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## Metamaterial Anti-Reflection Coating Alumina Optics for CMB-S4

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CMB-S4 and other next generation observatories for the cosmic microwave background (CMB) require high performance optical elements. Ideally, these optical elements need to provide a large aperture, have low losses, a high index of refraction, and operate at cryogenic temperatures. Alumina is a material that satisfies these requirements while also providing advantageous properties for filtering of infrared thermal radiation. The high index of refraction of non-porous high-purity alumina causes reflections at the level of forty percent which reduces optical throughput and can also compromise the imaging performance of the optical system. Therefore, it is critical that alumina optical elements be anti-reflection (AR) coated to improve performance. We have fabricated a metamaterial AR coating consisting of sub-wavelength structures directly diced onto the alumina substrate. This coating reduces reflections to lower than ten percent across frequencies from 70 to 170 GHz, and at angles of incidence up to 45 degrees with low cross polarization. We present the design, fabrication, measurement, and performance of this AR coating. We also discuss paths to increase production speed to accommodate large-scale experiments operating in millimeter and sub-millimeter wavelengths, such as CMB-S4.

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