

Simulation Framework for Brownian Thermal Noise in Dielectric Metasurfaces

Periodic metasurfaces offer a promising alternative to conventional multilayer coatings, providing very high reflectance with a significantly reduced coating thermal noise amplitude.

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Abstract

Brownian thermal noise in highly reflective dielectric coatings is a fundamental limitation for ultra-stable optical resonators, precision interferometry, and gravitational-wave detectors [1]. It originates from mechanical dissipation within the coating materials. At a finite temperature, thermal energy excites mechanical degrees of freedom, leading to a stochastic displacement of the coating layer surfaces, as well as dimensional changes of the layers.

Dielectric metasurfaces, coatings with subwavelength periodic nanostructures, offer a promising alternative to conventional multilayer coatings, as they can achieve very high reflectance while maintaining a significantly lower coating thermal noise [2]. However, the behavior of Brownian thermal noise in these surfaces is not straightforward to predict, because it depends on the interplay between optical field localization, geometry-dependent resonances, and elastic dissipation.

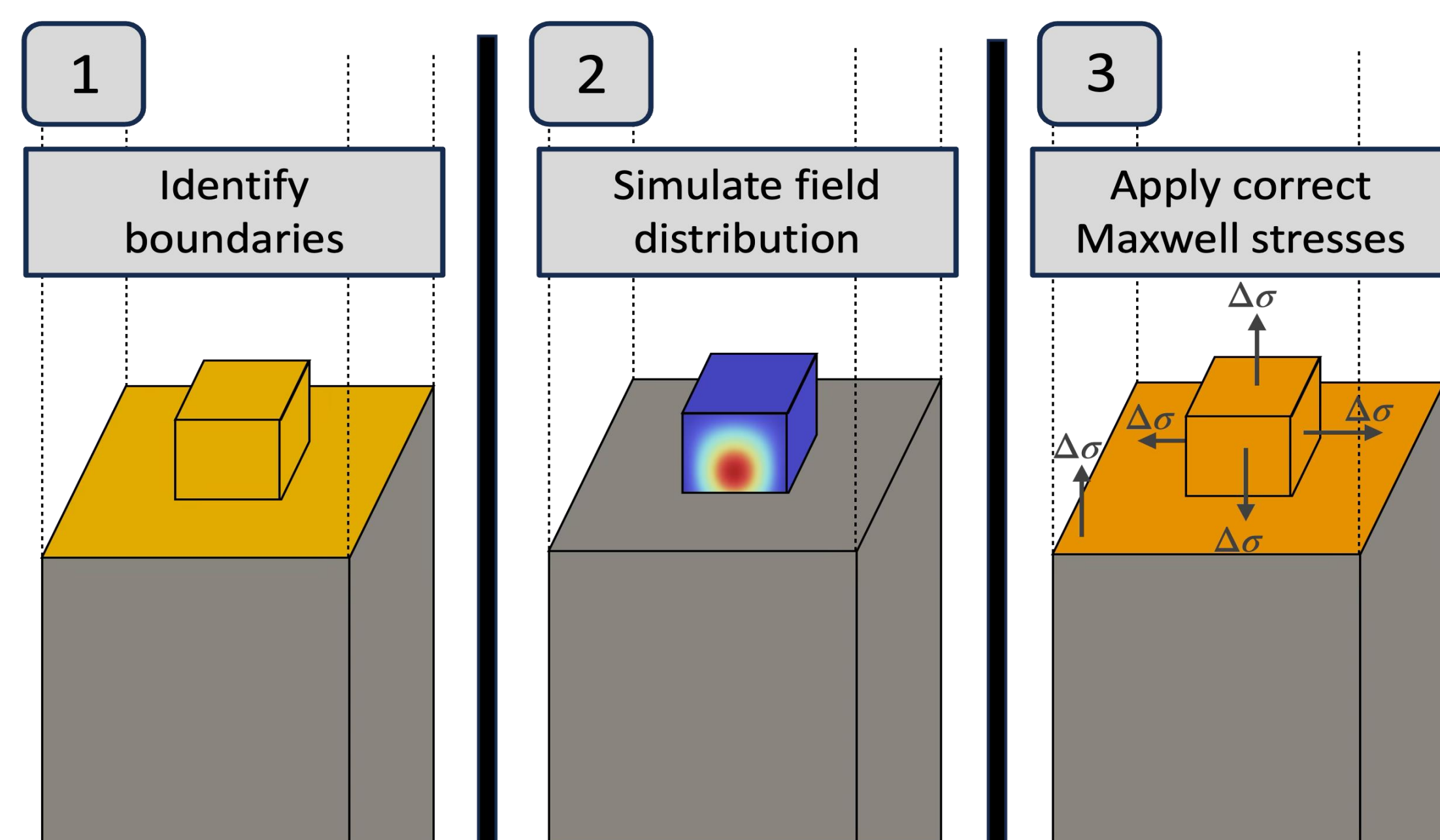


Figure 1: Simplified application of the fluctuation-dissipation theorem to metasurfaces. The field distribution inside the surface is simulated using Electromagnetic Waves, Frequency Domain studies. Afterwards the shape of the oscillating pressure and its local magnitude is given by applying Maxwell stresses to all corresponding boundaries. The dissipated power within the metasurface per period of oscillation is then determined with a Solid Mechanics, Stationary study.

Methodology

Our simulation framework is based on a formulation of the **fluctuation-dissipation theorem** [3, 4]. A virtual oscillating pressure is applied to the surface, which results in elastic energy being introduced into the material. The rate of the energy dissipation is fundamentally given by the mechanical loss of the coating material. The power spectral density of Brownian thermal displacement noise is given by [4]:

$$S(\omega, T) = \frac{8k_B T}{\omega^2} \frac{P_{\text{diss}}}{F_0^2}$$

The shape of the applied force is entirely determined by the distribution of electromagnetic energy within the structure. It is given by the Maxwell stress tensor:

$$\sigma_{ij} = \epsilon_0 \epsilon_r E_i E_j + \frac{1}{\mu_0 \mu_r} B_i B_j - \frac{1}{2} \left(\epsilon_0 \epsilon_r E^2 + \frac{1}{\mu_0 \mu_r} B^2 \right) \delta_{ij}$$

Results

The simulation framework enables the investigation of Brownian thermal noise in arbitrarily shaped metasurfaces. Results reveal a non-trivial dependence of Brownian thermal noise on both geometric parameters and optical response. Noise maxima consistently occur near the flanks of resonant features, where small parameter variations lead to rapid changes of the optical response. However, regions of high noise generally do not coincide with the regions of highest reflectance.

In addition to providing new insights into the mechanisms of Brownian thermal noise in metasurfaces, the collection of large amounts of data enables a machine-learning-assisted design optimization. This further facilitates the creation of a robust, highly reflective and low-noise metasurface for applications in high-precision metrology.

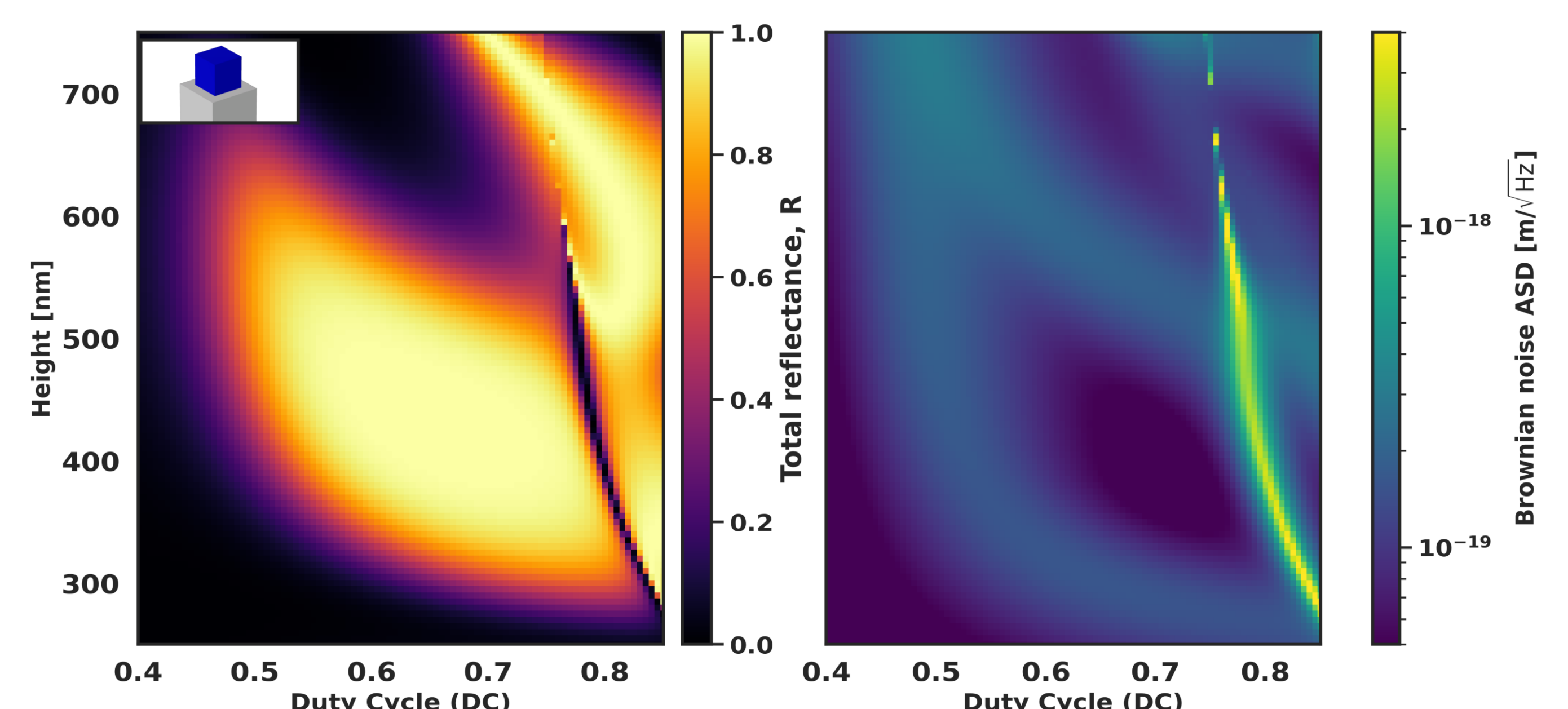


Figure 2: Exemplary results showing reflectance and Brownian noise ASD for a metasurface with cube-shaped metaatoms. Duty Cycle refers to the fill-factor of the cube with respect to the period of the unit cell of 675 nm. The calculation was performed for a temperature of 300 K, a mechanical frequency of 100 Hz and a beam radius of 500 μm . Noise maxima consistently occur near the flanks of resonant features, where small parameter variations lead to rapid changes of the scattering response.

REFERENCES

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