Quasi normal mode perturbation theory to achieve Q factor optimization of resonances in disordered photonic systems

N. Granchi[1*], F.Intonti[1], M. Gurioli[1] and G. Arregui[2]

[1]Department of Physics and Astronomy and LENS, University of Florence, Sesto Fiorentino (FI), Italy
[2]Department of Electrical and Photonics Engineering, DTU Electro, Denmark
[*]corresponding author: granchi@lens.unifi.it

Abstract: The optimization of the quality factor (Q) of photonic resonators is of great importance for applications exploiting both ordered and disordered systems. Here we propose a gradient-based automated optimization approach to maximize the Q of optical resonances in ordered and disordered dielectric slabs which uses first-order non-hermitian perturbation theory. By applying our method to optimize a selected Anderson mode in a random design exhibiting a Q-factor of 200, a new mode displaying $Q = 10^5$ is generated.

Photonic crystal cavities nowadays are the most widespread and versatile devices conceived to mold the flow of light at the nanoscale. They offer a versatile platform to study classical and quantum light-matter interaction in fields such as cavity quantum electrodynamics, non-linear optics, and cavity optomechanics. In parallel, other photonic systems, based on random distributions of point scatterers, have emerged and proposed as complementary alternative to ordered photonics [1]. They have been investigated for their basic physical insights, such as Anderson localization, and envisioned for several applications, due to their capability of exhibiting a higher spectral and spatial density of modes in a small spatial domain with respect to their ordered counterparts [1]. Conversely, the main disadvantage, mainly in purely random photonic systems operating at telecom wavelengths, is represented by the low Q factors that Anderson modes exhibits (typically ≈ 200). While the problem of Q factor optimization of photonic crystal cavities have been accomplished widely and successfully [2,3], in the case of Anderson modes localized in random structures, further complicated by the lack of an in-plane photonic band gap, it has never been addressed.

Here, we propose a gradient-based automated optimization approach to maximize the Q of a selected Anderson mode supported by a dielectric slab randomly patterned with air holes (Fig.1a). The method uses the theoretical framework of quasinormal modes (QNMs) [4] and relies on first-order non-hermitian perturbation theory to efficiently compute the gradients of Q relative to arbitrary material boundary displacements. Given its first order nature, the method requires only the calculation of the complex eigenfrequency and field profile of the QNM of interest. The optimization process, which determines a shift in the position of all holes in the structure (Fig.1b) to produce a Q-factor enhancement from 200 to 10^5 as well as a negligible average wavelength shift (Fig.1c). By monitoring the spatial distribution of the mode along the optimization we observe the mode central location and spatial distribution to change dramatically (Fig.1d), with a final spatial localization comparable with the one achieved in engineered photonic-crystal cavities ($Q/V \approx 10^6\ \mu m^{-3}$). Our result might be relevant for the employment of random structures for lasing an sensing applications and constitute an important step toward the full engineering of the random photonic platform.

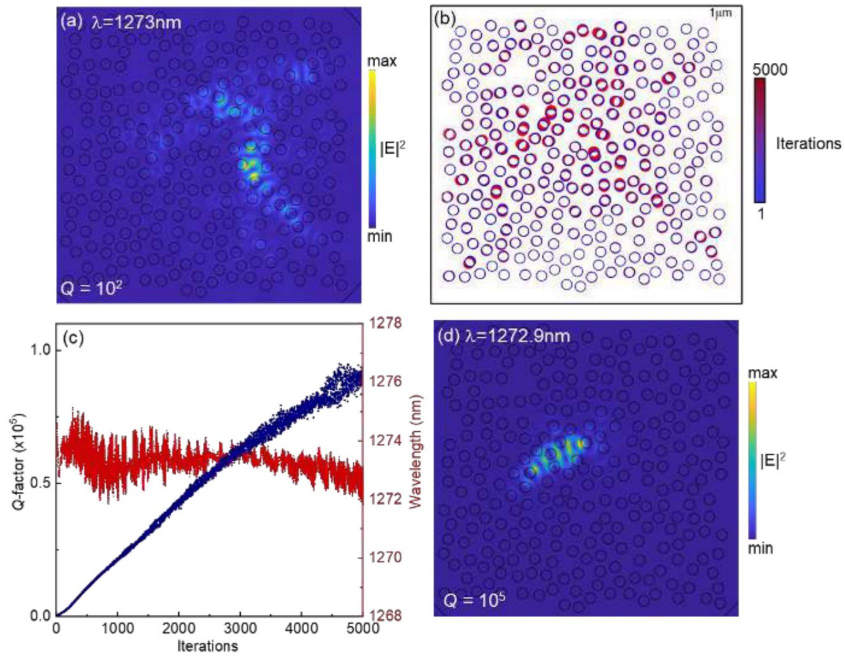

Figure 1: Results of the optimization process applied to a random design with slab thickness d=180 nm and air holes of radius r=110nm. (a) FEM Electric field intensity maps of the Anderson mode in the initial configuration; (b) Evolution of the position of all holes in the random design from the initial configuration (red) to the final one (blue). (c) Evolution of the resonant wavelength and quality factor of the Anderson mode for all iterations of the optimization process. (d) FEM Electric field intensity maps of the Anderson mode in the final configuration.

References

1. Balestri, D., Petruzzella, M., Checcucci, S., Intonti, F., Caselli, N., Sgrignuoli, F., van Otten, F. W. M., Fiore, A., and Gurioli, M., "Mechanical and electric control of photonic modes in random dielectrics", Adv. Mater., 31, 1807274, 2019.
2. Akahane, Y., Asano, T., Song, BS. And Noda, S., "High-Q photonic nanocavity in a two-dimensional photonic crystal", Nature 425, 944–947, 2003.
3. Sekoguchi, H., Takahashi, Y., Asano, T. and Noda, S., "Photonic crystal nanocavity with a Q-factor of ~9 million", Opt. Express 22, 916-924, 2014.
4. Lalanne, P., Yan, W., Vynck, K., Sauvan, C., Hugonin, J.P., "Light interaction with photonic and plasmonic resonances", Laser and Photonics Review, 12, 1700113, 2018.