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Characterization and Optimization of Quasi-Random Nanophotonic Structures with Intrinsic Robustness against Fabrication Defects

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Abstract

Quasi-random nanophotonic structures with random structural appearance but local structural correlations attract enormous attention recently owning to their intriguing optical properties. Their unusual optical properties facilitate a wide range of applications, such as the non-iridescent structural coloration, highly-efficient photon extraction in light-emitting diodes, light-trapping for solar cells, random lasing, and optical metamaterials. There is a growing interest in understanding the essential characteristics beneath the random appearance leading to the desired optical properties and how to optimize quasi-random nanostructures for high-performance photonic devices that are easily manufacturable. However, no unified approach has been developed to unveil such key characteristics in quasi-random structures for effective photon management.

In spite of the wide spectrum of quasi-random structures with different morphology characteristics, most of current works in designing the optimal quasi-random nanophotonic structures assume a specific type of morphology, such as the random-packed-sphere nanostructure. Moreover, relying on the conventional approach to tailor the structure in the real-space renders the design quasi-random nanophotonic structures constrained by the periodic, deterministic concept. Such conceptual restriction limits the potential of functional quasi-random nanophotonics structures to be cost-effectively fabricated using the bottom-up nanomanufacturing techniques.

In this work, we develop a theoretically sound computational framework based on the structural correlations for the characterization, representation, and optimization of the quasi-random photonic structures. We first establish the theoretical foundation of the proposed approach by exploiting the rigorous connection between the structural correlation function and the structural Fourier spectrum. Next, we illustrate that our proposed framework provides a natural and efficient representation method for modelling the structures via Gaussian random field, which enables automated computational designs of highly efficient quasi-random nanophotonic structures. This novel design methodology not only preserves the inherent stochasticity of quasi-random nanostructures, but also surpasses the conventional nanophotonic concept based on periodic structures. The proposed method is validated by successfully optimizing the quasi-random nanophotonic light-trapping structure in thin-film solar cells, resulting in over 120% improvement in energy harvesting efficiency over broad solar spectrum. This optimal quasi-random light-trapping structure without structural periodicity is further validated through physical experiments, which verifies our methodology for designing aperiodic, non-deterministic nanophotonic structures for highly-efficient light control. This work paves the way toward the cost-effective realization of high-performance nanophotonic devices using scalable bottom-up nanomanufacturing processes.