A Metamaterial Absorber for Microwave De-icing of Wind Turbine Blades and Its Electromagnetic and Thermal Properties

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Abstract: The icing of wind turbine blades in cold climates may reduce the power generation efficiency, shorten the life of the blades and even bring safety hazard. De-icing of wind turbine blades is very necessary. The current technical means such as heating resistance, warm air, and other means of de-icing have various limitations, and no mass produced commercial wind turbine blade de-icing system are available currently. Microwave heating has the characteristics of selectivity, non-contact and rapid heating, and is a potential and flexible de-icing way of wind turbine blades. In this paper, a kind of metamaterial absorber (MA) which can strongly absorb 2.45GHz microwave is designed. It can absorb the incident microwave and then convert the microwave energy into heat. Multi-physical simulation is carried out to analyse the heat generation, thermal distribution and temperature rise of the MA under microwave radiating. This preliminary simulation results show that MA is possible to be used in microwave de-icing of wind turbine blades.

1 INTRODUCTION

Wind power as a green energy is clean and renewable. According to the report of Technical Research Centre of Finland (VTT, 2013), wind power capacity is growing rapidly in the cold climates of the world, and between 45 and 50 gigawatts of wind power would be built in cold climates by 2017 for higher winds and proper density of cold air. However, turbine blades are highly susceptible to icing in these areas. Icing may significantly reduce the aerodynamic properties of blades and lead to mechanical failures, safety hazard (Seifert et al., 2003), and possible stoppage of operation (Hochart et al., 2010). Lots of wind turbines with no de-icing equipment will only stop to wait for ice to melt naturally. De-icing of wind turbine blades is very necessary.

Parent and Ilinca (Parent and Ilinca, 2011) provided a critical review of de-icing techniques for wind turbines include passive and active systems. Heating resistance and warm air are most used active techniques in de-icing. Due to direct heating, the heating resistance systems have high efficiency (up to 100%) (Battistil et al., 2005) and are mainly used in current. The heating materials such as carbon fiber sheet (Xu et al., 2018), polymer electric heating film (Shu et al., 2017, Mu et al., 2014) are studied intensively. However, icing of run back water at the edges of the heating elements may occur often in the heating resistance system, and there is no flexible once the heating elements were buried well. Warm air system had also been applied in wind turbines de-icing (Zhao et al., 2016). However, the warm air needs to heat the whole shell of the wind turbine blade from the inner surface of the shell. As the shell structures have small coefficient of thermal conductivity and becoming larger and thicker, the efficiency becomes very low. New de-icing techniques are called for.

Microwave heating is one of the active de-icing methods, and has the characteristic of selective, volumetric and rapid. Microwave heating is expected to realize wireless, scanning and rapid de-icing, and is expected more flexible than the heating resistance de-icing. One of the key of microwave heating is to find materials absorbing microwave strongly and with thin thickness as much as possible. L. Feher et al (Feher et al., 2009) studied microwave de-icing with carbon fiber reinforced plastic (CFRP) aimed to be applied on aircraft, and demonstrated selective, non-contacted and volumetric heating of microwave experimentally. Johansson et al (Johansson et al., 2015) demonstrate microwave

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heatable CNT coatings for wind turbine blade de-icing. The carbon fiber or CNT coatings absorb microwave but not totally, thus reflection and transmission of microwave power may cause microwave leakage or reduce power efficiency.

This paper presents a metamaterial absorber （MA） different from carbon fiber and CNT coating for wind turbine blades de-icing under microwave radiating. The heating source may be industrial magnetron or solid state microwave amplifier. The reflection of -26.0dB at 2.45GHz is reached with MA thickness of 2mm. An intuitive impression of electromagnet-thermal conversion of MA under microwave radiating is also presented.

This paper is organized as follows: The first part is introduction. The second part presents the design of electromagnetic absorbing property. The third part studies the electromagnet-thermal conversion under microwave radiating with multi-physical simulation software. Temperature distribution is also given. The forth part concludes the paper. These efforts have laid a solid foundation for further study of the MA.

2 ELECTROMAGNETIC DESIGN

2.1 MA for De-icing of Wind Turbine Blades under Microwave Radiating

The original form of MA is Landy's Perfect Metamaterial Absorber, which is consisting of two distinct metallic elements and a dielectric layer between them (Landy et al., 2008). Through fine adjusting of the metallic elements, the MA can absorb the incident microwave at a single frequency point almost totally. Gradually, whole back metallic layer replaces the split cut wires and various front metallic patterns emerge. The simple form made the design of perfect absorption easily achieved. In this situation, the double-facet Copper Clad Laminate (CCL) was usually used to fabricate MA.

The MA absorbs the incident microwave within a small thickness which usually less than one tenth of the operating wavelength. The small thickness and thereby a small volume made MA little self-heated energy consumed when used for microwave heating. Thus the MA is suitable for microwave de-icing.

From a concept view, the microwave source can be arranged inside the blade and fixed on the web. The microwave radiated from source by antenna and penetrates the balsa wood (heat insulator and transparent to microwave) or other supporting materials and reached onto the MA, as schematically shown in Figure 1. Due to the MA has entire back metal film and covers the entire outer surface of the blade, no microwave can leak outside and thus the microwave seldom has impacts on environment around the turbine.

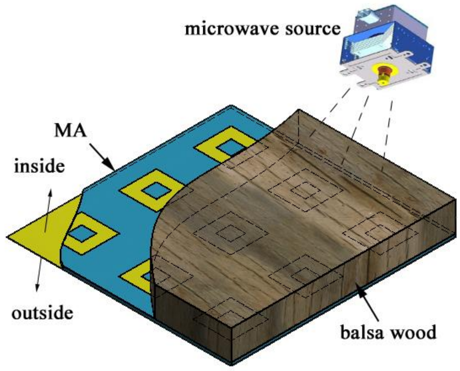
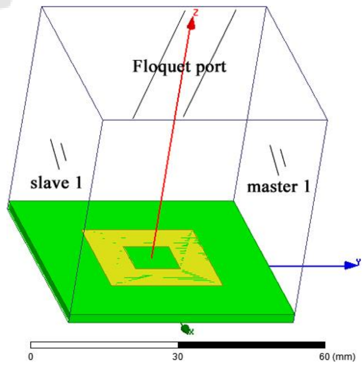


Figure 1: Schematic diagram of part of wind turbine blade under microwave heating.

2.2 The Electromagnetic Property Design of the MA

As higher energy conversion efficiency is expected, the absorption rate of microwave is expected as high as possible. The design of the MA is aimed to absorb the incident microwave totally at given frequency 2.45GHz. HFSS (Ansoft Inc, 2009) simulation study is carried out to achieve the goal. Hollow square ring is adopted as the front metallic pattern of the MA due to its simple and central symmetric property. A single unit of the periodic model is built. The model and the above air box in HFSS are shown in Figure 2.



Top layer (yellow): hollow square copper film ring;
Middle dielectric layer (green): FR-4, 2mm;
Back film (unseen): copper film

Figure 2: Model of the hollow square MA unit built within HFSS.

Master-slave boundaries are imposed on each pair of the opposite side faces of the domain to match the periodical model. Floquet port is imposed on top face of the computational domain. The material of the metallic ring and the back film are both 18μm copper films with conductivity of 5.998e7 S/m. The middle dielectric layer is FR-4 with 2mm thickness. The relative permittivity ε_r and permeability μ_r are 4.3 and 1.0, respectively. The dielectric loss factor of FR-4 is 0.02.

Table 1:Components parameters of the optimized MA.

Components	**layers**	**Parameters(mm)**		
	material	**Thickness**	**L_Outer**	**L_Inner**
Hollow square ring	copper	0.018	*25.2*	*10.0*
Mid-dielectric	FR-4	2.0	50.0	-
Back film	copper	0.018	50.0	-

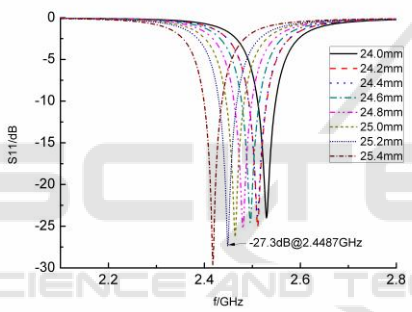


Figure 3: Parameter swept S11 curves of the MA.

Geometric parameters of the MA affect the absorb frequency point and absorbing intensity. The resonant frequency was mainly governed by the length of central line of the metallic ring, while the absorbing intensity is mainly affected by the thickness and the dielectric loss of the dielectric layer (Pang, 2013). The following optimization keeps in line with these principles.

In order to obtain a MA as thin as possible, the thickness of the MA is expected no greater than 2mm. Besides, the period of the unit is expected to be kept integer for convenience. The aim of optimization is to obtain a higher absorption rate while thickness and period of the MA kept fixed. The outer and inner side lengths of the hollow ring are selected as variables for optimization. The genetic algorithm built-in HFSS about the outer and inner side lengths with their physical limits range for better absorption at 2.45GHz are carried out, while other parameters are kept unchanged. The optimized L_outer and L_inner and other parameters are shown in Table 1.

Under the optimized parameters, the S_{11} reaches -26.0dB at 2.45GHz when L_outer=25.2mm, while the best absorb point is located at 2.4487GHz and the S_{11} reaches -27.3dB, the curves of S_{11} with swept L_outer as shown in Figure 3.

3 MULTI-PHYSICAL SIMULATION

The MA absorbs and converts microwave energy into heat. With the optimized parameters of the MA obtained above, we investigate the electromagnet-thermal conversion and energy efficiency with COMSOL (COMSOL Inc, 2012), a commercial simulation software suitable for multi-physical problems.

3.1 The Simulation Model of MA in COMSOL

A single unit model of MA similar to that in HFSS is built with COMSOL. The back of the model was set as an ideal conductor boundary rather than copper film while other components kept unchanged. As the thickness of the hollow copper ring is too small to resolute, a transition boundary is adopted to replace for. No meshes are built within the transition boundary, but physical properties including conductivity, thickness, etc are kept.

Periodic boundaries were assigned onto the side face pairs and periodical port was assigned onto the top face with TEM mode. The boundaries, port and incident mode made this unit model equivalent to an infinite plane MA radiated by plane microwave. Balsa wood or other supporting materials are not considered currently.

3.2 Electromagnet-thermal Conversion

The heat generated within the MA mainly come from microwave dielectric loss in FR-4 and ohmic loss in copper, and the loss occurs when electromagnetic field established within the MA. The temperature distribution of the MA will be governed by thermal conduction and convection and the conduction plays a major role.

To describe the time variant temperature T(x,y,z,t) distribution of the MA unit heated by microwave, one can accordingly solve the heat equation for temperature T given by (Pitchai, 2011a)

$$c\rho\frac{\partial T}{\partial t}=k\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}\right)T+P \qquad (1)$$

Where P is the heat power density which came from the dielectric loss and ohmic loss of the incident microwave, ρ is the density of the corresponding material, c is the specific heat capacity and *k* is the thermal conductivity. The heat power density can be expressed as a function of the electric field component in a non-magnetic loss medium by (Pitchai, 2011b)

$$P=\omega\varepsilon_0\varepsilon^{"}E^2 \qquad (2)$$

Here *E* is the electric component of the electromagnetic field built within the MA, $\varepsilon^{"}$ is the imaginary part of the dielectric FR-4, ω is the angular frequency of the incident microwave and ε_0 is the permittivity of free space.

Equations (1) and (2) describe that temperature distribution within the MA are governed by the electric field strength and the distribution of the electromagnetic field. The electric component strength is proportional to the microwave absorption rate of the MA, thus the energy conversion efficiency between the microwave and heat is strongly related to the absorption rate and the dielectric imaginary part of the FR-4.

As the microwave is radiated by antenna and transmitted through free space, and no extra wires and other accessories are needed, the microwave heating will be more flexible than electric heating. Besides, as equation (2) implies, the heat generated once the microwave field built up in MA, thus microwave heating is rapid.

3.3 Multi-physical Simulation Results

The frequency of the input microwave is 2.45GHz. In COMSOL, the default input power into the periodical port is 1W, and the power density is calculated of 400W/m^2 according to the cross section area of 50mm×50mm. The tangential loss angle of FR-4 is 0.02, while the magnetic one is 0. The simulation duration is set as 300s and total input energy calculated 300J. The ambient temperature surround the model is set as 20℃.

In COMSOL, the S_{11} drops to -3.25dB while the S_{11} is -26dB in HFSS, the parameters of the model are the same. This dramatic drop results in increase of reflection and decrease of absorbing which is effective in heating. Furthermore, simulations show that the relative permittivity ε_r of FR-4 has strong influence on microwave absorbing. Simulations are carried out on the variation of ε_r and the corresponding S_{11} are shown in Table 2. The power absorbed can be calculated from S_{11}, and then the temperature rise due to the absorbed power ΔT_{ab} can be calculated from the following equation

$$Q=c\rho V(T-T_0) \qquad (3)$$

Where *Q* is heat energy, *V* is volume. Take FR-4 into account, c=1369J/kg·K, ρ =1900kg/m^3, V=0.05×0.05×0.002m^3 and $T-T_0=\Delta T_{ab}$.

The weighted mean temperature ΔT_{ave} represents a supposed spatial uniform temperature rise within FR-4. It can be read directly from COMSOL, and the power conversion efficiency $\eta=\Delta T_{ave}/\Delta T_{ab}$ from microwave to heat can be calculated out. The corresponding calculation results are summarized and shown in Table 2. The efficiency is about 82% when ε_r changes. If the reflection is taken into account, the overall efficiency η_a drops to 21.2% to 58.1%.

Table 2: The EM-thermal conversion efficiency v.s. ε_r.

ε_r	4.1	4.2	4.3	4.4
S_{11}/dB	-2.28	-5.27	-3.25	-1.30
P_{ab}/W	0.41	0.70	0.52	0.26
ΔT_{ab}/℃	9.5	16.1	12.0	6.0
ΔT_{ave}/℃	7.8	13.4	10.0	4.9
η/%	82.1	83.0	83.3	81.6
η_a/%	33.7	58.1	43.3	21.2

Figure 4 gives the electric field strength distribution from a bottom view at the end of the simulation when ε_r=4.2. One can find that the electric component mainly concentrates below the copper ring, and the field distribution splits into two parts obviously. Animation of the field versus time reveals that the electromagnetic field acts like standing wave, which implies the incident microwave resonate within the MA. During this progress, the dielectric loss and ohmic loss occurred and the electromagnetic energy converted into heat.

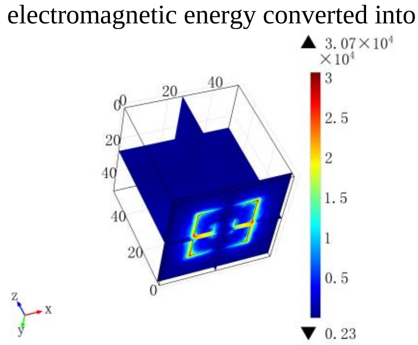


Figure 4: Electric field strength(V/m) distribution.

The temperature distribution on the middle cut plane of the simulation when ε_r=4.2 is shown in Figure 5. The maximum temperature is 68.2℃，48.2℃ higher than the ambient temperature due to a microwave power density of 400W/m^2 and heating duration of 300s.

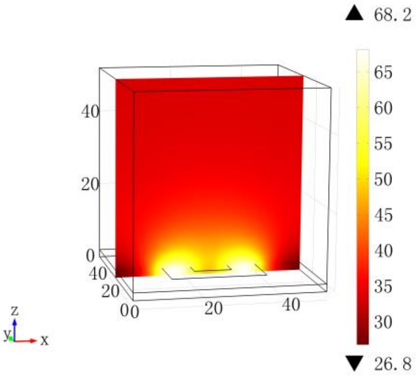


Figure 5: Temperature(deg) distribution on x-z cutting section of the MA unit model (simulation duration: 300s).

This simulation is preliminary for only FR-4 is taken into consideration in the calculation. But the power conversion and heating figure are presented. The overall efficiency is low in current simulation and further investigation on improving absorbing rate will be carried out to improve the overall EM-thermal conversion efficiency.

4 CONCLUSIONS

In this paper, we present the idea of the wind turbine blades de-icing with MA under microwave heating. The design of electromagnetic absorbing property of MA is presented. Multi-physical simulation is carried out to analyse the heat generation, thermal distribution and temperature rise of the MA under microwave heating. The energy conversion efficiency is given based on the multi physical simulation. This preliminary simulation show that MA is possible to be used in microwave de-icing of wind turbine blades as a wire-less, rapid and flexible means.

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REFERENCES

Ansoft Inc, 2009. HFSS online Help,Version 12.

Battistil, BrighentiA., DalSavio, S. DellAnna. 2005. Evaluation of anti-icing energy and power require- ment for wind turbine rotors in cold climates. BOREAS, VII, FMI, Saariselka, Findland, p13.

Comsol Multiphysics uers's guide. 2012. Version.4.3.

Feher, L., Seitz, T. and Nuss, V., 2009. Microwave De-/Anti-Icing Using the Midas-Technology. Journal of Microwave Power & Electromagnetic Energy ONLINE. Vol. 43, No. 1.

Hochart, C., Fortin, G., Perron, J. et al., 2010. Wind turbine performance under icing conditions[J]. Wind Energy, 11(4):319-333.

http://windren.se/WW2015/WW2015_12_311_Karthauser_ReTurn._Deicing_Micro.pdf

Johansson, K. et al., 2015. Deicing of Wind Turbines using Microwave Technology.

Landy, N. I., Sajuyigbe, S., Mock, J. J., Smith, D. R. and Padilla, W. J., 2008. Perfect Metamaterial Absorber. Physics Review Letter, 100(207402).

Mu, S., Wu, R., Chen, C., Yan, S. Y., 2014. RESEARCH ON THE THERMAL HEATING DE-ICING PROPERTIES OF WIND TURBINE BLADE COMPOSITE PLATES BASED ON POLYMER ELECTRIC HEATING FILM. Fiber Reinforced Plastics/Composites (FRP/CM).(in Chinese)

Pang, Y., 2013. The Theory and Design of Metamaterial Absorbers. Changsha: National University of Defense Technology.

Parent, O., Ilinca, A., 2011. Anti-icing and de-icing techniques for wind turbines: Critical review. Cold Regions Science and Technology 65 88–96.

Pitchai, K., 2011a. Electromagnetic and Heat Transfer Modeling of Microwave Heating in Domestic Ovens. University of Nebraska at Lincoln. P30.

Pitchai, K., 2011b. Electromagnetic and Heat Transfer Modeling of Microwave Heating in Domestic Ovens. University of Nebraska at Lincoln. P13.

Seifert, H., Westerhellweg, A., Kröning, J., 2003. Risk Analysis of Ice Throw from Wind Turbines[J]. Boreas.

Shu, L., Qi, J., Hu, Q. et al., 2017. Anti-icing Model and Sectionalized Anti-icing Method by Electrical Heating for Wind Turbine Blades[J]. Proceedings of the Csee, 37(5):1448-1454.(in Chinese)

Technical Research Centre of Finland (VTT), 2013. Cold climate wind energy showing huge potential. ScienceDaily. ScienceDaily.

Xu, B., Lu F., Song, G., 2018. Experimental Study on Anti-Icing and Deicing for Model Wind Turbine Blades with Continuous Carbon Fiber Sheets[J]. Journal of Cold Regions Engineering, 32(1).

Zhao, J., Yang, W., Peng, C. et al., 2016. ANTI-ICING AND DEICING METHOD AND DEVICE FOR HIGH-POWER WIND TURBINE BLADES, WO/2016/037476[P].