Production Method of Millimeter-Wave Absorber with 3D-Printed Mold

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We established a production method of a millimeter-wave absorber by using a 3D-printed mold. The mold has a periodic pyramid shape, and an absorptive material is filled into the mold. This shape reduces the surface reflection. The 3D-printed mold is made from a transparent material in the millimeter-wave range. Therefore, unmolding is not necessary. A significant benefit of this production method is easy prototyping with various shapes and various absorptive materials. We produced a test model and used a two-component epoxy encapsulant as the absorptive material. The test model achieved a low reflectance: ~1% at 100 GHz. The absorber is sometimes maintained at a low temperature condition for cases in which superconducting detectors are used. Therefore, cryogenic performance is required in terms of a mechanical strength for the thermal cycles, an adhesive strength, and a sufficient thermal conductivity. We confirmed the test-model strength by immersing the model into a liquid-nitrogen bath.

Superconductive detectors are used extensively for high-precision measurements of millimeter-waves. In such a measurement system, the reduction of stray light, i.e., undesirable rays from unintended optical paths, is essential. The light path is composed of multiple reflections on the inner wall of the optics system. Therefore, a millimeter-wave absorber installation on the wall is a promising strategy to reduce the stray light.3 Because the optics system is commonly cooled to suppress thermal noise, the absorber is required to have a good cryogenic performance: a mechanical strength for the thermal cycles, an adhesive strength, and a sufficient thermal conductivity.

A mixture of epoxy and carbon or stainless steel is used commonly as an absorber for low-temperature applications. Stycast2850FT (Henkel Corporation), which is a two-component epoxy encapsulant, is used commonly. Its index of reflection is \( n \sim 2.3 \). Its surface reflectivity is \(~15\%\). Further reduction of the surface reflectivity can be achieved by forming surface structures, such as pyramids and needles.4,5 Molding is the most popular production method for making the surface structures.3 However, a long lead-time is required to make a mold. Moreover, it is difficult to unmold the absorptive material because of its strong adhesion.

To produce a pyramidal-shaped absorber easily, we established a new production method for the absorber with a 3D-printed mold. This method does not require an unmolding step if the 3D-printed mold is made from a transparent material in the millimeter-wave range. The surface structure of the periodic quadrangular pyramid is shaped with the 3D-printed mold. As illustrated in Fig. 1, we fill the absorptive material from the rear of the mold. In a previous study,6 the absorber is made by the 3D printer. In this method, the choice of the absorptive material is limited. Various materials can be used in our method. It is easy to prototype the absorber with various shapes and various materials. This benefit also allows us to optimize the cryogenic performance, such as the thermal conductivity.

To demonstrate the usefulness of our production method, we produced a test model. For the 3D-printing, we used the PolyJet method (Stratasys Japan Ltd.), which was an analogous method that was similar to ink-jet paper-printing. The mold material was VeroBlack. The mold geometry can be controlled with a printing fineness of 0.03 mm, which is several times better than the conventional 3D-printing method6,12. As illustrated in Fig. 2, we made quadrangular pyramids with a height and width of 8.0 mm and 3.2 mm, respectively. The mold thickness was 0.5 mm. We used the same aspect ratio as in a previous study for the cosmic microwave background project4; the height over the pitch was 2.3. Photographs of the test mold are shown in Fig. 3.

We measured the transmittance of the VeroBlack flat sheet (1 mm-thickness) from 75 GHz to 170 GHz. We used a Martin–Puplett-type Fourier transform spectrometer (FTS)13,14 with a semiconducting bolometer. Figure 4 shows the measured transmittance at normal incidence. We repeated the measurements 20 times and assigned errors for each point with their standard deviations. The transmittance was \(\geq 70\%\) in the measured frequency range. By fitting the data, we extracted its optical parameters: the index of refraction, loss tangent, and the plate thickness, which were \(1.70 \pm 0.05, 0.020 \pm 0.005,\) and \(0.97 \pm 0.03\) mm, respectively. These results indicate that the absorption loss of the mold is sufficiently low and the mold can be used as a transparent material.

For the absorptive material, we used Stycast2850FT. By using the FTS described above, we measured the reflectance of the test model and flat Stycast2850FT (5 mm-thickness). The samples were set before an aluminum plate. The incident angle of the light to the samples was \(45^\circ\). We measured the reflected power at \(45^\circ\). Figure 5 shows the measured reflectance as a function of frequency. The periodic pyramidal structure reduced the reflectance significantly (\(~1\%\) at 100 GHz) compared with the case of the flat surface (\(\approx 70\%\))

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FIG. 1. Production procedure for the absorber: (a) pouring Stycast2850FT mixed with curing agent into the 3D-printed mold, (b) degassing in a vacuum desiccator, and (c) curing at room temperature. We fill the absorptive material from the rear of the 3D-printed mold.

FIG. 2. Cross-sectional schematic of the test model.

FIG. 3. Photographs of the test mold with a 100 mm \( \times \) 100 mm area. (a) is the front view, and (b) is the rear view.

FIG. 4. Measured transmittance of VeroBlack flat sheet (1 mm-thickness). A dashed line is a fit result to the data with floating optical parameters (see text for details).

FIG. 5. Measured reflectance of test model (circle) and flat Stycast2850FT (triangle) with incident angle of 45°. Dashed and dotted lines are simulation results for each case.

50% at 100 GHz). Based on catalog numbers for the index of refraction (2.32) and the loss tangent (0.051) of Stycast2850FT\textsuperscript{5} we performed a simulation by using the ANSYS-HFSS (ANSYS Inc.). We confirmed the reason for the improvement from the consistency between the measured and simulation results.

The test model is aimed primarily towards cryogenic application. The coefficient of thermal expansion (CTE) of the Stycast2850FT matches that of the aluminum. Stycast2850FT has a good adhesive performance at a low-temperature condition\textsuperscript{15,16}, and it is commonly used as an adhesive in cryostats\textsuperscript{15,16}. Stycast2850FT also has a sufficient thermal conductivity of \( \sim 50 \text{ mW/m} \cdot \text{K} \) at 4 K\textsuperscript{17}. The CTE
of the 3D-printed resin (∼ 100 ppm/K) is larger than that of the Styrcast2850FT (∼ 40 ppm/K). Because the CTE difference may cause a mechanical stress, we performed a stress test. We immersed the absorber that adhered to the aluminum plate into liquid nitrogen (77 K) three times. Figure 6 shows a photograph of the absorber after the immersion test. We do not find any cracks on its surface, and we confirmed the good adhesive performance. The immersion test generated a significantly higher thermal stress than in the actual applications. Ordinarily, cooling takes a long time (> 1 hour).

An important benefit of the 3D-printed mold absorber is easy prototyping for various applications, which is difficult for previous molding production. It is easy to change the shape and the absorptive material. A material exists with high adhesive strength, and a sufficient thermal conductivity. Flexibility for changing the geometry and the absorptive material are convenient to develop absorbers for new applications.

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1. Y. Inoue, P. Ade, Y. Akiba, C. Aleman, and K. A. et al., “POLARBEAR-2: an instrument for CMB polarization measurements,” in Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VIII, Vol. 9914, edited by W. S. Holland and J. Zmuidzinas, International Society for Optics and Photonics (SPIE, 2016) pp. 372–380.
2. R. J. Thornton, P. A. R. Ade, S. Aiola, and F. E. A. et al., “The Atacama Cosmology Telescope: The polarization-sensitive ACTPol Instrument,” The Astrophysical Journal Supplement Series 227, 21 (2016).
3. P. A. R. Ade, R. W. Aikin, M. Amiri, D. Barkats, S. J. Benton, and C. A. B. et al., “BICEP2. II. EXPERIMENT AND THREE-YEAR DATA SET,” The Astrophysical Journal 792, 62 (2014).
4. J. Singal, D. J. Fixsen, A. Kogut, S. Levin, M. Limon, P. Lubin, P. Mirel, M. Seiffert, T. Villela, E. Wollack, and C. A. Wuenche, “The Arcade 2 Instrument,” The Astrophysical Journal 730, 138 (2011).
5. Henkel Corporation, “Technical Data Sheet LOCTITE STYCAST2850FT,” (2016).
6. K. Yokomori, “Dielectric surface-relief gratings with high diffraction efficiency,” Appl. Opt. 23, 2303–2310 (1984).
7. Iida, H., Kinoshita, M., Amemiya K., “Accurate Measurement of Absolute Terahertz Power Using Broadband Calorimeter,” J Infrared Milli Terahz Waves 39, 409–421 (2018).
8. T. Chass, K. Rostem, E. J. Wollack, L. Berman, F. Colazo, M. DeGeorge, K. Helsen, and M. Sagliocco, “A cryogenic thermal source for detector characterization,” Review of Scientific Instruments 88, 104501 (2017). https://doi.org/10.1063/1.4996751.
9. M. Petroff, J. Appel, K. Rostem, C. L. Bennett, J. Eimer, T. Mariage, J. Ramirez, and E. J. Wollack, “A 3d-printed broadband millimeter wave absorber,” Review of Scientific Instruments 90, 024701 (2019). https://doi.org/10.1063/1.5050781.
10. Stratasys Ltd., “Vero Material Data Sheet,” (2018).
11. Stratasys Ltd., “FDM F123 Series Brochure,” (2018).
12. I. S. Ohma, M. Hattori, and H. Matsu, “Development of a multi-Fourier-transform interferometer: fundamentals,” Appl. Opt. 45, 2576–2585 (2006).
13. This FTS works according to the principle of an auto-correlation mode of a multi-Fourier-transform interferometer.
14. I. S. Ohma, M. Hattori, Y. Chinone, Y. Luo, Y. Hamaji, T. Takahashi, H. Matsuo, and N. Kuno, “Astronomical testing observation in multi-Fourier transform interferometer: Aperture synthesis technique and CMB,” in 2007 Joint 32nd International Conference on Infrared and Millimeter Waves and the 15th International Conference on Terahertz; Electronics (2007) pp. 335–336.
15. I. F. Silvera, A. Abate, A. Chijioke, and A. Pashin, “Adhesives for highly polished surfaces and low temperature: A simple test and results,” Review of Scientific Instruments 73, 2108–2114 (2002). https://doi.org/10.1063/1.1470257.
16. F. Rondeaux, P. Bredy, and J. M. Rey, “Thermal conductivity measurements of epoxy systems at low temperature,” AIP Conference Proceedings 614, 197–203 (2002). https://aip.scitation.org/doi/pdf/10.1063/1.1472543.
17. F. Rondeaux, P. Bredy, and J. M. Rey, “Thermal conductivity measurements of epoxy systems at low temperature,” AIP Conference Proceedings 614, 197–203 (2002). https://aip.scitation.org/doi/pdf/10.1063/1.1472543.
18. ASTM international, “Standard Test Method for Coefficient of Linear Thermal Expansion of Plastics Between -30 °C and 30 °C with a Vitreous Silica Dilatometer,” ASTM D696-16, 2108–2114 (2016).
19. Rubrice K., Castel X., Hind M., Parneix P., “Dielectric characteristics and microwave absorption of graphene composite materials,” Materials (Basel) 9, 1996–1944 (2016).