Breaking the limit of emission suppression in low contrast 3D media

Meraj E. Mustafa[1], Lukas Maiwald,[1] Soumyadeep Saha[1,2], Mikhail S. Sidorenko[3,4], Ruslan R. Yafyasov[3,4], Mikhail V. Rybin[3,4], Manfred Eich[3,5] and Alexander Yu. Petrov[1,3,5] *

[1]Institute of Optical and Electronic Materials, Hamburg University of Technology, Germany
[2]Department of Electronics and Telecommunication Engineering, Jadavpur University, Kolkata
[3]Department of Physics and Engineering, ITMO University, Saint Petersburg, Russia
[4]Ioffe Institute, Saint Petersburg, Russia
[5]Institute of Material Research, Helmholtz-Zentrum Hereon, Germany

*corresponding author, E-mail: a.petrov@tuhh.de

Abstract

Light emission can be significantly suppressed in 3D photonic crystals at the frequency of a photonic band gap but a refractive index contrast above 1.8 is needed. We present 3D quasiperiodic structures that can significantly reduce the density of states even at lower index contrasts. The suppression of 10 dB is demonstrated in simulations with refractive index contrast of 1.4. A refractive index contrast of 1.6 is investigated experimentally in microwave regime.

1. Introduction

Complete suppression of light emission can be obtained in 3D photonic crystals at the frequencies of a photonic band gap. For that to occur the band gaps for light propagation in different directions should overlap in a certain frequency range. Structures that were proposed so far require a refractive index contrast of at least 1.8 to open a complete photonic band gap [1]. This excludes the application of glasses and polymers. For these materials directional band gaps have a smaller frequency range. Also the central frequencies of directional band gaps differ for different directions in photonic crystals and thus an overlap cannot be obtained.

This problem was successfully resolved in 2D photonic crystals using quasicrystal structures with higher than 6-fold symmetry [2]. Though the possibility to suppress emission in structures with an arbitrarily small refractive index was not investigated, the required contrast was significantly reduced in comparison with periodic structures. At the same time the progress with 3D quasicrystals was limited up to now and complete emission suppression was not demonstrated so far in low refractive index media [3].

Here we present quasiperiodic structures that allow an exact positioning of the Bragg peaks in reciprocal space [4]. Using this approach we demonstrate complete photonic band gaps with very small refractive index contrast in 2D and strong emission suppression in 3D structures [5]. Additionally, we present experimental characterization of the proposed structure produced by additive manufacturing for the microwave regime.

2. Results

The quasiperiodic structures were generated using the levelling of a random wave function. The random wave function is a sum of N sinusoidal gratings with constant wave number $|\vec{g}_i| = g$, optimized orientation and random phase ϕ_i. The refractive index perturbation is then obtained by levelling with a sign function:

$$\Delta n(\vec{r}) = \Delta n \cdot \mathrm{sgn}\{\textstyle\sum_{i=1}^{N} \sin(g_i \cdot \vec{r} + \phi_i)\} \quad (1)$$

The $\Delta n(\vec{r})$ represents the refractive index variation around the average index $\bar{n}$. The structure for 46 gratings is presented in Fig. 1, where 92 Bragg peaks are homogeneously distributed on the sphere keeping an icosahedral symmetry.

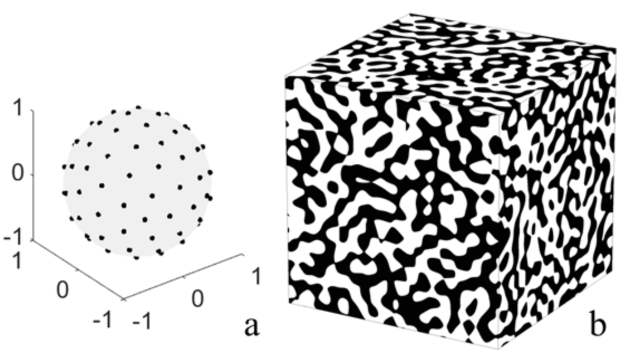

Figure 1: a) The distribution of the 92 Bragg peaks (46 gratings) on the sphere of radius 1. b) A small volume of the structure obtained by the overlap of the gratings from a).

The emission in the quasiperiodic structure is studied numerically by introducing a small dipole in the center of the simulation volume. The emission is compared to the emission in a homogenous structure with the mean refractive index $\bar{n}$. The structure size is increased to evaluate the maximal emission suppression. In the case of a complete photonic band gap, the suppression should increase exponentially with the structure size. In our structures we observe a saturation of suppression at large volume sizes, approaching 10 dB maximal suppression (see Fig. 2). A similar behaviour is observed for a larger number of gratings and a smaller refractive index contrast of 1.38.

The proposed structures were also manufactured using a 3D printer for the 40 GHz microwave range. For that polylactide (PLA) plastic was used which has a refractive index of approximately 1.59 at this frequency. The transmission through the slab of structured material was measured at different angles indicating the original distribution of Bragg peaks in reciprocal space.

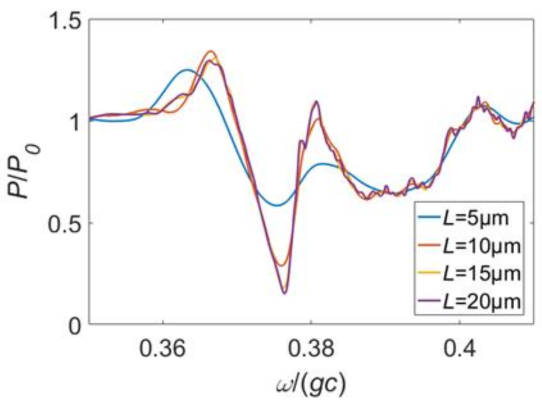

Figure 2: Normalized power emitted by a dipole antenna in the quasiperiodic structure with 46 gratings and a refractive index contrast of 1.6. The power is normalized to emission in the homogeneous medium with refractive index 1.3. The frequency is normalized by the wave number of the gratings and the speed of light. Different structure sizes *L* are shown, the lattice constant of the gratings was 220 nm.

3. Discussion and conclusion

The obtained results show that 10 dB suppression can be obtained in low refractive index media by careful reciprocal space design. Quasiperiodic structures allow an optimized distribution of Bragg peaks in reciprocal space which are not bound to periodic boundary conditions. The application of levelling and random phase distribution leads to homogenous structures out of two materials, where one material can be air.

The suppression of 10 dB in glasses and polymers opens the way for strong light manipulation with low refractive index media. Further investigations are required to improve the suppression beyond 10 dB.

Acknowledgements

We acknowledge the support from Dassault Systemes with their CST Studio Suite software. Funding: Deutsche Forschungsgemeinschaft (DFG) - Project number 278744289. The experimental studies have been supported by the grant of Russian Science Foundation (Grant No. 20-79-10316).

References

[1] H. Men, K. Y. K. Lee, R. M. Freund, J. Peraire, S. G. Johnson, Robust topology optimization of three-dimensional photonic-crystal band-gap structures. *Opt. Express* 22: 22632–22648, 2014.

[2] M. C. Rechtsman, H.-C. Jeong, P. M. Chaikin, S. Torquato, P. J. Steinhardt, Optimized structures for photonic quasicrystals. *Phys. Rev. Lett.* 101: 73902, 2008.

[3] W. Man, M. Megens, P. J. Steinhardt, P. M. Chaikin, Experimental measurement of the photonic properties of icosahedral quasicrystals. *Nature* 436: 993–996, 2005.

[4] L. Maiwald, S. Lang, D. Jalas, H. Renner, A. Yu. Petrov, M. Eich, Ewald sphere construction for structural colors. *Opt. Express* 26: 11352–11365, 2018

[5] L. Maiwald, T. Sommer, M. Schulz, M. Eich, A. Yu Petrov, The limits for complete photonic bandgaps in low-contrast media, *arXiv*:1909.09521, 2019