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Beyond Order: Random, Aperiodic, and Hyperuniform Photonic Materials: introduction to the special issue

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Abstract: The editors introduce the feature issue on "Beyond Order: Random, Aperiodic, and Hyperuniform Photonic Materials," which includes nine articles.

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Structurally complex photonic materials with disordered refractive index variations on the wavelength scale manifest a rich physics with profound analogies to the electron transport in disordered metallic alloys and semiconductors. In particular, mesoscopic phenomena known for the electron transport in disordered materials, such as the weak localization of light, universal conductance fluctuations, anomalous transport, and Anderson localization have found their counterparts in disordered optical materials as well. Recently, advancements in theory, computational modeling, and nanofabrication methods enabled the engineering of photonic materials with aperiodic order and tailored structural disorder. These complex optical systems exhibit more predictable responses suitable for a wide range of engineering applications including radiation control and imaging, enhanced optical sensing and spectroscopy, nonlinear optics, multidirectional lasing, and quantum photonics [1–5].

This feature issue brings together original contributions to the vibrant field of complex photonics and showcases nine research papers that delve into customized disordered optical materials and their applications in devices. Pourmasoud et al. proposed a novel design for highly reflective, broadband omnidirectional mirrors using chirped and hybrid-type periodic-aperiodic structures. Based on the aperiodic Thue-Morse sequence, their work demonstrated dielectric mirrors with a spectral width up to 2500 nm and 0-60° angular span [6]. Kim et al. derived an exact nonlocal effective medium theory valid in the strong-contrast regime beyond the long-wavelength approximation that enables inverse design of the effective wave characteristics of disordered structures by engineering their spectral densities [7]. By combining microgels and silica nanoparticles, Manne et al. demonstrated the fabrication of foam-like photonic media exhibiting structural coloration in the visible spectral range, paving the way to novel photonic

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pigments [8]. Okamoto et al. demonstrated control of laser emission using an optical trapping technique to engineer the distribution of scattering particles within a random lasing medium [9]. Kumar et al. presented a compact integrated spectrometer based on speckle correlations in scattering media with engineered multifractal geometry in a silicon-on-insulator platform and demonstrated enhanced throughput and signal-to-noise ratio outperforming traditional speckle spectrometers based on uncorrelated random media [10]. Razo-López et al. demonstrated experimentally strong localization effects beyond two spatial dimensions using deterministic structures with aperiodic Vogel spiral geometry in the microwave regime and presented a comprehensive analysis showing how Vogel spiral arrays outperforms the localization behavior of traditional disordered systems [11]. Mustafa et al. achieved tailored distributions of scattering directions in artificial structures designed in reciprocal space to scatter incident radiation only for defined wavelengths and directions [12]. Selvestrel et al. addressed the question of light intensity propagation through space- and time-dependent disorder in one-dimensional systems with short-range correlations and provided explicit expressions, valid in the in the weak scattering regime, for the scattering mean-free time and mean-free path in agreement with numerical simulations [13]. Finally, Shubitidze et al. introduced the localization landscape theory for classical optical waves in multifractal scattering potentials and experimentally investigated, using leaky-mode spectroscopy, the localization properties of silicon nitride nanophotonic membranes in the visible spectrum, establishing a scalable approach to enhance light-matter interactions in extended scattering media with tailored multiscale disorder [14].

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