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STUDY OF LINEAR OPTICAL PROPERTIES OF HYPERBOLIC METAMATERIALS

By

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Thesis Outline

Since the discovery of the concept of metamaterials, several metamaterials have been proposed and successfully applied in different domains of physics. Metamaterials have provided abundant possibilities for realizing unique properties which are not generally found in naturally existing materials. Recent advances in the nanotechnology and nano-fabrication techniques have greatly supported the applicability of metamaterials to the nano-photonics. One among the several classes is hyperbolic metamaterials (HMM), which play an important role in nano-photonics, because they support the enlargement of wavenumber. They have strong anisotropy and hyperbolic (or indefinite) dispersion, originating from the fact that one of the principal components of their electric permittivity or magnetic permeability tensors have an opposite sign to the other two components. They also provide us with the strong field confinement and enhancement, as well as the increase in the photonic density of states, and have recently attracted much of attention, because their applications to the new phases of photonics research are expected.

HMMs can be realized by several structures, such as periodic metal–dielectric multilayers, plasmonic nanorod arrays and natural HMMs. One of the HMM structures is cylindrical hyperbolic metamaterials (CHMMs), which have recently gained a significant role in the field of metamaterials. These multilayered nanotubes or cylindrical nano-cavities, constructed with marginal layers of dispersive and non-dispersive materials, have the capabilities of controlling light interaction with high proficiency. Although HMMs were widely studied for various applications but focus on CHMMs for scattering and absorption of light in the visible region has not been extensively explored yet. With recent advances in the nanotechnology fabrication technologies, it is expected that in very near future it will be possible to realize more complex and sophisticated metamaterial designs for important applications in the field of nano-photonics. So, in this thesis we focus on the analysis of linear optical properties of CHMMs.

This thesis is divided into six chapters, brief details of each chapter is as follows:

Chapter 1 consists of description about the concept of different types of HMMs and their applications in the field of nano-photonics. We briefly discuss about the role of effective medium approximation (EMA) models in understanding the physical mechanism behind the unusual optical properties of HMM structures. Further we introduce the concept of superscattering (SSc) of light, and its practical relevance. At last we discuss about the emerging research field of machine learning using the artificial neural networks (NN) for optimization schemes for nano-photonics area.

In **Chapter 2**, we present the different analytical and numerical methods used for the calculation of the optical properties of CHMM and the corresponding EMA models. The calculations of the linear optical properties of the CHMMs are based on the Lorentz-Mie theory. We also include the details about the NN based approach used for optimization of CHMM structures.

In **Chapter 3**, a comparative study of different EMA models used for the analysis of scattering property of CHMM is discussed. Several aspects of the applicability of EMA models for different cases are included. Primarily, we discussed about cylindrical EMA (CEMA) and planar EMA (PEMA) models and established that CEMA is comparatively better than PEMA. We also discussed that the validity of the EMA models is severely restricted by several factors.

In **Chapter 4**, we have shown the different systematic optimization schemes for designing CHMM structures for achieving the enhanced scattering (SSc) of light when compared to the reference homogeneous structures. We have used dispersive, non-dispersive and epsilon near zero (ENZ) materials in our design approach. Also, by including FDTD simulation analysis and EMA analysis, we have emphasized on the mechanism behind SSc condition.

In **Chapter 5**, we present the analysis showing the enhanced absorption of light from the CHMMs. We have demonstrated that using NN based approach we can get several optimized structures in a much faster way.

Finally, **Chapter 6** consists of final conclusions and future scope of this work.

6.1 <u>Conclusions:</u>

In this thesis, we investigated the scattering and absorption properties of CHMM structures for applications in the visible region. The significant observations of the thesis are summarized as follows:

- We were able to achieve the desired manipulation of the optical response of nano-particles, by incorporating the hyperbolic anisotropy of CHMM in the given structures.

- For a clear understanding, initially we performed a thorough comparative analysis of applicability of the different EMA models for CHMMs. We established that CEMA is a better approximation model compared to PEMA. However, the validity of the EMA models maybe restricted by several factors.

- Further, by using different optimization approaches we achieved superscattering of light from CHMM. We proposed different structures consisting of combinations of dispersive, non-dispersive and ENZ materials.

- By using CHMM consisting of practical and ENZ materials we achieved up-to 2-fold and 4-fold enhancement in the scattering performance, respectively.

- By employing FDTD simulation analysis we confirmed the presence of whispering gallery like modes at SSc conditions. Due to WGM like modes, additional functionality of such structures may emerge especially in the areas of sensing, quantum optics and energy harvesting applications.

- We observed that enhanced absorption can also be achieved from CHMM structures. By using a similar optimization method that was used for SSc, but with different suitable material combinations. It was possible to achieve up-to 5-fold enhancement in absorption property when compared to a reference homogeneous structure.

- Moreover, we confirm that superscattering and enhanced absorption property is primarily due to the presence of Type-1 hyperbolic anisotropy in CHMM structures.

- Further, by utilizing machine learning using artificial neural network based optimization technique, we were able to efficiently obtain the optimized CHMM structures for achieving enhanced absorption for different desired conditions.

We sincerely hope that the hyperbolic metamaterial structures discussed in this thesis can be relevant for different applications in communications, opto-electronics, photonic integrated circuits, sensing and other relevant areas in nano-photonics.

6.2 Future scope of this work

By observing the recent advances in the area of nano-photonics and nano-fabrication techniques, we are hopeful that in near future it will be convenient to fabricate novel and complex metamaterial structures for important applications in nano-photonics.

- We believe that it will be soon possible to experimentally verify the superscattering and super-absorption of light in the visible region.

- Following the similar approach as presented in this thesis, in future it may be possible to design superscattering and super-absorbing structures for different frequency ranges, such as near-infra red, microwave region etc.

- Also, in future there is a huge scope of using neural network based approach for the efficient optimization of nano photonic structures and discovering novel metamaterials.

- Following fabrication methods can may be used for realizing CHMMs: Atomic layer deposition, electro-chemical deposition, customized thermal evaporation, e-beam evaporation.

- Potential experimental methods for the optical characterization of CHMMs are : Dark-field optical microscopy, Inverse Fourier microscopy, cathodoluminescence spectroscopy.

- Although in this thesis we primarily focused on the linear optical properties of CHMMs, but there is plenty of scope to study in detail, about the non-linear optical responses of such nano-structures