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Improvement of Field Uniformity in Microwave Heating Cavity Using beam-splitting Metasurface

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Abstract

A one-bit coding metasurface is proposed and employed in a microwave heating cavity to improve the electric field uniformity. The proposed metasurface can split the incident beam into multiple ones, resulting in a more uniform field distribution. Simulation results show that the relative standard deviation (RSD) of the electric field distribution in the cavity decreases from 0.63 to 0.44 when the proposed metasurface is put in front of one cavity wall.

1 Introduction

Microwave heating has been applied in our daily life for many years [1]. However, non-uniformity is still the main factor which limits its wide applications in industry [2]. Heating uniformity is mainly determined by the electromagnetic field distribution inside an microwave cavity. Nonuniform heating may lead to local overheating of the object, resulting in hot spots and thermal runaway[3]. To improve the uniformity of microwave heating, some acknowledged technologies such as mechanical mode stirring, the rotating turntable, the selected or swept frequency, and optimization of the size and shape of the heating target, are proposed [4][6]. The mechanical mode stirring and rotating turntable are conventional ways for uniform heating, and the latter two methods also provide effective alternatives to improve the heating homogeneity.

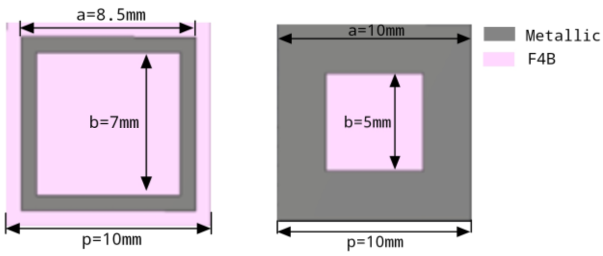
Electromagnetic metasurfaces are 2D arrays which are designed to flexibly manipulate the incident electromagnetic wave [7]. In this paper, a metasurface which can split the incident beam into multiple ones is proposed and utilized in a microwave heating cavity to improve the field uniformity. The proposed coding metasurface is attached on a side wall of the cavity to scatter the electromagnetic waves into multiple directions. Simulation results demonstrate that the filed uniformity with the proposed metasurface in the cavity is effectively improved.

2 Improvement of Field Uniformity Using Metasurface

2.1 Design of the Beam-Splitting Metasurface

The electromagnetic wave incident to the metallic wall in the microwave cavity is usually reflected in a direction specified by Snell's law. The superposition of the incident and reflected waves form a standing wave distribution in the cavity, even in a multi-mode cavity. Different from the reflection from the metallic wall of the cavity, the reflected wave can be manipulated by a uniquely designed metasurface to propagate in multiple directions. This may lead to a more uniform field distribution in the cavity. Therefore, a 1-bit coding metasurface is designed to split the incident beam into multiple ones. The "0" and "1" element in such a metasurface have 2π phase variations according to [8]. Scattered patterns can be controlled by the layout of these "0" and "1" elements. Based on this concept, diffusion metasurfaces have been realized with the aid of optimization methods [9][10].

The proposed "0" and "1" elements here are both square rings, as shown in Figure 1 (a) and (b). The dimension size of each element is 10 mm × 10 mm. The metellic square rings are etched on the 2 mm thick F4B substrate with dielelctric constant of ε_r = 2.65 and loss tangent of tgδ = 0.001.



(a) (b)

Figure 1. The proposed (a) "0" and (b) "1" elements in the 1-bit coding metasurface.

Usually, a metallic ground plate is attached at the bottom of the substrate. However, such a design requires as large as nearly 30 mm periodicity of each element to generate the expected phase change at operating frequency of 2.45 GHz ± 50 MHz for microwave heating. The area of the cavity wall is limit, which demands for the miniaturized design of "0" and "1" elements.

To reduce the dimension size of the element, the metallic wall of cavity is regarded as the bottom ground, the F4B substrate with the proposed square rings on its top is put 14 mm away from the metallic wall. By introducing the air gap between the ground and F4B substrate, the dimension size of the "0" and "1" elements reduce to 10 mm. As a result, the metasurface layout with enough number of "0" and "1" elements is obtained at 2.45 GHz to provide required phase variation for coding, as shown in Fig. 2.

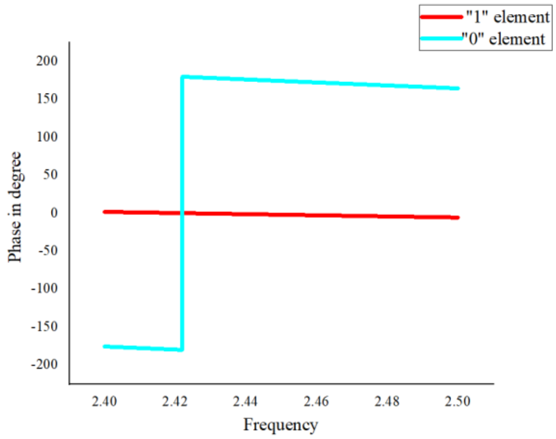


Figure 2. Phase response of the metasurface with only “0” or “1” elements

To manipulate the reflected beam direction and thus obtain a relatively uniform backward scattering, an abrupt phase change on the metasurface interface is introduced to fully control the wavefront based on the generalized Snell’s law [11]. The scattered energy is expected to be uniformly distributed in all directions to improve the filed distribution homogeneity in the cavity. Consequently, the “0” and “1” unit cells which are composed of 3 × 3-elements are randomly arranged, as shown in Fig. 3. As a result, the phase of reflected wave from each cell can be distorted as much as possible rather than in an equal or gradient shifting manner [12].

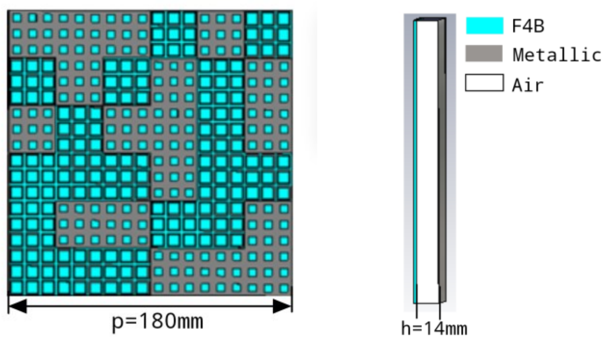


Figure 3. Random layout of 1-bit coding metasurface with dimension size of 180 mm × 180 mm ×16 mm (14 mm-thick air layer and 2 mm-thick F4B substrate)

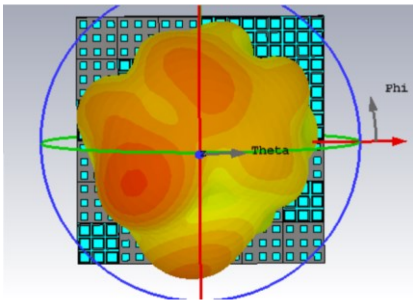
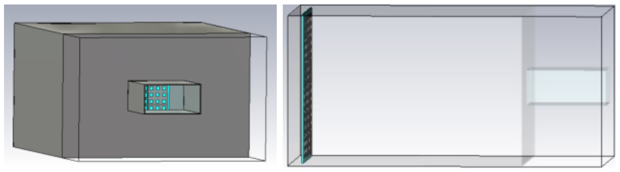


Figure 4. Scattered pattern for normal incidence.

Commercial software CST is employed to simulate the performance of the designed metasurface. The scattered field pattern for normal incidence is shown in Fig. 4. It is obvious that the reflected wave is scattered into multiple directions in a relatively uniform distribution.

3 Application of the Proposed Metasurface

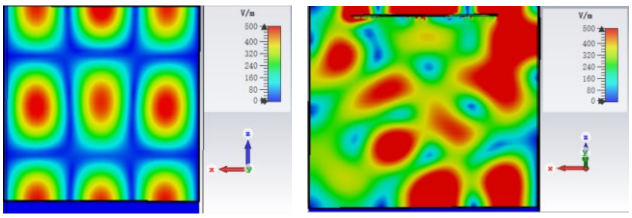
The proposed 1-bit coding metasurface is applied to the microwave heating cavity for uniformity improvement of the field distribution. The dimension size of the cavity is 291 mm × 291 mm × 186 mm. The proposed metasurface is put in the front of the wall opposite to the microwave feeding port of the cavity, as shown in Figures 5 (a) and (b).



(a) (b)

Figure 5. The microwave heating cavity with metasurface: (a) front view and (b) side view.

Figure 6 shows the electric filed distribution at a plane 45 mm higher than the bottom of the cavity. It is clear that the field distribution becomes more uniform by introducing the metasurface into the cavity. The area with very small electric field value considerably shrinks in Fig. 6(b).



(a) (b)

Figure 6. Electric field distribution at a plane 45 mm higher than the bottom of the cavity (a) without and (b) with the proposed metasurface.

The values of electric field at different positions in the cavity are extracted at the step of 5 mm. Totally, electric field values at more than 100000 points are exported. Then, the relative standard deviations (RSDs) of the electric field with and without the proposed metasurface are derived and compared in Table I.

Table 1. Relative standard deviation with and without the proposed metasurface

	RSDs
Without metasurface	0.63
With metasurface	0.44

The RSD of electric field decreases from 0.63 to 0.44 by employing the beam-splitting metasurface. This demonstrates the improved uniformity of filed distribution in the microwave heating cavity.

4 Conclusions

In this paper, a beam-splitting metasurface is proposed and employed to improve the electric field uniformity in a microwave heating cavity. Both the electric field distribution and relative standard deviation of the electric field demonstrate the uniformity enhancement of the field distribution in the cavity. Due to the intensive computation cost, the layout of the "0" or "1" elements in the proposed metasurface has not been optimized to provide better field uniformity. Future work may include this, introducing more beam-splitting metasurfaces in microwave heating cavity, and taking the practical heating process into consideration.

Acknowledgements

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References

[1] Liu H, E J, Deng Y, Xie C, "Zhu H. Experimental study on pyrolysis characteristics of the tobacco stem based on microwave heating method," *Appl Thermal Engineering*, **106**, August 2016, pp. 473-479, doi:10.1016/j.applthermaleng.2016.06.042.

[2] Vadivambal R, Jayas DS, "Non-uniform Temperature Distribution During Microwave Heating of Food Materials—A Review," *Food Bioprocess Tech*., **3**, 2, 2010, pp 161-171, doi:10.1007/s11947-008-0136-0.

[3] VÃ Clav Sebera ANKT, "Finite element analysis of mode stirrer impact on electric field uniformity in a microwave applicator," *Drying Technology*, **30**, 13, September 2012, pp. 1388-1396, doi:10.1080/07373937.2012.664800.

[4] Geedipalli SSR, Rakesh V, Datta AK, "Modeling the heating uniformity contributed by a rotating turntable in microwave ovens," *J Food Eng*, **83**, 3, March 2007, pp. 359-368, doi:10.1016/j.jfoodeng.2007.02.050.

[5] Tang Z, Hong T, Liao Y, et al, "Frequency-selected method to improve microwave heating performance," *Appl Thermal Engineering,* **131,** December 2018, pp. 642-648, doi:10.1016/j.applthermaleng.2017.12.008

[6] Pedreño-Molina JL, Monzó-Cabrera J, Catalá-Civera JM, "Sample movement optimization for uniform heating in microwave heating ovens," *Int J Rf Microw C E*, **17**, 2, 2007, pp. 142-152, doi:10.1002/mmce.20208

[7] C. Qi and A. M. H. Wong, "Discrete Huygens' Metasurface: Realizing Anomalous Refraction and Diffraction Mode Circulation With a Robust, Broadband and Simple Design," *IEEE Transactions on Antennas and Propagation*, **70**, 8, Aug. 2022, pp. 7300-7305, doi: 10.1109/TAP.2022.3164931.

[8] C T J, Q M Q, W X, et al. "Coding metamaterials digital metamaterials and programmable metamaterials," *Light Science & Applications*, **3**, 10, October 2014, doi:10.1038/lsa.2014.99.

[9] Dong D S , Yang J , Cheng Q , et al, "Terahertz Broadband Low-Reflection Metasurface by Controlling Phase Distributions," *Advanced Optical Materials*, **3**, 10, 2015, pp. 1405–1410, doi:10.1002/adom.201570065.

[10] Gao L H , Cheng Q , Yang J , et al, "Broadband diffusion of terahertz waves by multi-bit coding metasurfaces," *Light: Science & Applications* , **4**, 9, September 2015, doi:10.1038/lsa.2015.97.

[11] Patrice, Genevet, Mikhail, et al, "Light Propagation with Phase Discontinuities: Generalized Laws of Reflection and Refraction," *Science*, **334**, 6054, 2011, pp. 333-337, dio:10.1126/science.1210713

[12] Zhao, Y., Cao, X., Gao, J.et al, "Broadband diffusion metasurface based on a single anisotropic element and optimized by the Simulated Annealing algorithm," *Scientific Reports*, **6**, April 2016, pp 23896-., doi: 10.1038/srep23896