PLANAR METAMATERIAL ABSORBERS FOR CALIBRATION OF MICROWAVE RADIOMETERS FOR ATMOSPHERIC REMOTE SENSING

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ABSTRACT

In this work, we present metamaterial-based microwave absorbers fabricated on organic-based printed circuit boards as promising alternatives to traditional, bulky microwave absorbers for the calibration of microwave radiometers for atmospheric remote sensing. Their use is particularly attractive for on-board calibration of sensors on CubeSats and other small satellites. Planar metamaterials can be fabricated with near-unity absorption over a very broad frequency range, and are scalable by tuning the unit cell geometry. Specifically, we describe an approach and initial measurements toward designing a broadband metamaterial emitter operating at millimeter wave sounding channels from 50 GHz – 230 GHz, enabling a thin, cost-effective calibration target for millimeter-wave atmospheric remote sensing.

Index Terms— Metamaterial, absorber, CubeSat, small satellite, microwave radiometer, millimeter wave radiometer, calibration

1. INTRODUCTION

Calibration of space-borne microwave radiometers for Earth remote sensing is critical for their accuracy, precision and stability. Reliable microwave radiometer calibration is typically performed by the radiometer antenna viewing a minimum of two known sources of electromagnetic radiation that have significantly different radiances, such as the cosmic background radiation near 2.73 K ("cold space") and a blackbody calibration target at ambient temperature ("warm load"), e.g. Advanced Technology Microwave Sounder (ATMS) [1] and Global Precipitation Mission (GPM) Microwave Imager (GMI) [2]. Calibration of the multi-frequency millimeter-wave radiometer on the Temporal Experiment for Storms and Tropical Systems – Demonstration (TEMPEST-D) CubeSat was accomplished using cold space and warm load calibration sources, enabling end-to-end calibration every 2 seconds [3]. Validation of the TEMPEST-D passive microwave sensor through cross-calibration with GPM/GMI and four Microwave Humidity Sensor (MHS) instruments demonstrated accuracy, precision and stability similar to sensors on much larger, traditional satellites [4]. The Tropospheric Water and Cloud Ice (TWICE) millimeter-wave radiometer has been demonstrated as a prototype for future atmospheric remote sensing missions as part of a NASA Instrument Incubator Program collaboration among Colorado State University, Jet Propulsion Laboratory and Northrop Grumman Corporation [5, 6].

In many cases, a calibrated blackbody is viewed by the sensor near in time to each measurement to compensate for instrument drift. Materials used for blackbodies, however, often emit over very broad bandwidth, including over wavelengths where instruments do not operate, and are typically very bulky. Ferrite-loaded epoxy absorbers, for example, are often used as calibration targets, but have significant depth since the base dimensions of the pyramid must accommodate the lowest frequency of observation. Furthermore, such calibration targets may experience solar intrusion effects that may lead to undesirable temperature inhomogeneities across the target [7].

Metamaterials and metasurfaces may be used as an alternative to conventional blackbodies, and realize a number of key advantages [8]. Metamaterial emitters can achieve ideal blackbody emissivities over desired frequency bands, with extremely low out-of-band emissivities, reducing unwanted emission and thermal load [9]. Additionally, thin planar metamaterials are lightweight and allow for a large surface area with simultaneously uniform surface temperature for increased thermal stability.

Here, we present planar metamaterials as a promising alternative to traditional microwave absorbers for calibration of microwave radiometers, particularly in millimeter-wave bands of interest to atmospheric remote sensing. The thin form factor of metamaterial calibration targets allows for easy implementation and integration. Compatibility with inexpensive fabrication technologies (e.g. printed circuit board) is expected to lead to increased reliability and reduced costs. The combination of high

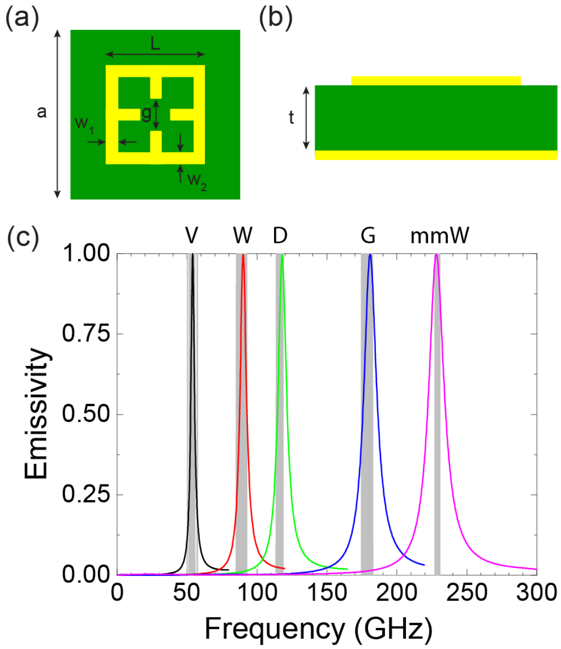

Fig. 1: (a) and (b) Schematic of the metamaterial absorber unit cell. (c) Simulated emissivity of five different metamaterial absorbers operating from 50 GHz to 230 GHz (solid colored curves). Shaded gray regions indicate desired window and sounding channels in the millimeter wave range.

emissivity, tunability, and efficiency make metamaterials very attractive for microwave radiometer calibration, and also suitable for deployment on CubeSats (~ 10 cm x 10 cm x 11 cm) and other small satellites.

2. METAMATERIAL ABSORBER DESIGN

The unit cell of the metamaterial absorber is shown in Figure 1(a,b). The metal-backed metamaterial absorber geometry consists of a 2D array of metallic resonator elements fabricated over a bottom ground plane, separated by a dielectric layer. The electric response of the composite originates primarily from the top resonator structure, while the magnetic response is generated from anti-parallel currents in the top and bottom metal layers [8]. Due to the metallic ground plane, there is no transmitted electromagnetic wave through the metamaterial structure, and any energy that is not reflected is instead absorbed. Thus, this base unit cell is capable of achieving high absorption through tuning the resonant metamaterial response, and was first experimentally demonstrated in the microwave regime [10], followed by extension to higher frequencies [11] up to the visible range [12].

According to Kirchhoff's law of thermal radiation, at equilibrium the emissivity of a material equals its absorptivity. Hence, metamaterials that are perfect absorbers will simultaneously be perfect emitters at a given temperature. Therefore, metamaterials with near-blackbody emissivity peaks can be achieved throughout the millimeter wave regime with judicious design of the unit cell geometry.

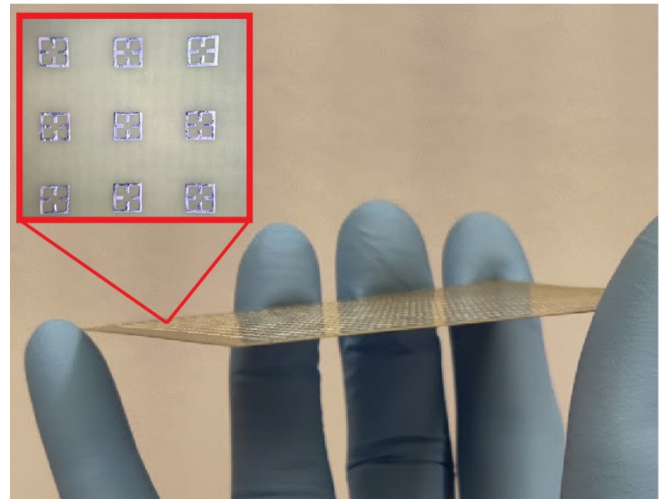

Fig. 2: 8 cm x 8 cm V-band metamaterial with a peak emissivity at 53.4 GHz, fabricated with PCB technology. The total thickness of the planar metamaterial is ~ 235 µm (λ/24 at 53 GHz). The inset shows several unit cells, with a periodicity of 2.3 mm.

Figure 1(c) shows the simulated emissivity of a variety of metamaterial geometries tuned for specific millimeter wave sounding channels from 50 GHz to 230 GHz. The metamaterial absorbers are based on design rules of printed circuit board (PCB) fabrication, with 152.6 g/m^2 copper metallic layers and an FR4 core dielectric spacer layer. The dimensions of the metamaterial absorbers in Figure 1(c) are shown in Table 1. Numerical simulations were performed using CST Microwave Studio, with a copper metal layer thickness of 17.5 µm and a dielectric with relative permittivity ε_r = 3.92 and loss tangent of tan δ = 0.2 for the spacer layer.

Table 1: Dimensions of metamaterial unit-cells in Fig. 1(c) to achieve peak emissivities in the millimeter-wave regime. Geometrical parameters are defined in Fig. 1 (a) and (b).

Band	Peak Freq. (GHz)	a (µm)	L (µm)	w_1 (µm)	w_2 (µm)	g (µm)	t (µm)
V	53	2300	920	100	120	240	203
W	89	1445	592	95	95	157	102
D	118	1130	458	70	75	146	76
G	181	795	302	50	55	101	51
mm-wave	228	665	266	65	50	84	25

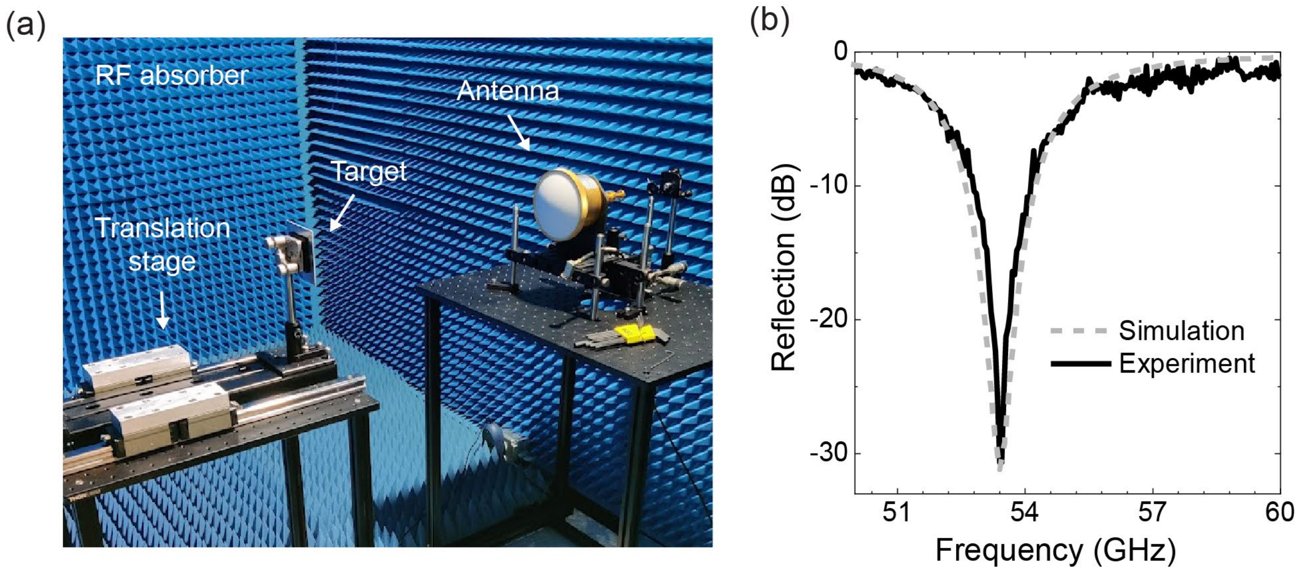

Fig. 3: (a) Photograph of NIST anechoic chamber in Boulder, CO, for monostatic reflection measurements. (b) Simulated (dotted grey curve) and experimentally measured (solid black curve) reflectivity of metamaterial target, exhibiting a resonant response at 53.4 GHz.

3. RESULTS AND DISCUSSION

Metamaterial emitter prototypes were fabricated using PCB-based technology by a commercial manufacturer. Figure 2 shows an 8 cm x 8 cm planar metamaterial target after production. The metallic resonator elements were designed to have a resonant response in V band, with a peak absorptivity/emissivity frequency at 53.4 GHz (see Table 1). The inset in Figure 2 shows several unit cells, with a periodicity of 2.3 mm. The top and bottom metallic layers consist of copper with a thickness of 17.5 µm, while the core dielectric layer consists of a 200 µm epoxy laminate. The total thickness of the metamaterial target is ~ 235 µm ($\lambda/24$ at 53 GHz).

To characterize the frequency response of the fabricated metamaterial absorber targets, we performed reflectivity measurements using an established technique developed at the National Institute of Standards and Technology (NIST) in Boulder, Colorado [13]. Figure 3 (a) shows a photograph of the experimental setup, performed inside a 2.3 m x 2.4 m x 3 m anechoic chamber using a monostatic measurement geometry. We used a WR15 spot-focusing lens horn antenna with a focal length of 26 cm, connected to a calibrated vector network analyzer (VNA). The target is mounted to a translational stage and placed at a separation greater than the far-field distance of the antenna (~ 72 cm at 53 GHz) from the focal spot.

The stage is swept a total of 2 cm in 200 µm steps, with a VNA spectral response collected from 50 GHz – 60 GHz at each position. The backscattered signal from the target, at a given frequency, measured by the receiver evolves as a standing wave, as the distance between the sample and antenna is varied. Through numerical fitting of the standing wave response, the reflection coefficient of the target can be extracted highly accurately, when normalized to a proper reference used to calibrate the experimental setup [13, 14].

Figure 3b shows the extracted reflection (solid black curve) of the fabricated V-band metamaterial emitter target. A metal plate cut to the same dimensions as the metamaterial (8 cm x 8 cm) was used as a reference. Using the as-fabricated dimensions obtained from sample metrology, as well as published permittivity values of the laminate material [15], we obtained good agreement between numerical simulation (dashed grey curve) and the measurement (solid black curve).

The experimental results in Fig. 3 (b) confirm a minimum reflection below -30 dB, corresponding to a peak absorptivity (emissivity) exceeding 99.9% at the target peak frequency of 53.4 GHz. Although the measured metamaterial absorption peak is relatively narrow, the spectral width can be broadened, e.g. through the use of substrate or capping layer materials with higher dielectric loss. Furthermore, individual metamaterial unit cells can be combined into tessellated super-cells and multi-layer stacks [8], to realize broadband, high emissivity across the entire 50 GHz - 230 GHz range.

4. CONCLUSION

We have demonstrated planar metamaterials as an attractive alternative to traditional microwave absorbers for the calibration of microwave radiometers for atmospheric remote sensing. Metamaterial calibration targets are highly suitable for deployment on CubeSats and other small satellites. The metamaterial response is highly tunable through the unit cell geometry. Thin metamaterial target prototypes fabricated from relatively inexpensive PCB technologies were demonstrated to achieve near-unity emissivity at V-band frequencies. Individual metamaterial unit cells can further be combined into super unit-cells, to realize broadband high emissivity at selected frequencies across the millimeter-wave range, enabling a lightweight, cost-effective alternative to more bulky blackbody sources.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

[1] Kim, E., C.-H. J. Lyu, K. Anderson, R. V. Leslie and W. J. Blackwell, "S-NPP ATMS Instrument Prelaunch and On-orbit Performance Evaluation," *Journal of Geophysical Research – Atmospheres*, vol. 119, no. 9, pp. 5653-5670, 2014.

[2] Draper, D. W., D. A. Newell, F. J. Wentz, S. Krimchanshy and G. M. Skofronick-Jackson, "The Global Precipitation Measurement (GPM) Microwave Imager (GMI): Instrument Overview and Early On-Orbit Performance," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 8, no. 7, pp. 3452-3462, 2015.

[3] Padmanabhan, S., T. C. Gaier, A. B. Tanner, S. T. Brown, B. H. Lim, S. C. Reising, R. Stachnik, R. Bendig and R. Cofield, "TEMPEST-D Radiometer: Instrument Description and Prelaunch Calibration," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 59, no. 12, pp. 10213-10226, 2021.

[4] Berg, W., S. T. Brown, B. H. Lim, S. C. Reising, Y. Goncharenko, C. D. Kummerow, T. C. Gaier and S. Padmanabhan, "Calibration and Validation of the TEMPEST-D CubeSat Radiometer," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 59, no. 6, pp. 4904-4914, 2021.

[5] Jiang J. H., Q. Yue, H. Su, S. C. Reising, P. P. Kangaslahti, W. R. Deal, E. T. Schlecht, L. Wu,
and K. F. Evans, "A Simulation of Ice Cloud Particle Size, Humidity, and Temperature Measurements from the TWICE CubeSat," *Earth and Space Science*, vol. 4, pp. 574-587, 2017.

[6] Cooke, C., K. Leong, A. Zamora, B. S. Gorospe, X. B. Mei, P. Kangaslahti, E. Schlecht, M. Ogut, Y. Goncharenko, S. C. Reising and W. R. Deal (2021) "A 670 GHz Integrated InP HEMT Direct-Detection Receiver for the Tropospheric Water and Cloud Ice (TWICE) Instrument," *IEEE Transactions on Terahertz Science and Technology*, vol. 11, no. 5, pp. 566-576, 2021.

[7] Kunkee, D. B., S. D. Swadley, G. A. Poe, Y. Hong and M. F. Werner, "Special Sensor Microwave Imager Sounder (SSMIS) Radiometric Calibration Anomalies—Part I: Identification and Characterization," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 46, no. 4, pp. 1017-1033, 2008.

[8] Watts, C. M., X. Liu, and W. J. Padilla, "Metamaterial Electromagnetic Wave Absorbers," *Advanced Materials*, vol. 24, pp. OP98-OP120, 2012.

[9] Liu, X. T. Tyler, T. Starr, A. F. Starr, N. M. Jokerst and W. J. Padilla, "Taming the Blackbody with Infrared Metamaterials as Selective Thermal Emitters," *Physical Review Letters*, vol. 107, pp. 045901:1-4, 2011.

[10] Landy, N. I., C. M. Bingham, T. Tyler, N. Jokerst, D. R. Smith, and W. J. Padilla, "Design, theory, and measurement of a polarization-insensitive absorber for terahertz imaging," *Physical Review B*, vol. 79, pp. 125104:1-6, 2009.

[11] Avitzour, Y., Y. A. Urzhumov, and G. Shvets, "Wide-angle infrared absorber based on a negativeindex plasmonic metamaterial," *Physical Review B*, vol. 79, pp. 045131:1-5, 2008.

[12] Aydin, K., V. E. Ferry, R. M. Briggs, and H. A. Atwater, "Broadband, polarization independent resonant light absorption using ultrathin, plasmonic super absorbers," *Nature Communications*, vol. 2, pp. 517:1-7 2011.

[13] Gu, D., D. Houtz, J. Randa, and D. K. Walker, "Reflectivity Study of Microwave Blackbody Target", *IEEE Transactions on Geoscience and Remote Sensing*, vol. 49, pp. 3443-3451, 2011.

[14] Gu, D. and D. Walker, "Application of Coherence Theory to Modeling of Blackbody Radiation at Close Range," *IEEE Transactions on Microwave Theory and Techniques*, vol. 63, no. 5, pp. 1475-1488, 2015.

[15] https://www.isola-group.com/pcb-laminates-prepreg/370hr-laminate-prepreg/