Radio-transparent multi-layer insulation for radiowave receivers

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In the field of radiowave detection, enlarging the receiver aperture to enhance the amount of light detected is essential for greater scientific achievements. One challenge in using radio transmittable apertures is keeping the detectors cool. This is because transparency to thermal radiation above the radio frequency range increases the thermal load. In shielding from thermal radiation, a general strategy is to install thermal filters in the light path between aperture and detectors. However, there is difficulty in fabricating metal mesh filters of large diameters. It is also difficult to maintain large diameter absorptive-type filters in cold because of their limited thermal conductance. A technology that maintains cold conditions while allowing larger apertures has been long-awaited. We propose radio-transparent multi-layer insulation (RT-MLI), composed from a set of stacked insulating layers. The insulator is transparent to radiowaves, but not transparent to infrared radiation. The basic idea for cooling is similar to conventional multi-layer insulation. It leads to a reduction in thermal radiation while maintaining a uniform surface temperature. The advantage of this technique over other filter types is that no thermal links are required. As insulator material, we used foamed polystyrene; its low index of refraction makes an anti-reflection coating unnecessary. We measured the basic performance of RT-MLI to confirm that thermal loads are lowered with more layers. We also confirmed that our RT-MLI has high transmittance to radiowaves, but blocks infrared radiation. For example, RT-MLI with 12 layers has a transmittance greater than 95% (lower than 1%) below 200 GHz (above 4 THz). We demonstrated its effects in a system with absorptive-type filters, where aperture diameters were 200 mm. Low temperatures were successfully maintained for the filters. We conclude that this technology significantly enhances the cooling of radiowave receivers, and is particularly suitable for large-aperture systems. This technology is expected to be applicable to various fields, including radio astronomy, geo-environmental assessment, and radar systems.

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I. INTRODUCTION

Progress in the development of low-temperature detectors has led to breakthroughs in various fields of radiowave detection including radio astronomy1–3 and submillimeter-wave imaging for geo-environmental assessment4. In particular, large detector arrays in a large-aperture system enable faint signals to be detected because the total amount of detected light is large. This has led to greater scientific achievements in various fields, such as cosmic microwave background radiation measurements5. A major challenge in radiowave receiver systems is keeping detectors cool. Various techniques have been developed, e.g., shading the inside of the aperture using absorptive-type filters with dielectric materials6, reflective-type filters (e.g., metal mesh filters), or combinations of these. These filters are kept cold using thermal links from the cold stages of a cryocooler or from a general cooling medium.

However, enlargement of the aperture leads to new difficulties, such as in fabricating large-diameter metal mesh filters and in maintaining uniformly cold temperature conditions over absorptive-type filter surfaces. Thermal re-emission from a warm filter then becomes a serious issue. Therefore, a technology that enables large-aperture systems to maintain a cold condition is required.

In this paper, we propose radio-transparent multi-layer insulation (RT-MLI) composed of a set of stacked insulating layers. The insulating material is transparent to radiowaves but blocks infrared radiation. The RT-MLI leads to a reduction in thermal loads while maintaining a uniform surface temperature. We measured the basic performance of RT-MLI in terms of reduction in thermal load and transmittance. We also demonstrated its cooling abilities in combination with absorptive-type filters.
II. RADIO-TRANSPARENT MULTI-LAYER INSULATION (RT-MLI)

A. Idea and design

A multi-layer insulation (MLI) is a thermal insulation system composed of multiple layers of thin insulating sheets. MLI is a major concept in thermal design and is primarily intended to reduce the heat contributed by thermal radiation. This technology is commonly used for applications in vacuum conditions, where conduction and convection are significantly reduced and heat radiation dominates. The principle behind MLI is to balance the thermal radiation between layers. More layers can be added to further reduce radiation losses.

| Material     | Foamed polystyrene |
|--------------|---------------------|
| Density      | 0.025 g/cm³         |
| Thermal conductivity | 0.028 W/m-K   |
| Coefficient of thermal expansion | 7 × 10⁻⁵ K⁻¹ |
| Index of refraction | 1.03       |

* TABLE I. Physical properties of Styroace-II Styrofoam at room temperature [a] *

[a] http://www.dowkakoh.co.jp/styrofoam/data.html

Evaporated metal films are popular materials for MLI. However, they are not transparent to radio waves. Replacement of evaporated metal films with a radio-transparent material enables the same principle as MLI to be exploited for radio waves. Foamed polystyrene is an appropriate insulation material. It has high transmittance in the millimeter-wave range but almost zero transmittance in the infrared region. Additionally, anti-reflection coatings are unnecessary on the surface because the index of refraction of foamed polystyrene is low. We used a commercial material, Styroace-II Styrofoam, provided by the Dow Chemical Company. The physical properties of this material are summarized in Table I.

We fabricated a RT-MLI using a set of stacked Styrofoam layers, as shown in Fig. 1.

B. Principle

![FIG. 2. Layout showing the principle behind RT-MLI. Exchanges of thermal radiation between the layers are balanced. The thermal loads conducted from the top surface to the bottom surface in each layer are also balanced with the exchanged radiation on each surface.](image)

The principle underpinning RT-MLI is similar to that of conventional MLI. As shown in Fig. 2, thermal radiation exchanges between the layers are balanced. By neglecting higher-order effects, the exchanged thermal loads per unit area can be described as follows:

\[
q_1 = \sigma \left[ (T_{\text{high}})^4 - \varepsilon (T_{\text{top}1})^4 \right],
\]

\[
q_2 = \sigma \left[ \varepsilon (T_{\text{bottom}1})^4 - \varepsilon (T_{\text{top}2})^4 \right],
\]

\[\vdots\]

\[
q_N = \sigma \left[ \varepsilon (T_{\text{bottom}N-1})^4 - \varepsilon (T_{\text{top}N})^4 \right],
\]

\[
q_{N+1} = \sigma \left[ \varepsilon (T_{\text{bottom}N})^4 - (T_{\text{low}})^4 \right],
\]

where \(q_i\), \(\sigma\), and \(\varepsilon\) denote the load into the \(i\)-th layer from the direction of the previous layer, the Stefan-Boltzmann constant, and the effective emissivity of the Styrofoam, respectively. Because each component of the radiation is balanced, i.e., \(q_1 = q_2 = \cdots = q_{N+1}\), summation of the above equations over all layers gives:

\[
q = \frac{1}{N+1} \cdot \sigma \left[ (T_{\text{high}})^4 - (T_{\text{low}})^4 \right] - \frac{1}{N+1} \cdot \varepsilon \sigma \sum_{i=1}^{N} \left( (T_{i}^{\text{top}})^4 - (T_{i}^{\text{bottom}})^4 \right). \tag{5}
\]

Inside each layer, the thermal conductance is also balanced with respect to the thermal radiation for each layer surface:

\[
q = \frac{\kappa}{d} (T_{i}^{\text{top}} - T_{i}^{\text{bottom}}), \tag{6}
\]

where \(\kappa\) and \(d\) are the thermal conductivity and layer thickness, respectively. This equation indicates that the contribution of the second term in Eq. 5 is significant
when the magnitude of \( q \) is large (i.e., the number of layers is small)\(^{11}\).

For conventional MLI, the second term in Eq. 5 is negligible because of \( T_i^{\text{top}} = T_i^{\text{bottom}} \). With this approximation, Eq. 4 reduces to:

\[
q = \frac{1}{N + 1} \sigma (T_{\text{high}}^4 - T_{\text{low}}^4). \tag{7}
\]

The thermal radiation is proportional to the inverse of the number of layers plus one, i.e., \( q \propto 1/(N + 1) \). This simplified model for the conventional MLI is called the \( 1/(N + 1) \) law in this paper. For RT-MLI, the balanced radiation tends to be smaller than that predicted by the \( 1/(N + 1) \) law because \( T_i^{\text{top}} > T_i^{\text{bottom}} \). Therefore, a dedicated simulation has to be performed by simultaneously solving Eqs. 5 and 6.

Another unique feature of RT-MLI is that the above equations are independent of the layer area. This means that the uniformity of the surface temperature is guaranteed in principle. RT-MLI is applicable to large-aperture systems without any change in thermal shielding performance; this is a major advantage of the technology.

### C. Reduction of thermal radiation

The performance in terms of the reduction in thermal radiation was measured using the setup shown in Fig. 3. The cryostat consisted of a vacuum chamber and a copper radiation shield inside the chamber. A two-stage Gifford-McMahon (GM) cryocooler (Sumitomo Heavy Industries Ltd., RDK-408S) maintained cold conditions inside the cryostat; the first stage maintained shield temperatures at around 27 K, and no thermal link from the second stage was used in this test. The cylindrically shaped chamber had a diameter of 508 mm and height of 480 mm. There was a circular aperture of diameter 260 mm on top of the chamber. This aperture was sealed with a high-density polyethylene window. The aperture of the shield was 210 mm in diameter. A pyramid-shaped absorber array was located under the aperture. Each absorber piece consisted of an Eccosorb-coated aluminum block and therefore had good thermal conductance, similar to that of a metal\(^{12,13}\). The absorbers were set on a copper plate (of thickness 5 mm) that was also cooled by the first stage of the cryocooler; this resulted in a uniform temperature across all absorbers\(^{12,13}\). The thermal conductance between the copper plate and the cryocooler was approximately 1 W/K. A blackbody emitter (Eccosorb CV-3 from Emerson & Cuming Microwave Products, Inc.) at room temperature (\( \sim 298 \) K) was also set outside the vacuum window.

We set the RT-MLI layers behind the shield aperture using a Styrofoam cylinder (inner and outer diameters 215 mm and 225 mm, respectively, and height 50 mm). At the bottom of the cylinder, small tabs prevented the RT-MLI layers from falling. The RT-MLI layers were placed in the cylinder without any pressure except that due to gravity. The cylinder was placed on top of Styrofoam columns that were placed at the edge of the copper plate of the absorbers. The upper side of the RT-MLI directly faced the vacuum window. The thermal conductivity of the support structure was negligible; the RT-MLI did not indicate any cooling other than radiative cooling. While varying the number of Styrofoam layers used, we measured the temperatures achieved at the locations shown in Fig. 3.

![FIG. 3. Layout for measuring the basic performance of the RT-MLI in reducing room temperature radiation. Five thermometers were located at the positions marked by solid dots, a–e. We monitored the top and bottom surface temperatures of the RT-MLI as well as the temperatures on the absorber array and the radiation shield. Thermal loads passing through the RT-MLI were measured by obtaining the temperature difference between thermometers d and e.](image)

| RT-MLI: number of layers | 3 | 6 | 12 | 17 |
|--------------------------|---|---|----|----|
| a: RT-MLI (top-center)   | 259.4 | 267.4 | 274.5 | 282.4 |
| b: RT-MLI (bottom-center)| 186.5 | 171.8 | 154.7 | 142.5 |
| c: RT-MLI (bottom-edge)  | 185.4 | 169.3 | 154.4 | 142.1 |
| d: Absorber              | 29.9  | 29.3  | 28.6  | 28.1  |
| e: GM first stage        | 27.6  | 27.4  | 27.2  | 27.0  |

The temperatures for each configuration are summarized in Table II. The bottom side of the RT-MLI achieved lower temperatures as the number of layers increased. In contrast, the top side temperature increased because of the smaller temperature gradient associated with the larger number of layers, as predicted by Eq. 5. A comparison between the temperatures obtained from measurements and those from simulations based on Eq. 6 and Eq. 7 is shown in the top panel of Fig. 4. The middle panel of Fig. 4 demonstrates temperature uniformity across the RT-MLI surface. For each configuration, the thermal loads passing into the absorbers are shown in the
The transmittance of the RT-MLI was measured using two different systems: a Fourier transform spectrometer (FTS) and a radiowave signal generator. The FTS system consisted of Fourier transform infrared spectrometers from the Japan Spectroscopic Corporation (JASCO, Tokyo, Japan) having a combination of two sensors: an indium antimonide (InSb) hot electron bolometer (QMC Instruments Ltd., Cardiff, United Kingdom) for measurements between 180 GHz and 1.6 THz, and a pyroelectric detector for measurements above 1.6 THz. In the latter system, the radiowave signals were generated by a signal generator (E8247C, Agilent Technologies Inc., Santa Clara, California) with multiplication performed using the AMC-10-RFH00 (AMC-05-RFH00) of Millitech Inc. (Northampton, Massachusetts) for the 80 GHz–110 GHz (140 GHz–220 GHz) frequency band. The intensity of the signal was measured using diode detectors: DET-10 (or DET-05) of Millitech Inc. for the 80 GHz–110 GHz (or 140 GHz–220 GHz) frequency band. The transmittance was obtained from the ratio of the measured signal intensity before inserting the RT-MLI to that after its insertion.

The reduction in thermal load was approximately 1 W. This confirmed the reduction in thermal load, which follows the description provided in section II B.

The measured transmittance for each layer configuration is shown in Fig. 5. We did not deposit any anti-reflection coating on the RT-MLI surface. The logarithm of the transmittance was roughly proportional to the number of layers (N), i.e., the transmittance of an N-layer RT-MLI was approximately 0.997^N at a frequency of 200 GHz.
RT-MLI at radiowave frequencies. The transmittance of a Styrofoam block is also shown in Fig. 5. The Styrofoam block thickness (18 mm) was equivalent to the thickness of the 6-layer RT-MLI; a consistent transmittance was obtained.

III. DEMONSTRATION WITH A COMBINATION OF RT-MLI AND ABSORPTIVE-TYPE FILTERS

We also demonstrated the effects of RT-MLI in a system having absorptive-type filters. We emulated the receiver system shown in Fig. 6 and Fig. 7, but we used an absorber array instead of a detector array. We installed two sets of RT-MLIs between each layer, including the layers of the vacuum window, polytetrafluoroethylene (PTFE) filter, and 66-Nylon filter. Using copper wires (2 mm diameter) and copper jigs that held the filters, the PTFE filter was thermally linked to the first stage of the GM cryocooler. The Nylon filter and the absorbers were also linked to the second stage of the GM cryocooler. For the demonstration, the thermal conductance values of each thermal link were maintained at the low value of approximately 0.05 W/K. We did not need any thermal link to the RT-MLI because the heat was expelled through radiative cooling. Therefore, the installation of the RT-MLI did not place any additional load on the cryocooler.

We confirmed a significant reduction in the thermal loads passing into the absorbers (Fig. 8). The lower temperatures achieved in the cryocooler also indicated a reduction in thermal load of the system. This cryocooler achieved temperatures of 26.5 K and 5.5 K for each stage without any additional load from outside the radiation shield. The typical heat capacity curve of the cryocooler indicates a significant load reduction of \(~4\) W (\(~3\) W) for the first (second) stage. We confirmed that RT-MLI

\[ \text{TABLE III. Temperatures (K) obtained the setup in Fig. 6; the additional radiation shielding took the form of no shielding, installation of the Styrofoam blocks, and installation of RT-MLI (12 layers above the PTFE filter and 5 layers above the Nylon filter).} \]

| Additional shields | Nothing | Styrofoam block | RT-MLI |
|--------------------|---------|-----------------|--------|
| A : PTFE           | 218.9   | 133.8           | 95.7   |
| B : Nylon (center) | 128.5   | 48.7            | 36.3   |
| B' : Nylon (edge)  | 43.5    | 31.5            | 24.9   |
| C : Absorber       | 15.5    | 9.2             | 8.2    |
| D : GM second stage| 8.0     | 6.2             | 5.9    |
| E : GM first stage | 29.6    | 27.1            | 26.7   |

We confirmed a significant reduction in the thermal loads passing into the absorbers (Fig. 8). The lower temperatures achieved in the cryocooler also indicated a reduction in thermal load of the system. This cryocooler achieved temperatures of 26.5 K and 5.5 K for each stage without any additional load from outside the radiation shield. The typical heat capacity curve of the cryocooler indicates a significant load reduction of \(~4\) W (\(~3\) W) for the first (second) stage. We confirmed that RT-MLI
is useful to shield the aperture from outside thermal radiation.

FIG. 8. [Top]: Temperatures attained at each layer as shown in Fig. 6 and Table III. [Bottom]: Thermal loads passing into absorbers measured using temperature differences between C and D in Fig. 6 and Table III. Estimated thermal radiation from the Nylon filter is also shown. The difference between the measured load and the estimated radiation (≈ 0.1 W) indicates that effects of reflected radiations from the upper layers. A setup that has tight shielding to prevent reflection is expected to reduce the difference.

IV. CONCLUSION

We developed RT-MLI composed of a set of stacked layers of polystyrene foam. RT-MLI reduces thermal radiation while maintaining transparency to radiowaves. We confirmed both surface temperature uniformity and a reduction in thermal loads. No anti-reflection coating is necessary. We also confirmed that RT-MLI has high transmittance for radiowaves but blocks infrared radiation. Another advantage of the RT-MLI compared with other filter types is that no thermal links are necessary. We demonstrated the effects of RT-MLI in combination with absorptive-type filters in a large-aperture setup (where the aperture diameter of each filter was 200 mm); low filter temperatures were successfully maintained. The principle of RT-MLI also guarantees applicability to significantly larger aperture systems, e.g., those with diameters of a few meters.

We conclude that RT-MLI is a useful technology in the cooling of radiowave receiver systems and particularly for the enlargement of a system aperture while maintaining a uniform surface temperature and high-transmittance conditions. RT-MLI can possibly be applied in various fields including radio astronomy, geo-environmental assessment, and radio detection and ranging (radar) systems.

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The second term in Eq. 5 is also significant when the difference between the temperatures $T_{\text{high}}$ and $T_{\text{low}}$ is small (this is true in general when $T_{\text{high}}$ is small). However, the effects of stray light is more problematic in a real system; the absorption of stray light can degrade the performance of an RT-MLI when $T_{\text{high}}$ is small.