Homogenization of Metamaterials in Macroscopic Quantum Electrodynamics

Amooghorban, Ehsan; Wubs, Martijn

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Amooghorban, E., & Wubs, M. (2023). *Homogenization of Metamaterials in Macroscopic Quantum Electrodynamics*. Abstract from 2023 PhotonIcs and Electromagnetics Research Symposium, Prague, Czech Republic.

Homogenization of Metamaterials in Macroscopic Quantum Electrodynamics

E. Amooghorban[1, 2] **and M. Wubs**[3, 4, 5]

[1]Faculty of Science, Department of Physics, Shahrekord University
Shahrekord 88186-34141, Iran
[2]Nanotechnology Research Group, Shahrekord University
P. O. Box 115, Shahrekord 88186-34141, Iran
[3]Department of Electrical and Photonics Engineering
Technical University of Denmark, 2800 Kgs. Lyngby, Denmark
[4]Center for Nanostructured Graphene, Technical University of Denmark
2800 Kgs. Lyngby, Denmark
[5]NanoPhoton-Center for Nanophotonics, Technical University of Denmark
2800 Kgs. Lyngby, Denmark

Abstract— It is well known that by changing the subwavelength unit cell of a metamaterial, one can design its effective-medium properties. Homogenization or effective-medium theories then tell what the effective parameters are. There are various methods to compute the effective index of a metamaterial, based on its dispersion relation or on a spatial average, and for longer wavelengths, these methods tend to agree more.

Metamaterials and metasurfaces are also increasingly considered as designer environments for quantum emitters, to increase their brightness, directional emission, etcetera. These quantum emitters send out single photons or other non-classical states of light, which require a quantum electrodynamics description. It is then usually tacitly assumed that the effective-medium properties of the metamaterials are the same in quantum as in classical electrodynamics, so that photons are thought as propagating through effectively homogeneous media with effective parameters computed with the usual homogenization theory of classical electrodynamics.

Here we describe our tests of that assumption, starting from a macroscopic QED [1] description of the metamaterial. For simplicity, we consider layered metamaterials [2], and we consider how quantum states of light propagate through them, for all possible propagation and polarization directions [3].

Metamaterials and especially hyperbolic metamaterials often contain metals as one of their constituents, so that loss can't always be neglected. Sometimes this loss can partly be compensated by gain in another constituent, in the so-called loss-compensated metamaterials. In macroscopic QED, both loss and gain have associated quantum noise, and these noise sources add up rather than compensate each other.

We find that the effective index is the same in quantum as in classical electrodynamics. We also find that an effective description of the quantum noise in a metamaterial is possible. However, only in special cases can this effective quantum noise be described in terms of the effective index. The general outcome is therefore that even in the long-wavelength limit, homogenization in macroscopic QED requires an additional parameter compared to classical electrodynamics, and our quantum homogenization theory gives the correct value for that parameter. As an example, we illustrate that our homogenization theory accurately describes the propagation of squeezed states of light through metamaterials.

REFERENCES

1. Vasylyev, D. Y., W. Vogel, G. Manzke, K. Henneberger, and D.-G. Welsch, *Phys. Status Solidi B*, Vol. 246, 293, 2009.
2. Amooghorban, E., N. A. Mortensen, and M. Wubs, *Phys. Rev. Lett.*, Vol. 110, 153602, 2013.
3. Amooghorban, E. and M. Wubs, *Nanomaterials*, Vol. 13, 291, 2023.