The Simons Observatory: Metamaterial Microwave Absorber (MMA) and its Cryogenic Applications

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In modern microwave astrophysics instrumentation, system noise is dominated by statistical photon noise. The photon noise can be reduced by terminating stray light paths at cryogenic instead of room temperatures. Controlling stray light at millimeter wavelengths requires careful optical design and selection of absorptive materials, which must be compatible with the cryogenic operating environment. While a wide selection of absorptive materials exists, these typically exhibit high indices of refraction, which reflect/scatter a significant fraction of light before the light can be absorbed. For many lower index materials such as commercial microwave absorbers, applications in cryogenic environments require overcoming a variety of challenges. In this paper we present a new tool to control stray light: metamaterial microwave absorber (MMA) tiles. These MMA tiles are comprised of an outer metamaterial layer, which approximates a gradient index anti-reflection coating. They are fabricated via injection molding carbon loaded polyurethane (25% by mass). The injection molding technology enables mass production at low cost. The design of these tiles is presented, along with the measurements demonstrating efficient cooling to 1 K. We measured their optical performance at room temperature. Measurements verify control of reflectance to less than 1% up to 65° angles of incidence, and control of wide angle scattering below 0.01%. The dielectric properties of the material were also measured, confirming that the material maintains similar dielectric properties down to 3 K. © 2020 Optical Society of America

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1. INTRODUCTION

The Simons Observatory (SO) is a series of millimeter-wave telescopes designed to observe the Cosmic Microwave Background (CMB) temperature and polarization signals to an unprecedented sensitivity [1, 2]. With the combination of one Large Aperture Telescope (LAT) [3, 4] and three Small Aperture Telescopes (SAT) [5], the experiment will measure the temperature and polarization anisotropy of the cosmic microwave background with \( \sim 100,000 \) photon-noise dominated detectors operating at 100 mK. SO will test cosmic inflation during the early universe, characterize the primordial perturbations, measure the effective number of relativistic species and the sum of the neutrino masses, and improve our understanding of galaxy evolution and the era of cosmic reionization [2]. Modern ground-based millimeter-wave telescope receivers have advanced to the point where the noise is dominated by photon noise, meaning the thermal or electronic noise intrinsic to the detectors (and the associated readout system) is less than the statistical noise from the quantized incoming photons. Photon noise is closely related to loading from different sources, including the sky signal, the atmosphere, and extra loading from stray light. The sky signal and the atmosphere loading cannot be reduced by improving the instrument design, whereas the stray light loading can be reduced by a more efficient instrument design. Instead of following the main optical path, stray light, especially the fraction carrying room temperature photons, are reflected or scattered by the side walls of cryogenic receivers before being absorbed by the detectors. Therefore, stray light not only introduces side-lobes, but also increases detector loading which simultaneously increases the detector noise. In this paper we concentrate on suppressing stray light by minimizing reflection and scattering within cryogenic receivers.

Terminating stray light at the lowest possible temperature suppresses side-lobes and decreases the total detector loading (or “optical loading”), equivalently decreasing the photon noise. This is typically achieved by cryogenic baffling design which minimizes reflection and scattering. The baffling surfaces must be constructed of millimeter-wave absorbing material, with high absorptivity and low reflection and scattering over a wide range of incident angles and frequencies. Beyond the required optical properties, the absorbers must be efficiently cooled to cryogenic temperatures with robust thermal contacts, withstand the mechanical stress associated with the cooling process. Since cryogenic space is scarce, the absorbing material is often required to be as compact as possible. Ideally, the absorber should be light in mass, especially for future space missions.

Available options include conductively-loaded-epoxy [6], and commercially-available absorptive sheets\(^1\)/tiles\(^2\). The conductively-loaded-epoxy relies on the conductive materials to absorb the radiation, however, the high index of refraction of the epoxy gives high reflectance and scattering, depending on the roughness of the surface. In addition, the epoxy normally has a \( \sim 2 \) g cm\(^{-3}\) density, adding a significant mass to the cryogenic system. The commercially-available absorptive sheets and tiles provide high absorption, while mechanically and cryogenically attaching them to low-temperature surfaces poses great challenges. To overcome these obstacles, we developed injection-molded tiles with a gradient index anti-reflection coating. This solution provides high absorption with customized thermal and mechanical interface to low-temperature stages.

\( ^{1} \) For example, HR-10 sheets from Emerson & Cummings.

\( ^{2} \) For example, Tessellating TeraHertz RAM, Thomas Keating Ltd.

We describe the design (Section 2, 3) and characterization (Section 4, 5) of this technology, along with its application within the Simons Observatory (SO) Large Aperture Telescope Receiver (LATR) [3, 4] and Small Aperture Telescopes (SAT) [5].\(^3\) We also discuss potential future applications in Section 6.

2. OPTICAL DESIGN

The ideal baffling material minimizes reflection and scattering for light over the relevant range of angles of incidence, while mechanically (and even cryogenically) fitting within optical systems. In the case of the SO LATR, the desire to close-pack the optics tubes limits the radial extent of the absorbing material to about 1 cm to avoid clipping the beam near the front of the optics tubes (between Lens 1 and Lens 2 in Fig. 1). The tight radial space prohibits the application of ring baffles [8, 9], which are implemented in the middle section of the LATR optics tubes (between Lyot stop and Lens 3 in Fig. 1) and the SO small aperture telescopes (SAT).

A detailed study of the SO LATR optics tubes revealed that improving light absorption near the front of the optics tubes would most significantly reduce optical loading [10]. This study also showed that stray light on that section of the optics tubes ranges from \( 55^\circ \) to \( 90^\circ \) relative to the surface normal, taking up \( \sim 2\% \) of the solid angle. Controlling the stray light in that section improves the telescope’s mapping speed by \( 40\% \)–\( 80\% \), significantly increasing the sensitivity of the instrument. The Fresnel Equations show that the reflectance for dielectric materials approaches unity near grazing angles. To improve performance at these high angles the absorbers were fabricated with the absorbing face tilted at \( 26^\circ \) relative to the normal of the optics tube surface (see Fig. 2). The tilting reduces the angle of incidence by \( 26^\circ \) to \( < 64^\circ \) (incoming light cannot exceed \( 90^\circ \) angle of incidence) where it is relatively easy to absorb light with an anti-reflection coating. Please note that the angle of incidence is viewed in a time-reverse fashion here.

\( ^{3} \) This technology is also used in CCAT Prime-cam [7].

\( ^{4} \) Mapping speed is defined as \( 1/\text{NET}^2 \), where NET is the noise-equivalent-temperature (NET). More details about mapping speed are available in [11].
The goal of mass production led to the selection of injection molding carbon-loaded plastics. The carbon content increases the optical loss of the plastic materials so that the radiation is sufficiently attenuated within a small depth of bulk materials. However, the carbon-loaded plastics have relatively high dielectric functions, leading to high reflectance on a smooth surface. Therefore, an effective anti-reflection coating is designed.

At the start of the design process, the exact material properties were not known. Furthermore, it was anticipated that variations in the composition, preparation, and processing of the material could lead to significant variations in the dielectric properties of the final materials. In addition, manufactured structures may not realize the design geometry perfectly. For these reasons, the design is based on a gradient index metamaterial comprised of sub-wavelength pyramids with a 5:1 height to half-pitch ratio (see Fig. 2).

The optical performance was simulated by High Frequency Structure Simulator (HFSS). The initial simulations, assumed a relative dielectric permittivity of $\varepsilon_r \approx 4 + 0.66i$ and ideal geometry, predicted reflectance below 1% (5%) for angles of incidence up to 45° (60°) and above 75 GHz. In comparison, simulations using the manufactured geometry (see Fig. 3) and measured relative dielectric permittivity of the bulk material (Equation 1) predict reflectance below 2% (8%) for the same angles of incidence and frequency range. This performance changed within a factor of two to the initial simulation even though the input material dielectric function changed by a factor of four and the pyramid shapes are different. However, the results from this model are not as good as the measured performance. It is noteworthy that the carbon particle size is large compared to the tips ($\sim 150 \mu m$ in diameter) of the carbon loading near the tips. This implies there must be a gradient in the dielectric properties. To explore this, a model with measured pyramidal features and a four-layer approximation to a gradient in the dielectric properties was constructed. This reduced reflectance and introduced a frequency dependence similar to what is observed in Section 5. There was no indication of scattering in these simulations below 250 GHz and scattering appears to be at most percent level to 300 GHz. This family of simulations highlights the robustness of this design to changes in the dielectric properties and to a lesser extent the geometry, which is the key feature of this approach.

In developing the fabrication process, several carbon loaded material formulations were explored (e.g., carbon loaded polypropylene, carbon loaded polyethylene, carbon-fiber loaded polypropylene, and carbon loaded polyurethane). Considering manufacturability and cryogenic robustness (more details in Section 4), we chose thermoplastic polyurethane (TPU) with 25% carbon loading by mass. The loaded carbon content is conductive carbon powder with mesh between 200 – 300, corresponding to 50 – 75 $\mu m$ in diameter. The finite size of the carbon particles and the fine tip ($\sim 150 \mu m$ in the product, Fig. 3) of the pyramids leads to an inhomogeneous carbon particle filling fraction from the top to the bottom of the pyramids, resulting in a gradient in the dielectric properties as mentioned above.

Several waveguide samples with the bulk TPU material filling the 2:1 rectangular cross section were prepared in WR-28 (i.e., guide broadwall 7.11 mm and shim thicknesses of 1.4 and 5.6 mm) and WR-22 (i.e., guide broadwall 5.69 mm and shim thickness 0.6 mm). Two different methods were used to realize each waveguide sample type: (1) press fitting machined dielectric samples into a split-block waveguide fixture and (2) directly thermally molding the material into a waveguide shim. Then the complex dielectric function,

$$\varepsilon_x = \varepsilon'_x + \varepsilon''_x i \approx 16 + 11 i, \quad (1)$$

was measured by a vector network analyzer in the frequency range from 26 GHz to 52 GHz [6]. All of the samples had the same real part of the dielectric function. The imaginary parts were similar for the cast samples, but were found to be 25% higher for the mechanically inserted piece. We believe that this could be due to the presence of voids in the cast samples, mechanical stress in the inserted sample or some combination. This implies the dielectric function of this material has some degree of process dependence. Another transmission measurement implies the dielectric function changes <5% for the real part and <50% for the imaginary part from 20 GHz to 200 GHz. However, the metamaterial layer structure is designed to be robust to the variation in the complex dielectric function, which is verified by the optical measurements in Section 5.

Given the measured dielectric properties, the field penetration depth is calculated as,

$$\delta = \frac{\lambda}{2\pi k} \approx 0.12 \lambda, \quad (2)$$

where

$$k = \frac{1}{\sqrt{2}} \left( (\varepsilon''_x + \varepsilon''_x^2)^{1/2} - \varepsilon'_x \right) \approx 1.3 \quad (3)$$

is the imaginary component of the refractive index. $\varepsilon'_x$ and $\varepsilon''_x$ are the real and imaginary part of the dielectric function in Equation 1. For a free space radiation with a wavelength of $\lambda$, one obtains a power attenuation,

$$P/P_0 = e^{-2z/\delta}, \quad (4)$$

Fig. 2. MMA tile design. Top: A snapshot of a single tile design. The tilted upper surface has the pyramidal structures as described in Section 2. A zoom-in plot shows the details of the pyramidal structures, acting as a metamaterial anti-reflection coating. The bottom is curved to fit the cylindrical inside surface of the optics tube. A lip and a dent are for seamless tessellating. Bottom: A cross section of the segmented tilted surface is shown in the lower part. In a time-reverse fashion, light rays coming from the left would hit the tilted surface with a <64° angle of incidence, ensuring the required optical performance.
Fig. 3. Manufactured MMA tiles. The manufactured tiles are presented from different perspectives. The top left photo shows one tile from the absorbing surface. A microscope photo of the pyramids is shown in the insert. The pitch between pyramids is kept as 0.6 mm as designed. The bottom left two photos show the back of the tile from two other perspectives. The lightweighting pockets are visible along with the brass injected M3 nut for fastening. The photo on the right shows the assembly of 240 tiles installed on the wall of the optics tube section (see Fig. 1). A ruler (∼30 cm) is placed in the center for scale. Note that the absorbing surface appears to be black and featureless in the assembly photo. The condition stays the same regardless of lighting in the room, which supports the effectiveness of the AR-coating design even in optical.

showing that the radiation is attenuated by a factor of $1/e$, every $\delta/2$ of the bulk thickness $z$.

3. MECHANICAL DESIGN AND FABRICATION

A cross section of the segmented surface is shown in the lower part of Fig. 2, which is along the optics tube axis. Each of the segments forms a ring rotating around the cylinder axis. Within one ring, we also separate the structure into 24 arcs, spanning $15^\circ$ each. Therefore, the cylindrical surface is decomposed into one single tile by this method.8

A snapshot of the tile design is presented in the upper part of Fig. 2. The absorbing surface is covered with the optimized pyramidal structures, acting as an anti-reflective coating. Beneath the coating, the design has at least 2 mm of bulk material to absorb the radiation. According to Equation 4, radiation at different wavelengths will be effectively attenuated by

$$P/P_0 \simeq 3.6 \times 10^{-2} \simeq -14 \text{ dB} \ (\lambda = 10 \text{ mm}),$$

$$P/P_0 \simeq 1.5 \times 10^{-5} \simeq -48 \text{ dB} \ (\lambda = 3 \text{ mm}).$$

(5)

(6)

Adjacent to the absorbing surface, two sides are also designed to tilt inwards to properly form a ring once assembled. A lip and a dent are designed for tessellating to eliminate gaps between the tiles in an assembly. The bottom of the tile is curved to the surface of the optics tube cylinder where it will be installed. Fastening hundreds of the tiles in a metal cylinder raises another challenge. Ideally, there should be only one point of contact for one tile: at cryogenic temperatures, differential thermal contraction between the metal mounting structure and the plastic tile could cause a stress failure if the tile is constrained at more than one point. On the other hand, one mechanical contact limits the thermal conductance for cooling the tile. Therefore, each tile is only $3 \times 5$ cm in size, small enough that one contact is sufficient to conduct heat away at cryogenic temperatures. This is also a convenient size for mass production.

To accommodate the fine features in the design and facilitate mass-production, we choose injection molding for manufacture. During this process, a metal mold is machined to high precision first. Then the melted plastic is injected into the mold at high pressure to form the designed shape before it is removed as one piece. After the injection molding process, a brass M3 nut is installed by heat-pressing as the single point of fastening. There are several lightweighting features on the back and the bottom of the tile. Those features were developed in collaboration with an injection molding manufacturer to help the tile maintain its shape during injection molding. They are also designed with the necessary drafting angles to release the part from the injection mold. Once the mold was available, thousands of the tiles were manufactured in a month.

The successfully manufactured tiles (shown in Fig. 3) weigh $\sim 7.7$ g each. We inspected the tip of the pyramids under a microscope. The tips are rounded with a $\sim 150 \mu$m radius, a quarter of the pyramid spacing. The actual height to half-pitch ratio reduced from the designed 5:1 to around 3:1. However, a flat version of the MMA tiles were later manufactured with sharper tiles almost achieving the 5:1 ratio, as shown in Fig. 11.

4. THERMAL TESTING

For our current application in the SO LATR optics tubes, the tiles will be used in a 4 K radiation environment and cooled down to 4 K. The concern was that the 4 K radiation load can potentially heat up the absorbing surface if the tile thermal conductance is insufficient. In addition, other applications may require cooling
the tile to 1 K, for example on the Lyot stop of the SO LATR and in the SO Small Aperture Telescopes (SO SAT Cryogenic Baffling Development, 2020 in preparation). Thus, our thermal conductance test is to show whether the tile can be cooled to 1 K in a 4 K radiation environment. In a 4 K radiation environment, the estimated radiation loading per tile is ~40 nW. The test must therefore show that 40 nW applied to the absorbing surface does not appreciably raise the temperature of the surface.

Initially, we tested mechanical integrity of several carbon-loaded plastic materials under cryogenic temperatures. Samples were repeatedly immersed in liquid nitrogen to verify that they would survive multiple thermal cycles. Considering both the cryogenic survivability and the injection-molding manufacturability, carbon-loaded thermalplastic polyurethane was chosen for initial production. When the tiles were ready, the thermal conductance of the product was tested at 1 K using a dilution-cooled cryostat. One tile was first prepared with a resistive heater and three ruthenium oxide (ROX) thermometers installed (see Fig. 4). The heater was installed in a pocket on the back; the three thermometers were installed in three different positions on the absorbing surface. For mechanical and thermal conductance purposes, the heater was glued in one lightweight pocket with GE Varnish. The three thermometers were then bolted and glued (with GE Varnish) to the tile. The three thermometers were distributed in the center and on two sides of the absorbing surface. The absorbing surface, being far away from the mounting surface, is predicted to have the most significant temperature difference from the cold plate. The heater and the thermometers were connected to the outside of the cryostat via four cryogenic wires each. All of the wires together introduced <1 nW total thermal conductance, much less than the 40 nW power level being tested.

The prepared tile was fastened to the 1 K plate within the cryostat using a stainless steel M3 bolt. The M3 bolt passed through the 1 K cold plate and was threaded into the brass nut embedded in the tile. The M3 bolt was torqued to 0.35 N·m with a torque screw driver. The same value was used when installing the tiles in the SO LATR optics tubes. The radiation environment around the tile was also 1 K. Since the tile has a curved bottom surface, the thermal contact with the flat cold plate was primarily at the exposed surface of the brass nut. The middle sketch in Fig. 4 illustrates the curved-to-flat surface interface. The resistive heater had a resistance of 120 kΩ at room temperature and was measured to have a resistance of 129.7 kΩ at ~1 K. This resistance was much greater than the ~1 kΩ wire resistance, meaning that the heat dissipation on the cables was negligible. The three thermometers installed on the tiles have an absolute accuracy of ±0.1 K at 1.4 K; the thermometer installed on the cold plate has an accuracy of ±0.005 K at 1 K. During the measurement, the voltage applied across the heater was gradually increased with a one hour time interval between adjustments. This interval was much longer than the previously-measured 200-second system thermal relaxation time. The applied voltage was stepped up eight times, covering a power range of 20 nW to 30 µW. The three thermometers were read out at a rate of 5 Hz during the entire measurement. The 1 K cold plate temperature near the tile changed <0.001 K throughout the test.

At each power level, three equilibrium temperatures were obtained from the three thermometers (see Fig. 5). With 0 nW

Fig. 4. Thermal conductance test setup. These sketches on the left show the positions of the thermometers and the heater from three different perspectives. The photos on the right show the actual setup from relative perspectives. The top row shows a top view of the positions of three thermometers and a heater. The middle row shows how the tile is mounted to the 1 K cold plate with a stainless steel M3 bolt. The temperature of the 1 K cold plate is continuously monitored by a fourth thermometer. Given the curved-to-flat interface, gaps are clearly seen around the single screw contact. The bottom row shows the positions of the M3 nut and the lightweight pocket together with the position of the heater. Because of the upper pocket, power from the heater does not short to the M3 nut directly.

Fig. 5. Thermal conductance measurement. The x-axis shows the additional power applied through the heater (in addition to the static 18 nW from each thermometer); the y-axis shows the equilibrium temperatures for each of the three thermometers installed on the tile. The location of each thermometers are illustrated in Fig. 4. The 0.1 K uncertainty in the thermometer temperatures is expressed in error bars. The three sets of temperature data are shifted for clarity. The black line at the bottom records the temperature of the cold plate. The vertical red line notifies the position of the 40 nW radiation loading in a 4 K radiation environment.
heater power applied, all three thermometers exhibited a higher temperature than the cold plate. The center thermometer measured around 0.1 K above the cold plate temperature, and the right and left side thermometers measured about 0.1 K above the center thermometer. This can be explained by a combination of the absolute accuracy of the thermometers (± 0.1 K) and the thermometer self-heating. The self-heating comes from the current running through the thermometers generating around 18 nW for each thermometer. However, the accuracy of the base temperatures did not affect the following measurement since we were interested in how the temperatures would change when extra loading was applied. The thermometers may not have an accurate absolute calibration, but they are sensitive to relative changes.

As illustrated in Fig. 5, no change in the absorbing surface temperature was measured below 100 nW of applied extra power. As the applied loading reached 30 µW, the temperatures from the three thermometers increased by ∼1 K. A red vertical line is plotted in Fig. 5 to emphasize the value of 40 nW, which is the expected radiative loading from a 4 K radiation environment. This result implies that a 4 K radiation environment does not raise the temperature of the optical surface at 1 K. Furthermore, Fig. 5 shows that no significant temperature rises occur until around 300 nW, implying that the tile can stay at 1 K in a radiation environment as high as:

\[
T_{\text{upper}} = \left( \frac{P_{\text{upper}}}{P_{\text{4K}}} \right)^{\frac{1}{4}} T_{\text{4K}} = \left( \frac{300}{40} \right)^{\frac{1}{4}} \approx 4.4 \pm 6.6 \text{ K.} \tag{7}
\]

As the final means of verification, recently the upper optics tube section was successfully cooled to 4 K in the LATR with 240 MMA tiles installed, as shown in Fig. 3 on the right.

5. OPTICAL TESTING

Optical properties of the MMA tiles were measured for diffuse reflection, or scattering, at 110 GHz and specular reflection in the frequency range from 90 GHz to 170 GHz. The measurements also covered different angles of incidence. The results verified that the tiles achieved the desired high absorptivity and low reflection and scattering.

The optical measurements were conducted at room temperature. A consideration in using the technology at low temperatures is the following – the detailed composition and realization of the material (e.g., amorphous lamp black, activated carbon, pyrolytic carbon, graphite, etc.) influences the temperature dependence of the bulk resistivity and thus the dielectric function of the plastic [12, 13]. From our measurement of the bulk resistivity at 3 K relative to ambient, this is a modest effect for the carbon loaded TPU formulation explored here. Therefore, dramatic changes of the tile’s optical properties are not expected in cryogenic temperatures down to 3 K or lower.

A. Optical Hardware

In our measurement setup, a source emits a millimeter-wave through a feed-horn toward a parabolic mirror, which then reflects a plane wave toward the sample, at an angle of incidence controlled by a rotary stage. The signal reflected off the sample propagates to a second mirror, followed by the receiver feed-horn [14]. The sketch of the setup is shown in Fig. 6. Eccosorb HR-10 sheets are placed on surrounding surfaces to reject multipath propagation. The alignment of the receiver is controlled with a three-axis stage. The tilt of the sample is controlled with a three-point micrometer mount.

B. Receiver Electronics

A correlation receiver is used for these measurements. The receiver compares a reference tone to a signal which has passed through the optical path, creating an interference pattern between the two [14]. The correlation receiver is summarized in Fig. 7. The Re-configurable Open Architecture Computing Hardware (ROACH-2) board correlates the reference and modulated signals. The millimeter-wave source sends a signal, ranging from 10.5 GHz to 13 GHz, to a multiplier which passes through a passive multiplying chain. The W-band (80 – 125 GHz) and D-band (125 – 180 GHz) millimeter-wave sources use multiplication factors of 9 and 12, respectively. The signal is then modulated by the sample. The modulated and the reference signals are separately sent to two harmonic mixers. The mixers extract interference information caused by the offset frequency and send it to the correlation device. This receiver outputs the amplitude and phase of the signal in narrow (50 MHz) spectral bands. Only the amplitude is used in this analysis, though we note that the phase information could be used to improve these measurements in the future.

C. Measurement

In order to measure their optical properties, an array of tiles are screwed down to a 3D-printed plate. The 3D-printed plate compensates the wedge shape of individual tiles so that absorbing surfaces of all tiles are aligned and oriented upward, forming a 12” × 12” flat surface (Fig. 8).

For comparison, we acquired the Tessellating TeraHertz RAM from TK Instruments. The TK tiles are 25 mm × 25 mm square tiles that can be tessellated to cover a flat surface. The pyramidal structures (~2.5 mm in pitch and height) on the optical surface are designed to reduce the specular reflection and scattering in the 100 – 1000 GHz region. Although the TK tiles and our MMA tiles both have pyramidal structures on the optical surface.
Fig. 7. Summary of the holographic imaging setup. A splitter sends one signal from a millimeter-wave source to a Pacific Millimeter harmonic mixer, while sending the same signal to be modulated by the device under test. The reference and modulated signal are mixed with an LO with an offset frequency \( f_{\text{offset}} \) from the millimeter wave source. The two Pacific Millimeter harmonic mixers extract interference information caused by \( f_{\text{offset}} \) and sends this to the ROACH-2 field programmable gate array (FPGA) board where the two signals are correlated.

Fig. 8. MMA measurement sample. MMA tiles are individually bolted into a 3D-printed plate such that each MMA surface sits flat to form a 12” × 12” testing surface.

C.1. Reflection Measurement

Once the setup is aligned using an aluminum plate in place of the sample, a calibration data set is taken by measuring the specular reflectance of the same aluminum plate as a function of frequency. The sample measurements are then normalized using the aluminum plate data.

Fig. 9 shows the reflected power measured for the MMA and TK samples, with the MMA tiles measured from 90 GHz to 170 GHz and the TK tiles measured from 90 GHz to 110 GHz. The measured results demonstrate the relative performance of the two. For the MMA tiles, specular reflection is at sub-percent levels (< -20 dB) for all angles of incidence except for 65° (∼ -15 dB). Note that 65° is higher than the angle of incidence upper limit in our application (see Section 2, 3). To demonstrate the effectiveness of the anti-reflection coating, a smooth-surface carbon-loaded black polyethylene sample is measured. With the coating, the MMA tiles reduce the specular reflection by ∼−20 dB. Meanwhile, the TK tiles were also measured in part of the frequency range. The specular reflection from the TK tiles is 5 to 10 dB higher than that from the MMA tiles at different angles of incidence.

C.2. Scattering Measurement

The scattered power off the surface of the sample is determined by measuring the received power as a function of the receiver’s angle, fixing the source feed horn at a set angle (Fig. 6). The source (incident) and receiver (reflected) angles are controlled by two rotary stages. The radiative source sends one frequency and is held at a constant position (i.e. angle of incidence), while the receiver sweeps across different angles. Fig. 10 shows the scattering measurement with a 110 GHz source at four angles of incidence: 15°, 30°, 45°, and 60°. To account for the uneven surface, they function differently. Pyramids in our MMA tiles, with the sub-wavelength scale, act more as a layer of medium with changing index of refraction; while pyramids in the TK tiles works more within the geometric optics regime to increase the number of bounces of the incoming radiation, due to the adopted surface geometry [15]. The TK tiles have long been the preferred absorbers in millimeter wavelengths due to their optical performance. Because our MMA tiles are optimized to perform well at our operating wavelengths, we expect an improvement in performance. Even though our measurement only verifies the performance within 90 – 170 GHz, our MMA tiles are designed to work from 30 – 270 GHz following the same physics principles.
Fig. 9. Specular reflection measurements. The two panels show the specular reflection measurements of the MMA tiles and the TK tiles at different angles of incidence, including $15^\circ$, $30^\circ$, $45^\circ$, $60^\circ$, and $65^\circ$. The samples are measured in W-band (90 GHz to 110 GHZ) and D-band (130 GHz to 170 GHz). The top panel shows the W-band (90 GHz to 110 GHZ) and D-band (130 GHz to 170 GHz) reflection of the MMA tiles. The measurement gap in the top panel is due to the different frequency bands of the two sources used in the setup. The bottom panel measures the W-band (90 GHz to 110 GHZ) reflection of the TK tiles. The measurement of a smooth-surface black polyethylene is included in both panels, which is conducted with a $30^\circ$ angle of incidence. Comparing the smooth-surface sample (purple triangles) and our MMA tiles (blue crosses), $\sim -20$ dB specular reflection reduction is achieved with the anti-reflection coating.

Fig. 10. Scattering measurement. The four panels show front scattered power off the sample with the source located at four angles of incidence, $15^\circ$, $30^\circ$, $45^\circ$, and $65^\circ$. The source was set at 110 GHz. Each of the measured data points was averaged over 17 different rotation angles, from which the associated error bars were also estimated. The vertical black lines indicate the position of the specular reflection directions. The red data points show the results from the TK tiles while the blue data points show the results from the MMA tiles. The TK tiles are measured to have a systematically higher scattering than the MMA tiles, which is consistent with the increased specular reflection shown in Fig. 9.

The integrated scattering power is calculated by integrating the scattering over the corresponding solid angles (Eq. 8). The sample’s fractional integrated scattering power, denoted as $S_r$, is estimated from the 17 repeated measurements for each angle of incidence.

| $\theta_1$ | $15^\circ$ | $30^\circ$ | $45^\circ$ | $60^\circ$ |
|-----------|-----------|-----------|-----------|-----------|
| MMA       | 0.49 ± 0.03% | 0.12 ± 0.002% | 0.27 ± 0.01% | 0.83 ± 0.01% |
| TK        | 0.67 ± 0.02% | 0.53 ± 0.01% | 1.98 ± 0.02% | 2.24 ± 0.02% |

Table 1. Integrated scattering power (in percentage) with different source angle of incidence $\theta_1$ at 110 GHz for MMA and TK tiles. Integration is from $\theta_R = 0^\circ$ to $45^\circ$ away from the specular reflection direction. The cited error is the standard error of the mean over the 17 repeated measurements for each angle of incidence.
Fig. 11. Manufactured square tiles. The 2.5 cm × 2.5 cm flat tiles are also manufactured via injection molding with the same MMA structure on the absorbing surface. The main photo on the bottom shows two square tiles from the front and the back. Major features on the tiles were denoted as well. A microscope photo of the pyramids is shown on the top left. The photo shows the sharp features of the pyramids which are only 0.6-mm wide and 1.5-mm tall. The pyramids show sharper features compared to the ones in the tilted tiles (Fig. 3). That is because the square tiles are smaller and less complicated in shape, which makes the injection molding process easier.

is normalized by the total integrated input power where \( B \) is the sample measurement, \( A \) is the normalized aluminum plate reflection and scattering profile, and \( \theta_r \) is receiver angle.

\[
S = \int_0^\pi B \sin(\theta_r) d\theta_r / \int_0^\pi A \sin(\theta_r) d\theta_r. \tag{8}
\]

We do not include the power beyond 45° (\( \pi/4 \)) away from the specular reflection direction, considering its negligible contribution. We calculate the integrated scattering power for our MMA tiles and the TK tiles, listed in Table 1. The results demonstrate the MMA tiles have lower integrated scattering power compared to the TK tiles, meeting the 1% requirement for angle of incidence ≤ 45°.

6. FUTURE APPLICATIONS

For more general use, a flat and square version of the MMA tile was already manufactured in the quantity of > 10,000. The square tiles come in the size of 2.5 cm × 2.5 cm with the same anti-reflection surface (Fig. 11). Each of the flat tiles weigh ~ 4 g. Tessellating features cover the sides of the square tiles; two sides of the square overhang as lips while the other two sides indent. These features enable seamlessly tessellating multiple tiles together. Given the limited thickness (~ 6 mm), an injected nut cannot be installed; instead a shaft was designed on the back for alignment. For fastening, four over-sized M2 screw holes were designed on the tessellating lip. Correspondingly, four recesses for the screw head (from adjacent tiles) were designed on the tessellating dent (see Fig. 11). This version of MMA tile is designed to be applied on any flat surfaces by tessellation. They are already used to cover both sides of the Lyot stop in the SO LATR optics tubes (as shown in Fig. 1). The tile-covered Lyot stop has been tested for thermal properties to 4 K.

Given the vast potential in customization, the MMA technology provides a viable solution to blacken cryogenic surfaces with diverse geometries. Therefore, the technology can be useful for many future cryogenic experiments.

7. CONCLUSION

The meta-material absorber (MMA) provides an effective, novel, and low-cost solution to absorb millimeter-wave radiation at cryogenic temperatures. Once the injection mold is manufactured, the tiles are mass-produced at low cost (< 1/10 of conventional methods) with a thousands-per-month production rate. Both the initial mold machining and injection molding were performed completely by an external shop, without any involvement from the research group. In addition, the technology also enables a high level of customization in the design. For future cryostat development, customized tiles can be designed and manufactured in this way to achieve the enhanced absorption properties, while fitting the geometry of the specific cryostat designs.

The absorber was successfully cooled down to 1 K with a single thermal contact. The optical properties, including specular reflection and scattering, were measured at different angles of incidence in the frequency band from 90 GHz to 170 GHz. The specular reflection is < −30 dB for angles of incidence ≤ 45°. Even at 65°, the specular reflection is only ~ −15 dB. The integrated scattering power is less than 1% with the angle of incidence ≤ 45°. Even though this application was tailored for the frequency band from 30 GHz to 270 GHz, the metamaterial anti-reflection coating parameters can easily be tuned for longer wavelengths. Tiles tuned for shorter wavelengths will be challenging because the feature size is limited by injection-molding and carbon grain dimensions.

The design philosophy breaks the overall surface into basic tiles, facilitating their application to an extended surface. Unlike painted absorbing surfaces, the modularized design allows for the easy replacement of tiles, should part of the surface be damaged. The wedge-shape tile introduced in this paper is designed to work in a specific cylinder for Simons Observatory and CCAT-Prime. But different geometries, such as flat square tiles, are also available with similar optical performance.

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REFERENCES

1. N. Galitzki et al., “The Simons Observatory: instrument overview,” in Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy IX, vol. 10708 J. Zmuidzinas and J.-R. Gao, eds., International Society for Optics and Photonics (SPIE, 2018), pp. 1 – 13.
2. Simons Observatory Collaboration et al., “The simons observatory: science goals and forecasts,” J. Cosmol. Astropart. Phys. 2019, 056 (2019).
3. N. Zhu, J. L. Orlowski-Scherer, Z. Xu et al., “Simons Observatory large aperture telescope receiver design overview,” in Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy IX,.
4. J. L. Orlowski-Scherer, N. Zhu, Z. Xu et al., “Simons Observatory large aperture receiver simulation overview,” in *Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy IX*, vol. 10708 J. Zmuidzinas and J.-R. Gao, eds., International Society for Optics and Photonics (SPIE, 2018), pp. 644 – 657.

5. A. M. Ali et al., “Small aperture telescopes for the simons observatory,” J. Low Temp. Phys. (2020).

6. E. J. Wollack, D. J. Fixsen, R. Henry, A. Kogut, M. Limon, and P. Mirel, “Electromagnetic and thermal properties of a conductively loaded epoxy,” Int. J. Infrared Millim. Waves 29, 51–61 (2008).

7. E. M. Vavagiakis et al., “Prime-Cam: a first-light instrument for the CCAT-prime telescope,” in *Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy IX*, vol. 10708 J. Zmuidzinas and J.-R. Gao, eds., International Society for Optics and Photonics (SPIE, 2018), pp. 187 – 202.

8. R. J. Thornton et al., “THE ATACAMA COSMOLOGY TELESCOPE: THE POLARIZATION-SENSITIVE ACTPol INSTRUMENT,” The Astrophys. J. Suppl. Ser. 227, 21 (2016).

9. J. Iuliano, J. Eimer, L. Parker, G. Rhoades et al., “The Cosmology Large Angular Scale Surveyor receiver design,” in *Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy IX*, vol. 10708 J. Zmuidzinas and J.-R. Gao, eds., International Society for Optics and Photonics (SPIE, 2018), pp. 259 – 277.

10. J. E. Gudmundsson, P. A. Gallardo, R. Puddu, S. R. Dicker et al., “The Simons Observatory: Modeling Optical Systematics in the Large Aperture Telescope,” arXiv e-prints arXiv:2009.10138 (2020).

11. C. A. Hill, S. M. M. Bruno, S. M. Simon et al., “BoloCalc: a sensitivity calculator for the design of Simons Observatory,” in *Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy IX*, vol. 10708 J. Zmuidzinas and J.-R. Gao, eds., International Society for Optics and Photonics (SPIE, 2018), pp. 698 – 718.

12. A. W. Smith and N. S. Rasor, “Observed dependence of the low-temperature thermal and electrical conductivity of graphite on temperature, type, neutron irradiation, and bromination,” Phys. Rev. 104, 885–891 (1956).

13. A. Sihvola, *Electromagnetic Mixing Formulas and Applications* (Institution of Engineering and Technology, London, United Kingdom, 2008), Electromagnetic Wave Series ed.

14. G. E. Chesmore, T. Mroczkowski, J. McMahon, S. Sutariya, A. Josaitis, and L. Jensen, “Reflectometry Measurements of the Loss Tangent in Silicon at Millimeter Wavelengths,” arXiv e-prints arXiv:1812.03785 (2018).

15. T. K. Ltd. “Space qualified tessellating terahertz rams for the 50 to 1000 ghz region and beyond,” (2020).