Quasi-localized coupled-cavity modes in Deterministic Aperiodic Nano Structures: theory and applications

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Outline

- **DANS**: between random & periodic
  - Construction and classification
  - Bandgap formation
  - Light localization

- **Applications**
  - Optical sensors
  - Radiative rate & emission pattern manipulation
  - Microlasers
  - Plasmonics
Random media

Random scattering
Anderson localization

non-reproducible
design rules cannot be defined

Picture courtesy of H. Cao (Yale Univ)
Periodic photonic crystals

Bragg scattering
Photonic bandgap formation
Light localization in defects

reproducible
well-defined design rules exist
Deterministic structures

periodic
Deterministic structures

- Periodic
- Aperiodic

- Rudin-Shapiro
- Fibonacci
- Penrose
- Co-prime

& many more …
Deterministic aperiodic nanostructures

Photonic bandgap formation
Light localization

can be reproducibly engineered & optimized
higher design flexibility

Local density of states

Frequency, $a/\lambda$

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Local Density of States (LDOS) is to be calculated to study radiation dynamics of emitters embedded in APS:

\[
\rho(\vec{r}; \omega) = -\frac{2\omega}{\pi c^2} \text{Im}\left\{G(\vec{r}, \vec{r}; \omega)\right\}
\]

Green’s function

A.A. Asatryan, et al, PRE (2001)

no global symmetries \rightarrow conventional methods are inefficient

- Coupled dipole approximation
- Boundary Integral Equations

Circular rods: Generalized Mie theory (multipole expansion method):

- all optical interactions within the structure are taken into account
- high-order multipoles are included in the analysis
- superior speed and accuracy

S.V. Boriskina, JOSA B 23, 1565 (2006)
Fibonacci

\[ A \rightarrow AB, \ B \rightarrow A \]

\[ A, \ B, \ AB, \ BAB, \ ABBAB, \ BABABBAB \]

multi-layer dielectric stack

metal nanoparticle chain

E. Macia, Phys. Rev. B., 63, 205421 (2001)
Fibonacci

Gen1: $A ightarrow AB$

Gen2: $AB ightarrow ABA$

Gen3: $BA ightarrow BAB$


DANS classification: reciprocal lattice

Bloch-wave like

- Fibonacci
- δ-like Bragg peaks

Anderson-wave like

- T-M structure
- Singular continuous
- Random
- Absolutely continuous

DANS classification

1D

- Bloch-wave like
  - Fibonacci
  - δ-like Bragg peaks
  - T-M structure
  - Singular continuous
  - Random
  - Absolutely continuous

Anderson-wave like

2D

- Periodic: discrete
- Fibonacci: quasi-periodic
- Thue-Morse: singular-continuous
- Rudin-Shapiro: absolutely continuous (flat)

Optical spectra & localization

Periodic lattice

Reciprocal space (Fourier transform)

Local density of states

Frequency, $a/\lambda$

- $N_c = 36$
- $N_c = 100$
- $N_c = 256$

Dielectric rods $r/a = 0.2$, $\varepsilon = 10.5$

Band-edge modes
Optical spectra & localization

Thue-Morse lattice

Reciprocal space (Fourier transform)

singular-continuous

Quasi-localized critical modes

dielectric rods $r/a=0.2$, $\varepsilon=10.5$

Optical spectra & localization

Rudin-Shapiro lattice

Reciprocal space (Fourier transform)

Flat (=random structure)

Quasi-localized critical modes

Coupled-defect modes are pushed into the bandgap from below the dielectric band edge.

Coupled-cavity modes in DANS

Symmetrical (bonding)  

Anti-symmetrical (anti-bonding)

eigenmodes of different symmetry can be supported by coupled defects

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Fractal-like scaling of a critically-localized band-edge mode in a Thue-Morse structure
Modes scaling with structure size

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Scaling of a critically-localized mode in a Rudin-Shapiro structure

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Modes scaling with structure size

Scaling of a critically-localized mode in a Rudin-Shapiro structure
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Scaling of a localized mode in a Rudin-Shapiro structure
Modes scaling with structure size

Scaling of a localized mode in a Rudin-Shapiro structure
Modes scaling with structure size

Scaling of a localized mode in a Rudin-Shapiro structure
Nanofabricated nanopillar DANS

(a) Periodic, (b) Fibonacci, (c) Thue-Morse, (d) Rudin-Shapiro nanopillar arrays, spacing 400 nm.
Nanofabricated membrane DANS

Suspended Fibonacci structure, with 800nm holes and 400nm separation
Applications: biosensing

Trade-off between spectral resolution & sensitivity

Detection limit = resolution / sensitivity

the smallest measurable RI change
Applications: biosensing

Trade-off between spectral resolution & sensitivity

**Evanescent-wave microcavity sensors**

- Low sensitivity (poor overlap of evanescent field with analyte)
- High spectral resolution (ultra-narrow WG-mode linewidths)

Detection limit = resolution / sensitivity
the smallest measurable RI change


Yalcin et al, JSTQE (2006)

BU Department of Electrical & Computer Engineering
Applications: biosensing

Trade-off between spectral resolution & sensitivity

Detection limit = resolution / sensitivity
the smallest measurable RI change

Evanescent-wave microcavity sensors

- Low sensitivity (poor overlap of evanescent field with analyte)
- High spectral resolution (ultra-narrow WG-mode linewidths)


Yalcin et al, JSTQE (2006)

Surface plasmon resonance sensors


- High sensitivity (hot spots on particle surfaces)
- Low resolution (broad linewidths)
Traditional PhC sensors

band-edge modes

Mortgensen, Microfluid Nanofluid (2008)
Traditional PhC sensors

defect-localized mode

Lee & Fauchet, OPEX (2007)

band-edge modes

Mortgensen, Microfluid Nanofluid (2008)
Sensing with critical modes in DANS

dielectric rods
\( r/a = 0.2, \varepsilon = 10.5 \)
\( \lambda \sim 1550 \text{ nm} \)

many high-Q modes

Sensing with critical modes in DANS

Dielectric rods $r/a=0.2$, $\varepsilon=10.5$ $\lambda\sim1550$ nm

Many high-Q modes + higher sensitivity to ambient refractive index change

Analyte filling fraction:

$$f_h = \frac{\int \varepsilon_h |E(\mathbf{r})|^2 dV}{\int \varepsilon(\mathbf{r}) |E(\mathbf{r})|^2 dV}$$

Manipulation of radiation rates & patterns in DANS

dielectric rods $r/a=0.35, \ n=2.3$

Radiative rate enhancement in the structure center:

$$\rho/\rho_0 = 10.25$$

- Source emission pattern is shaped by the lattice symmetry & the optical mode pattern symmetry
- Aperiodic structures act as directional antennas

Beam-shaping with periodic PhC structures

line defects + surface tailoring

S.K. Morrison et al, APS 86, 081110 (2005)
Beam-shaping with periodic PhC structures

periodicity modification

L. Pajewski et al, PIER 80, 179 (2008)

line defects + surface tailoring

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line defects + surface tailoring

L. Pajewski et al, PIER 80, 179 (2008)

shape tailoring

**Directivity:**
the ratio of the intensity of light radiated in the main-beam direction $\phi_0$ to the intensity averaged over all directions.

$$D = 2\pi |\Phi(\varphi_0)|^2 \cdot \left(\int_0^{2\pi} |\Phi(\varphi)|^2 d\varphi\right)^{-1}$$
Emission directivity

Critically-localized modes in a Rudin-Shapiro structure provide directional emission
Applications: micro-lasers

Periodic

Altug & Vučković, OPEX (2005)

Random

Applications: micro-lasers

Periodic

Altug & Vučković, OPEX (2005)

Quasi-periodic


Random

Microlaser design challenges

- Trade-off between localization and radiative losses
- Collection efficiency (directional emission)
Trade-off between localization & losses

mode field patterns

\[ \frac{1}{Q} = \frac{1}{Q_\parallel} + \frac{1}{Q_R} \]

• band-edge modes Q-factors are limited by the in-plane losses

• defect-localized mode is leaky in the vertical direction

corresponding Fourier transforms

Circle: lossy region (light cone)
Trade-off between localization & losses

High-Q states design by momentum space engineering

Trade-off between localization & losses

High-Q states design by momentum space engineering


Natural balancing of radiative losses of delocalized modes in random structures

Optical confinement in aperiodic structures

extended character of modes in aperiodic structures balances the in-plane and out-of-plane radiation losses

Numerical simulation of lasing in a Rudin-Shapiro array. (a) Emission spectrum. (b) Emission intensity as a function of time, showing the buildup of laser oscillation above the lasing threshold. (c)-(f) Spatial intensity distribution of four lasing modes that appear in (a).

Picture courtesy of H. Cao (Yale Univ)
Plasmonic DANS

Wednesday, 28 Jan

Luca Dal Negro
Light scattering & localization in DANS
10:30 AM – 11:00 AM

Ashwin Gopinath
Aperiodic metal nanoparticle arrays for SERS
2:30 PM – 2:50 PM

Aperiodic photonic structures provide a large pool of high-Q optical modes with pre-determined spectral and spatial characteristics useful for:

- Light localization
- Radiative rate enhancement/suppression
- Emission pattern manipulation
- Label-free optical biosensing
Acknowledgments

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