW) ► Broad, Bright
$n=3,5,...$ (HW) ► Narrow, Dark

2DSIE

Modified Fano line-shape fit
Fano resonance/Nanowire

Spatial Mode Interference

López-Tejeira, Rodriguez-Oliveros, Paniagua-Domínguez, Sánchez-Gil, preprint

TNT 2011, Tenerife (Spain)
Outline

- Introduction: Plasmon Fano reso/single-NP
- Nano-Spheroids
  - Quasi-analytical approach: Mode interference
- Nano-rods & nano-wires
  - Numerical calcs
  - $1^{st}$-$3^{rd}$ mode: Spatial interference
- Conclusions:
  Spectral & spatial overlap
Conclusions

► Fano-like LSPR on a single nanorod

► Spectral & Spatial overlap

Explore new physics & configurations

► Applications: Fano made simple!!

Plasmonics, Nanophotonics, Metamaterials, ...EM

Sensing, lasing, switching, NL optics,...
Acknowledgements

Coworkers

Instituto de Estructura de la Materia (CSIC), Madrid (Spain)

Rogelio Rodríguez-Oliveros

Ramón Paniagua-Domínguez

Fernando López-Tejeira
Acknowledgements

Funding agencies

TNT 2011, Tenerife (Spain)
...Thank you