EPJ Web of Conferences **335**, 05015 (2025) https://doi.org/10.1051/epjconf/202533505015
EOSAM 2025

Robust meta-surface designs for ultra-high reflectivity in precision interferometry

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Abstract. Metasurfaces enable precise light manipulation, like fostering reflections close to unity, through resonance mechanisms. While traditional Bragg mirrors enable very high reflectivity they limit the achievable thermal noise. Meta-material-mirrors (MMM) can overcome the noise limitations but suffer from limited reflectivity. This trade-off is crucial for next-generation cryogenic gravitational wave detectors, such as the Einstein Telescope, which need high reflectivity and low thermal noise test mass coatings to achieve dramatic sensitivity. Hence, we are proposing a new combined design unifying the advantages from both approaches - composed of an MMM, a Fabry–Pérot spacer, and a Bragg mirror – achieving extremely high reflectance and low thermal noise. We are evaluating different 1D and 2D design approaches to achieve MMM robust to fabrication tolerances while offering broad, high reflection at 1550 nm. A key focus is on bandwidth, manufacturability, and thermal noise. This systematic analysis provides a pathway to promising MMM for production via e.g. character projection electron beam lithography, paving the way for high-performance mirrors in gravitational wave astronomy and beyond.

1 Introduction

The reduction of thermal noise plays a crucial role for future high precision optics, like interferometers. High-reflectivity mirrors have been traditionally realized using Bragg stacks. While these stacks can reach nearly 100% reflectance, their multilayer structure introduces significant thermal noise. In contrast, meta-mirrors inherently offer lower thermal noise, yet are hampered by fabrication-induced reflectivity limits. The Michelson interferometers revolutionized physics, paving the way for gravitational wave astronomy. Second-generation

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detectors observed black hole and neutron star mergers, but next-gen systems need even greater sensitivity to capture subtle space-time fluctuations [1]. Critical drivers include extended path lengths, advanced interferometer geometries, and test-mass mirrors that achieve near-unity reflectivity with minimal thermal noise. The design presented here advances prior approaches by combining a meta-surface atop a Fabry-Pérot spacer and a Bragg mirror [2], yielding enhanced performance while broadening fabrication tolerances.

2 Methodology

Our approach leverages the gradient-free optimization capabilities of the Nevergrad package [3] together with a semi-analytical rigorous coupled wave analysis (RCWA) tool [4]. The figure of merit is designed to maximize reflectivity and ensure stability around the desired wavelength (1550 nm) despite fabrication deviations. A comprehensive catalogue of candidate designs is generated and assessed through parameter sweeps and realistic Markov Chain Monte Carlo simulations using RCWA. To further validate the performance, selected designs undergo finite-difference time-domain (FDTD) simulations to monitor electromagnetic field distributions during reflection. Complementary finite element method analyses, including line-edge roughness and surface energy simulations, preselect the most promising candidates for detailed thermal noise investigation [2]. This robust workflow supports a successful pre-production phase by scoring structures based on reflectance, bandwidth, thermal noise, and reproducibility.

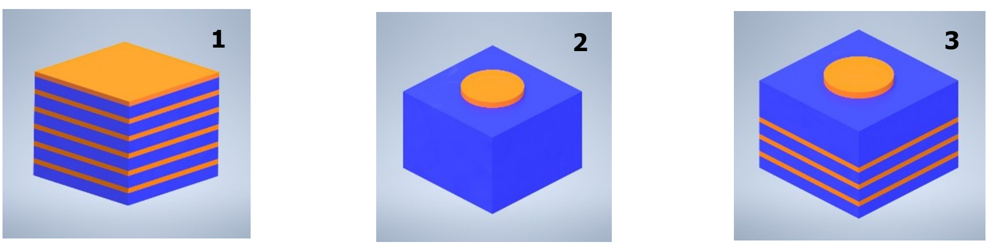

Fig. 1. Our design approach combines earlier separated Bragg (1) and Meta mirrors (2) together with a Fabry-Pérot spacer in between [2], creating a robust design with high reflectance (3).

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