International Workshop

The Neumann-Poincaré Operator, Plasmonics, and Field Concentrations

Feb. 8-10, 2018, Ramada Jeju Hamdeok Hotel, Jeju, S. Korea


LA MÉTHODE DE NEUMANN ET LE PROBLÈME DE DIRICHLET

PAR

H. POINCARÉ

Introduction.

Dans ce qui suivra je désignerai sous le nom de fonction harmonique toute fonction finie et continue ainsi que ses dérivées, satisfaisant à l'équation de LAPLACE et s'annulant à l'infini, de sorte que le problème de DIRICHLET peut s'énoncer ainsi:

Trouver une fonction ... dans un certain domaine prenant des valeurs données sur la frontière de ce domaine.

... méthodes qui donnent la solution de ce problème, nous distinguerons ... de NEUMANN qui est fondée sur les propriétés des ...

Acta mathematica. 20. Imprimé ... novembre 1895.

Invited speakers

Kazunori Ando (Ehime)
Eric Bonnetier (Grenoble)
Charles Dapogny (Grenoble)
Brian Fitzpatrick (ETH)
Johan Helsing (Lund)
Haigang Li (Beijing Normal)
Mikyoung Lim (KAIST)
Hongyu Liu (HK Baptist)
Graeme Milton (Utah)
Yoshihisa Miyanishi (Osaka)
Victor Nistor (Lorraine)
Karl-Mikael Perfekt (Reading)
Mihai Putinar (UC-Santa Barbara)
Faouzi Triki (Grenoble)
Sanghyeon Yu (ETH)
KiHyun Yun (HUFS)
Hai Zhang (HKUST)

Organizers

Habib Ammari
Eric Bonnetier
Hyeonbae Kang (Chair)
Mikyoung Lim
Graeme Milton
Mihai Putinar

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NRF National Research Foundation of Korea

International Workshop
The Neumann-Poincaré Operator, Plasmonics, and Field Concentrations

Ramada Jeju Hamdeok Hotel, Jeju, S. Korea

February 8, Thursday, 2018

Chair: Hyeonbae Kang

8:30-9:00, Registration and Opening

9:00-9:50, Mihai Putinar (UC-Santa Barbara)
Carleman's legacy in the spectral analysis of the Neumann-Poincaré operator

10:00-10:50, Yoshihisa Miyanishi (Osaka)
Spectral geometry of the Neumann-Poincaré operator on three dimensional smooth domains

Coffee Break

11:20-12:10, Karl-Mikael Perfekt (Reading)
The spectrum of the Neumann-Poincaré operator on domains with corners and conical points

Lunch

Chair: Mihai Putinar

2:00-2:50, Charles Dapogny (Grenoble)
Homogenization of the eigenvalues of the Neumann-Poincaré operator

3:00-3:50, KiHyun Yun (HUFS)
Blow-up estimates of the field in a narrow region between two conducting inclusions

Coffee Break

4:20-5:10, Haigang Li (Beijing Normal)
Optimal estimates for Lamé systems from composite material

5:20-6:10, Mikyoung Lim (KAIST)
Corner effects of planar domains on the electric potential

Dinner

February 9, Friday, 2018

Chair: Mikyoung Lim

9:00-9:50, Victor Nistor (Lorraine)
Integral operators and Fredholm conditions on polyhedral domains

10:00-10:50, Johan Helsing (Lund)
On a Helmholtz transmission problem in planar domains with corners

Coffee Break

11:20-12:10, Brian Fitzpatrick (ETH)
Subwavelength acoustic resonators: From super-resolution to metamaterials

Lunch

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Excersion to
Seongsan Ilchulbong Peak

6:00-8:00, Banquet
all participants are invited

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February 10, Saturday, 2018

Chair: Eric Bonnetier

9:00-9:50, Graeme Milton (Utah)
Optimal design for shielding or field enhancement in electrostatics and linear elasticity

10:00-10:50, Kazunori Ando (Ehime)
Spectral analysis of the elastic NP operator in two dimensions and cloaking by anomalous localized resonance

Coffee Break

11:20-12:10, Hai Zhang (HKUST)
Mathematical studies of extraordinary field enhancement in subwavelength slits

Lunch

Chair: Graeme Milton

2:00-2:50, Hongyu Liu (HK Baptist)
Anomalous localized resonance and plasmonic cloaking in linear elasticity

3:00-3:50, Faouzi Triki (Grenoble)
On the electro-sensing of weakly electric fish

Coffee Break

4:20-5:10, Sanghyeon Yu (ETH)
Field concentrations in plasmonics and linear elasticity

5:20-6:10, Eric Bonnetier (Grenoble)
Spectral properties of the Neumann-Poincaré operators in domains with a point degeneracy

Dinner

Spectral analysis of the elastic NP operator in two dimensions and cloaking by anomalous localized resonance

Kazunori Ando

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Abstract.

We study the spectrum of the Neumann-Poincaré (NP) operator for elasto-static system on two-dimensional bounded domains with smooth boundaries. We find that the spectrum consists of discrete eigenvalues of finite multiplicities which accumulate at $\pm\frac{\mu}{2(\lambda+2\mu)}$, where (λ,μ) are the Lamé parameters of the corresponding elastostatic system. Using the spectral analysis of the NP operator, we show that the cloaking by anomalous localized resonance occurs at the accumulation points of the eigenvalues of the NP operator on ellipses and annuli. We compute the blow-up rates of the resonance energy and the critical radii for CALR at the two accumulation points.

References

[1] Kazunori Ando, Yong-Gwan Ji, Hyeonbae Kang, Kyoungsun Kim, and Sanghyeon Yu. Spectral properties of the Neumann-Poincaré operator and cloaking by anomalous localized resonance for the elasto-static system. *European Journal of Applied Mathematics,* (2017). doi:10.1017/S0956792517000080.

[2] Kazunori Ando, Hyeonbae Kang, Kyoungsun Kim, and Sanghyeon Yu. Spectrum of Neumann-Poincaré Operator on Annuli and Cloaking by Anomalous Localized Resonance for Linear Elasticity. *SIAM Journal on Mathematical Analysis,* Vol. 49, No. 5 (2017), pp. 4232-4250.

Spectral properties of the Neumann-Poincaré operators in domains with a point degeneracy

Eric Bonnetier

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Abstract. This series of lectures will be devoted to the spectral properties of the Neumann-Poincaré operator associated to close-to-touching domains or to domains with corners. Our intention is to try to understand, through a spectral representation of the solution to the governing conductivity equation, how singularities in the geometry of an inclusion affect the resonant properties (enhancement and localization of the fields) of that inclusion.
The first lecture addresses the case of 2 smooth close-to-touching inclusions, where we try to obtain pointwise estimates on the gradient of the voltage potential in terms of the conductivity contrast and the inter-inclusion distance.
The second and third lectures concern the spectral properties of the Neumann-Poincaré operator of planar domains with corners. In this case, the operator is not compact, and may have essential spectrum. We show how this fact relates to the theory of elliptic corner singularities. In particular, we construct singular Weyl sequences associated to solutions of the conductivity equation which are not in the proper energy space.
We also consider the case of a domain shaped as a bowtie, where the presence of two touching or close to touching corners may enhance the concentration of the fields. In the former case, the essential spectrum occupies the whole interval $[0, 1]$, while in the latter case, the essential spectrum is completely determined by the angles of the opposite wings of the bowtie, and thus is strictly embedded in $[0, 1]$. We show how eigenvalues fill the gap between the spectra as the distance between the wings of the bowtie tends to 0.
The work we present here was realized in collaboration with Charles Dapogny, Faouzi Triki and Hai Zhang.

Homogenization of the eigenvalues of the Neumann-Poincaré operator

Charles Dapogny

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Abstract. This work, in collaboration with E. Bonnetier and F. Triki, is a contribution to the study of the spectrum of the Neumann-Poincaré operator, in the particular situation of a periodic distribution of 'many' small inclusions with size ε.
Combining techniques pertaining to the fields of homogenization and potential theory, we prove that the *limit spectrum* is composed of the 'trivial' eigenvalues 0 and 1, and of a subset of $(0, 1)$ which stays bounded away from 0 and 1 uniformly with respect to ε. This non trivial part is the reunion of a so-called *Bloch spectrum*, a collection of bands accounting for the collective resonances between packs of inclusions, and of a *boundary layer spectrum*, associated to eigenfunctions which spend a not too small part of their energies near the boundary of the macroscopic device.
These results shed new light about the homogenization of the voltage potential u_ε caused by a given source in a medium composed of a periodic distribution of small inclusions with an arbitrary (possible negative) conductivity a surrounded by a dielectric medium, with unit conductivity.

References

[1] G. Allaire and C. Conca, *Bloch wave homogenization and spectral asymptotic analysis*, J. Math. Pures et Appli., 77, (1998), pp.153–208.
[2] E. Bonnetier, C. Dapogny and F. Triki, *Homogenization of the eigenvalues of the Neumann-Poincaré operator*, submitted, (2017).
[3] H. Kang, *Layer potential approaches to interface problems*, In Inverse Problems and Imaging: Panoramas et synthèses, 44. Société Mathématique de France, (2013).

Subwavelength acoustic resonators: From super-resolution to metamaterials

Brian Fitzpatrick

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Abstract. The aim of this talk is to review recent results on the propagation of acoustic waves in bubbly media. Our main focus is on developing a mathematical and computational framework for the analysis of Minnaert bubbles. By characterizing and exploiting the Minnaert resonance frequencies of bubbles in a variety of situations, we construct a unified theory of super-focusing of acoustic waves, acoustic metamaterials, and controlling acoustic wave propagation at the subwavelength scale. Super-resolution and metamaterials are usually studied within the context of different approaches. Remarkably, as shown in this talk, they owe their origin to the same underlying physical mechanism, namely, wave interaction with a subwavelength resonator.

References

[1] H. Ammari, B. Fitzpatrick, D. Gontier, H. Lee and H. Zhang, Sub-wavelength focusing of acoustic waves in bubbly media, Proc. R. Soc. A., to appear.
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[3] H. Ammari, B. Fitzpatrick, H. Lee, S. Yu and H. Zhang, Subwavelength phononic bandgap opening in bubbly media, J. Diff. Eq., 263 (2017), 5610-5629.

On a Helmholtz transmission problem in planar domains with corners

Johan Helsing

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Abstract. A particular mix of integral equations and discretization techniques is suggested for the solution of a planar Helmholtz transmission problem with relevance to plasmonics. The transmission problem describes the scattering of a time harmonic transverse magnetic wave from an infinite dielectric cylinder with complex permittivity and sharp edges. Numerical examples illustrate that the resulting scheme is capable of obtaining total magnetic and electric fields, including corner fields and surface plasmon waves, to very high accuracy in the entire computational domain.

References

[1] https://arxiv.org/abs/1711.09796
[2] http://www.maths.lth.se/na/staff/helsing/animations.html

Optimal estimates for Lamé systems from composite material

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Abstract. We study the gradient estimates for solutions of the Lamé system with partially infinite coefficients, which arises from the study of the concentration phenomenon in high-contrast fiber-reinforced composite materials. We develop an iteration technique with respect to the energy integral to overcome the difficulty from the lack of maximal principles. Thus, we obtain the optimal blow-up rates of the gradients when two inclusions are close to touch. Our results hold for convex inclusions with arbitrary shape and in all dimensions [1,2]. Especially, an interesting fact is proved recently that the concentration will not occur once these two adjacent inclusions fail to be locally relatively strictly convex [3]. This is based on joint work with Professor JiGuang Bao (BNU), HongJie Ju (BUPT) and YanYan Li (Rutgers).

References

[1] Bao, JiGuang; Li, HaiGang; Li, YanYan Gradient estimates for solutions of the Lam system with partially infinite coefficients. Arch. Ration. Mech. Anal. 215 (2015), no. 1, 307–351.

[2] Bao, JiGuang; Li, HaiGang; Li, YanYan Gradient estimates for solutions of the Lam system with partially infinite coefficients in dimensions greater than two. Adv. Math. 305 (2017), 298–338.

[3] Hou, YuanYuan; Ju, HongJie; Li, HaiGang The convexity of the inclusions and the gradient's concentration for Lam system with partially infinite coefficients. Preprint. (2017).

Corner effects of planar domains on the electric potential

Mikyoung Lim

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Abstract. In this talk I present new geometric factors of a simple planar domain in terms of a conformal mapping associated with the domain. The defined factors share properties of the generalized polarization tensors associated with the insulating inclusion. They are the Fourier series coefficients of a generalized external angle of the inclusion boundary, where the external angle function has the Dirac delta singularity at corner points. Reconstruction of corner points will be discussed with numerical examples. This work is in collaboration with Doo Sung Choi and Johan Helsing.

Anomalous localized resonance and plasmonic cloaking in linear elasticity

Hongyu Liu

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Abstract. The speaker shall discuss their recent research progress on the anomalous localized resonance and plasmonic cloaking in linear elasticity governed by the Lamé system. The study is based on both variational argument and spectral argument via the use of the spectral properties of the Neumann-Poincáre operator.

Optimal design for shielding or field enhancement in electrostatics and linear elasticity

Graeme W. Milton

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Abstract.

Near touching cylinders or spheres or sharp or oblique corners in highly contrasting media provide large enhancements or reductions in the local fields. Such reductions in the local field are also useful for cloaking as an object placed in a region where the field is small will cause little disturbance in the exterior field: it is effectively shielded. Here we ask: given a two-phase geometry, how can one configure it to maximize shielding or field concentration? For the shielding problem the dimensionality plays a big role. In three dimensions, geometries of interlocking rings (not available in two-dimensions) give very good local shielding from a given uniform applied field. In general the problem can be posed as a topology optization problem and reformulated as a relaxed problem in which one allows not just the two phases but also also composites of them. Key to this reformulation is the resolution of the "weak G-closure problem": for electrical conductivity (or the analogous dielectric problem) this is the task of identifying the possible (current field, electric field)-pairs. This was solved by Raitum (1978,1993). We recently solved the elastic "weak G-closure problem" for $3d$-printed materials [1], paving the way for designing new types of field shields and concentrators for elasticity. The solution is a corollary of progress towards characterizing the complete set of elasticity tensors of $3d$-printed materials [2].

References

[1] Graeme W. Milton and Mohamed Camar-Eddine, Near optimal pentamodes as a tool for guiding stress while minimizing compliance in $3d$-printed materials: a complete solution to the weak G-closure problem for $3d$-printed materials. submitted to J. Mech. Phys. Solids.
[2] Graeme W. Milton and Marc Briane and Davit Harutyunyan, On the possible effective elasticity tensors of 2-dimensional and 3-dimensional printed materials, Math. Mech. Complex Sys., 5, 41-94 (2016)

Spectral geometry of the Neumann-Poincaré operator on three dimensional smooth domains

Yoshihisa Miyanishi

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Abstract. We show the Weyl-type asymptotic formula for eigen- and singular values of the Neumann-Poincaré operator. Denoting the j-th eigen- and the j-th singular value by λ_j and σ_j respectively, we have

$$|\lambda_j| \leq s_j \sim C(\partial\Omega) j^{-1/2} \quad \text{as } j \to \infty.$$

Here the constant $C(\partial\Omega)$ is expressed by the square root of the Willmore energy. Thus, even when the boundary of the domain has genus greater than or equal to one, the minimum decay rate is achieved by the Willmore surfaces. In this talk, we also mention about related problems and results.

Integral operators and Fredholm conditions on polyhedral domains

Victor Nistor

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Abstract. I will describe a construction of pseudodifferential operators on polyhedral domains and on other singular spaces. For suitable singular spaces, one has good criteria to determine whether one of these operators is Fredholm or not. They are given by the invertibility of the principal symbol (ellipticity, as in the smooth case) plus the invertibility of certain other associated operators (called indicial or normal or, yet, limit operators). I will also discuss some connections with some recent work of Yu Qiao on layer potentials. These results are joint work with Carvalho, Putinar, and Qiao.

The spectrum of the Neumann-Poincaré operator on domains with corners and conical points

Karl-Mikael Perfekt

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Abstract. The Neumann–Poincaré (NP) operator (or the double layer potential) has classically been used as a tool to solve the Dirichlet and Neumann problems of a domain. It also serves as a prominent example in non-self adjoint spectral theory, due to its unexpected behavior for domains with singularities. Recently, questions from materials science have revived interest in the spectral properties of the NP operator on domains with corners, edges, and conical points. This surge in attention is owed to the connection with resonances of transmission/scattering problems used to model surface plasmons in nanoparticles.

I aim to give an overview of recent developments, with particular focus on the NP operator's action on the energy space of the domain. I will also present recent work for domains in 3D with conical points featuring rotational symmetry. In this situation, we have been able to describe the spectrum both for boundary data in L^2 and for data in the energy space. In the former case, the essential spectrum consists of the union of countably many self-intersecting curves in the plane, and outside of this set the index may be computed as the winding number with respect to the essential spectrum. In the latter case the essential spectrum consists of a real interval.

Based on joint work with Johan Helsing and Mihai Putinar.

References

[1] J. Helsing and K.-M. Perfekt, *The spectra of harmonic layer potential operators on domains with rotationally symmetric conical points*, J. Math. Pures Appl., in press.

[2] K-M. Perfekt and M. Putinar, *The essential spectrum of the Neumann–Poincaré operator on a domain with corners*, Arch. Ration. Mech. Anal. **223** (2017), 1019–1033.

Carleman's legacy in the spectral analysis of the Neumann-Poincaré operator

Mihai Putinar

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Abstract. Carleman's doctoral dissertation was devoted to the spectral analysis of the Neumann-Poincaré operator on domains with corners. Published exactly a hundred years ago as a 200 pages small book, it remains largely unknown and unexplored. Written at a time when Hilbert's spectral decomposition theorem was unfolding, a few years after Fredholm's major contribution to the theory of integral equations and contemporary to Hadamard's canonical factorization theorem of entire functions, the thesis remains very modern and inspiring for todays researchers. In my lecture I will try to summarize Carleman's highly original ideas and convey the freshness of discovery emanating at every page of his thesis.

References

[1] T. Carleman, *Über das Neumann-Poincarésche Problem für ein Gebiet mit Ecken* , Almqvist and Wiksells, Uppsala, 1916.

On the electro-sensing of weakly electric fish

Faouzi Triki

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Abstract. In this talk we are interested in electro-sensing inverse problems. Our objective is to understand the electro-perception mechanism of weakly electric fish. These species of fish have the ability to recognize the environment around them in complete darkness by generating a weak electrical field at different frequencies, and perceiving the transdermal potential perturbation. Assuming that the target has a known conductivity profile, the electro-sensing inverse problem consists in recovering the shape and location of the target from measurements of the electric potential over the skin. We will present uniqueness and stability estimates to the considered inverse problem as well as numerical validations of our theoretical approach using synthetic data in dimension two.

Field concentrations in plasmonics and linear elasticity

Sanghyeon Yu

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Abstract. When two inclusions are close to touching, the physical field such as the stress or the electric field may be arbitrarily large in the narrow region between the inclusions. In this talk, we will present the recent developments on the qunatitative understanding of the field concentrations. This problem requires to analyze the Neumann-Poincaré operator on two nearly touching domains. We will consider 3D plasmonic spheres systems [6] and 2D particles with general convex shapes. We then show how the plasmonic resonant fields (or the spectral properties of the NP operator) behave when the particles get closer. The plasmonic sensing by strong interaction between the particles will also be discussed [1,2]. We will also consider the stress concentration, which is a similar problem in the linear elasticity. We find singular functions which characterize the stress blow-up in the narrow region [3,5]. As an application of our singular functions, we are able to justify the asymptotic formulas for the effective properties of a denesely packed elastic composite [4].

References

[1] H. Ammari, M. Ruiz, S. Yu, and H. Zhang, Reconstructing fine details of small objects by using plasmonic spectroscopic data, to appear in *SIAM Journal on Imaging Sciences*.

[2] H. Ammari, M. Ruiz, S. Yu, and H. Zhang, Reconstructing fine details of small objects by using plasmonic spectroscopic data. Part II: The strong interaction regime, submitted.

[3] H. Kang and S. Yu, Quantitative characterization of stress concentration in the presence of closely spaced hard inclusions in two-dimensional linear elasticity, *arXiv:1707.02207*.

[4] H. Kang and S. Yu, A proof of the Flaherty-Keller formula on the effective property of densely packed elastic composites, *arXiv:1707.02205*.

[5] M. Lim and S. Yu, Stress concentration for two nearly touching circular holes, *arXiv:1705.10400*.

[6] S. Yu and H. Ammari, Plasmonic interaction between nanospheres, To appear in *SIAM Review*.

Blow-up estimates of the field in a narrow region between two conducting inclusions

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Abstract. We consider the field enhancement, that is, the gradient blow-up, due to presence of two perfectly conducting inclusions nearly touching to each other. Some estimates of the field are derived from an eigenfunction corresponding to the eigenvalue 1/2 of a Neumann-Poincaré type operator. This talk also deals with a bow-tie structure of inclusions with corners. We establish optimal estimates of the gradient in terms of the distance between two inclusions and aperture angles of the corners. This talk is based on joint works with Hyeonbae Kang, Hyundae Lee and Mikyoung Lim.

References

[1] H. Ammari, G. Ciraolo, H. Kang, H. Lee and K. Yun, Spectral analysis of the Neumann Poincaré operator and characterization of the stress concentration in anti-plane elasticity, Arch. Ration. Mech. An. 208 (2013), 275304.
[2] H. Ammari, H. Kang and M. Lim, Gradient estimates for solutions to the conductivity problem, Math. Ann. 332(2) (2005), 277286.
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[4] H. Kang, M. Lim and K. Yun, Characterization of the electric field concentration between two adjacent spherical perfect conductors, SIAM J. Appl. Math. 74(1), 125146
[5] H. Kang and K. Yun, Optimal estimates of the field enhancement in presence of a bow-tie structure of perfectly conducting inclusions in two dimensions, submitted
[6] M. Lim and K. Yun, Blow-up of electric fields between closely spaced spherical perfect conductors, Commun. Part. Diff. Eq. 34 (2009), 12871315.
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[9] K. Yun, Optimal bound on high stresses occurring between stiff fibers with arbitrary shaped cross-sections, J. Math. Anal. Appl. 350 (2009), 306-312.

Mathematical studies of extraordinary field enhancement in subwavelength slits

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Abstract. Since the discovery of the extraordinary optical transmission through nanohole arrays in metallic films by Ebbesen, a wealth of research has been sparked in the experimental and theoretical investigation of localized electromagnetic field enhancement in subwavelength nanostructures. This remarkable phenomenon can lead to potentially significant applications in near-field imaging, bio-sensing, etc. However, there has been a long debate on the interpretation of the enhancement effect since Ebbesen's work. In addition, a quantitative analysis of the field enhancement in subwavelength structures is still widely open. In this talk, using two-dimensional slits as a prototype, I will present mathematical studies of the field enhancement in the subwavlength structures. Based upon the layer potential technique, asymptotic analysis and homogenization theory, the enhancement mechanisms for both the single slit and an array of slits are studied quantitatively.

References

[1] Scattering by a periodic array of subwavelength slits II: surface bound state, total transmission and field enhancement in homogenization regimes,
Junshan Lin and Hai Zhang, arXiv:1706.02126, 2017.
[2] Scattering by a periodic array of subwavelength slits I: field enhancement in the diffraction regime,
Junshan Lin and Hai Zhang, arXiv:1706.02122, 2017.
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Junshan Lin and Hai Zhang, SIAM Journal on Applied Mathematics, 951-976, 77(3), 2017.