Design of patterned fluorine-doped tin oxide for radome de-icing heater

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Abstract

We suggested microwave transparent heaters by using a patterned fluorine-doped tin oxide (FTO). The pattern is a continuous waveform, and the DC voltage is applied for Joule heating. While the pattern of conductive materials is mostly associated with electromagnetic behavior, this study extends its potential application to thermodynamics. Especially for radome applications, the microwave transparent heater is able to remove the ice accretion on the radome surface in order to prevent not only aerodynamic instability, but also communicative failure. The characteristics of the RF transmission and saturation temperature, which are the key parameters of FTO as a conductive material, were investigated by using numerical simulation and an experiment. A reasonable agreement between the measurements and the numerical simulations was achieved. This multi-functional waveform-patterned FTO has both X-band transparency and Joule heating performance so that it can be a cornerstone for electromagnetic and thermal applications.

Keywords: transmission, X-band, Joule heating, microwave application

1. Introduction

Radome, which is a dielectric enclosure, has been widely used to protect the antenna from the external environment. The traditional materials for radome are ceramics and glass-fiber composites, among others, which satisfy both the structural stiffness and radio frequency (RF) transmission [1]. Radomes have been used for ground vehicles, ships, or aircraft, but in recent years, they have also become an important component of unmanned aerial vehicles (UAVs) [2–5]. According to military missions, the UAVs can be exposed to a freezing atmosphere. As a result, ice can easily build up on the UAV surface under such circumstances. It has been reported that ice accretion-driven problems associated with the structural load can significantly degrade the flight performance, which can particularly threaten RF communication [6–13]. Therefore, it is our goal to remove the accumulated ice with stable antenna operation as well as minimal damage on the weight, structure, and appearance of UAVs.

Recently, many studies have achieved electromagnetic improvement by manipulating the design of conductive materials. For example, an inversely-designed metamaterial platform was designed to solve the general Fredholm integral equation [14]. A near-zero index dielectric waveguide to overcome mode degeneration, attenuation/losses, and energy dispersion was also modeled [15]. For the assembly of Au nanorods along the edges of an equilateral triangle, the collective surface plasmon resonances of individual assemblies were also characterized [16]. An analytical approach to characterize electromagnetic waves on a curvilinear metasurface structures has also been presented [17]. To overcome the trade-off between the field confinement and coupling efficiency in a graphene acoustic plasmon resonator, an efficient plasmon conversion process was also harnessed [18]. A method that not only improves the electromagnetic properties, but also
the thermal properties of Ag nanoparticles, has also been presented [19].

As representative of the previous applications, similar studies have been conducted to enhance the RF transparency and thermal properties by using graphene nanoribbons (GNR) or carbon nanotube (CNT) [20–22]. These electro-thermal de-icing heaters are able to remove the ice on the radome’s surface, but it requires a very high voltage (>150 V) to compensate for a low conductivity of RF transmission. However, in certain cases for UAVs, since the usable electric power is limited, the high-power heater is an obstacle that dramatically reduces the operation time of UAVs. In this study, we designed a multi-functional waveform-patterned FTO for de-icing and RF communication with a low electric power. The optimized geometric parameters were investigated in order to achieve an X-band transmission of over 80% and a saturation temperature above 75 °C at 40 V.

2. Simulation and experimental set-up

The waveform-patterned FTO, which includes the geometric repetition of a unit cell, manipulates certain macroscopic behaviors, and it can customize the electromagnetic properties of the designed material. The optimal parameters were investigated by varying the structural parameters such as width, radius, and electromagnetic properties of the FTO film. As a result, it was possible to achieve the targeted RF transmission of FTO film by adopting a proper design of geometric patterns.

The numerical simulation for the X-band transmission was performed by the frequency-domain solver and the unit-cell boundary of the CST Microwave Studio® (CST MWS). The CST MWS allowed us to perform the simulation in an x-y plane where the 2D conductive material modeling was aligned, and the z-coordinate was in an electromagnetic wave propagating direction, as shown in figure 1. The numerical simulation for Joule heating was achieved by the CST Multi-Physics Studio® (CST MPS). The CST MPS performed an electric circuit-thermal coupling co-simulation by using three-dimensional finite integration with open boundary conditions. The DC voltage was applied to the end of each electrode of the waveform-pattern FTO. The thermal loss generated from the applied DC voltage was transferred to the heat source for thermal simulation. From the transferred thermal loss, it was possible to simulate the temperature profile of the waveform-patterned FTO from a three-dimensional model. The widest conductive area as possible was needed to secure the heating area. However, the wide conductive area caused a decrease in the RF transmittance. The dimensions of the waveform-patterned FTO were optimized by using the trust region framework based on the MWS-MPS coupling simulation to obtain an 80% or more X-band transmission and the best heat distribution. By repeating the electromagnetic-thermal co-simulations with changes in the pattern dimensions, we derived an optimal waveform-pattern with the widest deposition area. We deposited the FTO by ultrasonic spray pyrolysis on the dielectric substrates (Corning, Eagle XG Slim Glass) [23, 24]. The dielectric constant was 5.20 and the loss tangent was 0.30% for the glass substrate with thickness of 0.50 mm. The sheet resistance of FTO was controlled by adjusting the spray time and was optimized at 6.38 Ωsq. Also, the sheet resistance was measured by a 4-point probe (AIT, CMT-SR200N). The waveform-pattern was fabricated by using a deposition mask for a thin film. The transmission spectra were measured by the free-space measurement (MM Technologies), which was connected to the microwave horn antenna that operated at 8.2–12.4 GHz, as shown in figure 1. The free-space measurement is an improved system for measuring the electromagnetic properties of materials by providing a contactless and nondestructive environment. The transmission according to the polarization from 0° to 90° was investigated for waveform and straight-patterned FTO. The straight-patterned FTO is for a contrast with a waveform-pattern by highlighting the high RF transmission of a waveform-patterned FTO. The Joule heating performance is represented by a saturation temperature when the DC voltage was applied. The sample size for heating was 50 × 60 mm with 5 mm electrodes.
attached at each end. The temperature profile was recorded by a K-type thermocouple (Yokogawa, MV2000) at the center of the waveform-patterned FTO, which was in a temperature and humidity chamber at −20 °C (ENEX Science, EN-STH-604). Moreover, an IR camera was used to visualize the thermal distribution of the sample (Topins, FLIR-AX5).

3. Results and discussion

Figure 2(a) shows the schematic and fabricated sample that has a size of 50 × 60 mm. Figure 2(b) shows the unit cell of the waveform-patterned FTO, which is characterized with the following dimensional parameters: width (w), radius (r), and amplitude (a) under the length (l), and height (h) of the unit cell. The optimal length of the unit cell (l) is to 16.56 mm, and the optimal height of the unit cell (h) is to 3.31 mm. The change in the size of the unit cell can cause a mismatch in resonant frequencies, which can induce multiple peaks. The optimal radius of the curve (r), as another representation of the distance between the lines, is 1.23 mm. The optimal width (w) is 0.80 mm. The optimal amplitude (a), i.e. a half length of the waveform-pattern in the x-direction, is 2.20 mm. The optimal sheet resistance of the waveform-patterned FTO is 6.38 Ω sq⁻¹.

We numerically measured the transmission spectra of the waveform-patterned and straight-patterned FTO according to the polarization from 0° to 90° with a 15° step at the X-band, as shown in figures 3(a) and (b), respectively. An experimentally measured transmission of the waveform-patterned FTO at a polarization of 90° was provided to validate the simulation and emphasize the lowest transmission of the waveform-patterned FTO, as shown in figure 3(a), red circle line. The corresponding lowest transmission was 81.15% at 12.0 GHz with a polarization of 90°. The maximum error between the experiment and simulation was 2.55% at 8.2 GHz. Therefore, we can say the simulation and experimental transmission were in good agreement. The slight error came from the imperfect fabrication.

To understand the transmission mechanism, we should investigate the transmission coefficient, i.e. a ratio of substance that permits the passage of energy. The transmission coefficient \( 1 + \Gamma \) is defined as

\[
1 + \Gamma = \frac{E_t}{E_i} = \frac{2Z_1}{Z_0 + Z_1},
\]

where \( E_t \) and \( E_i \) are the transmitting and incident electric fields, respectively, \( Z_0 \) and \( Z_1 \) are the free-space impedance and intrinsic wave impedance of the conductive medium.
Figure 3. (a) Simulated transmission spectra according to the polarization from 0° to 90° and experimentally measured transmission with a polarization of 90° of the waveform-patterned FTO. The lowest transmission was 81.15% at 12.0 GHz with a polarization of 90°. (b) Simulated transmission spectra of straight-patterned FTO with a polarization from 0° and 90°. The lowest transmission was 63.65% at 8.2 GHz with a polarization of 0°. (c) Simulated surface current of the waveform-patterned and straight-patterned FTO at 8.2, 10.3, and 12.4 GHz. It is clear that the curved shape of the waveform pattern mitigates the high surface current of the straight pattern.

The intrinsic wave impedance of conductive medium is presented by

\[ Z_1 = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}}, \]

where \( \sigma \) is the electrical conductivity of the medium, \( \omega \) is the angular frequency of the wave, and \( \varepsilon \) and \( \mu \) are the permittivity and permeability of the medium, respectively [25]. Note that both the material properties and geometric pattern of the FTO film are related to the intrinsic wave impedance. Since the curved shape of the waveform pattern attenuates the intensity of the induced current, it is able to apply the conductive materials with a high electrical conductivity. Figure 3(b) shows the simulated transmission spectra of the straight-patterned FTO with a polarization ranging from 0° to 90°. The transmission of the straight-patterned FTO was simulated in order to prove the effectiveness of the waveform pattern. It was found that the deposition area of the straight pattern was identical to that of the waveform pattern. The width \( w \) of the straight pattern was 2.20 mm, and the length \( l \) and height \( h \) of the straight pattern were identical to that of the waveform pattern. The lowest transmission of the straight pattern was 63.65% at 8.2 GHz. Even though the deposition area of the waveform pattern was identical to that of the straight pattern, the waveform pattern was able to have superior transmission since the curved shape of the waveform pattern mitigated the electromagnetic wave interference from the surface current, as shown in figure 3(c).

Figure 4(a) shows the temperature profile at the center of the waveform-patterned FTO when a specific voltage was applied at −20 °C. The sphere-shape line presents the experimental data and the dashed line presents the simulation data, respectively. When the voltage was applied, the temperature was rapidly saturated. The experimental saturation temperature of the waveform-patterned FTO was −8.3 °C, 14.2 °C, 43.6 °C, and 75.9 °C at 10, 20, 30, and 40 V, respectively. The simulated saturation temperature was −13.6 °C, 5.6 °C, 37.7 °C, and 82.5 °C at 10, 20, 30, and 40 V, respectively. The maximum error 8.6 °C at 20 V came from the imperfect fabrication of the waveform pattern, nonuniform sheet resistance of the FTO film, and an inconsistent convective heat transfer coefficient. The response time, which was defined as the time it takes to reach 90% of the saturation temperature, was consistent with 84–133 seconds, regardless of the applied voltage [26]. At a steady state, the simulated and measured saturation temperatures of the waveform-patterned FTO are presented in figure 4(b). Figures 4(c) and (d) show the thermal images of the experimental and simulated steady states when 40 V was applied. By applying the power, it generated an electric potential, which led the electrons to accelerate in the conductive materials. These accelerated electrons constituted the
Figure 4. (a) Temperature profile at the center of the waveform-patterned FTO when a specific voltage was applied at $-20^\circ$C. The dashed lines represent the simulation and the solid lines represent the experimental temperature profile, respectively. (b) The simulated and measured saturation temperatures of the waveform-patterned FTO. Thermal images of the waveform-patterned FTO are shown as indicating when 40 V is applied (c) by IR camera and (d) by thermal simulation.

Figure 5. (a) Simplified thermal resistance circuit for the waveform-patterned FTO. (b) Simulated saturation temperature of the waveform-patterned FTO at position $x$.

During the quasi-equilibrium state, while Joule heat was generated in the conductive materials, the heat was transferred from the conductive materials to air and a dielectric substrate by thermal convection and conduction, respectively. In this way, a previous study reported on a multi-functional model that describes the electromagnetic and thermal behavior of a nanoscale circuit element [27]. Since it analyzes the general way to describe electric and thermal properties, by developing this nanoscale element to macroscale devices, we can characterize the temperature distribution of waveform-patterned FTO. Figure 5(a) shows the saturation temperature ($T$) of the waveform-patterned FTO at the thermal equilibrium. It is expressed by

$$
\begin{bmatrix}
R_{\text{conv}} & R_{\text{cond}} & R_{\text{cond}} \\
R_{\text{conv}} & 2R_{\text{cond}} & 1 \\
R_{\text{conv}} & R_{\text{cond}} & R_{\text{cond}}
\end{bmatrix}
\begin{bmatrix}
T - T_a \\
T - T_m \\
T - T_e
\end{bmatrix}
= \frac{Q_g}{3}
\begin{bmatrix}
1 \\
1 \\
1
\end{bmatrix},
$$

where $R_{\text{conv}}$ is the thermal resistance by convection, $R_{\text{cond}}$ is the thermal resistance by conduction, $T$ is the saturation temperature at the waveform pattern, $R_{\text{conv}}$ is the ambient temperature, $R_{\text{cond}}$ is the saturation temperature at the point between the waveform pattern, $R_{\text{conv}}$ is the temperature of the end contact, and $R_{\text{conv}}$ is the heat generated from the DC voltage. The thermal resistance is expressed as

$$
R_{\text{conv}} = \frac{hA_{\text{surface}}}{T},
$$

and

$$
R_{\text{cond}} = \frac{kA_{\text{section}}}{l},
$$
where $h$ is the convective heat transfer coefficient, $R_{\text{conv}}$ is the surface area, $k$ is the thermal conductivity, $A_{\text{section}}$ is the cross-section area, and $l$ is the length between each node [28]. Solving this matrix by the finite element method, the simulated saturation temperature of the waveform-patterned FTO in the x-directional position as shown in figure 5(b) was obtained. In the thermal simulation, the convective heat transfer coefficient of 13.9 W m$^{-2}$ K was determined empirically. The thermal conductivity of the FTO film was 10.0 W m$^{-1}$ K and the specific heat was 2.32 MJ m$^{-3}$ K. The density of the FTO film was approximated to the density of SnO$_2$, which was 6.99 g cm$^{-3}$ [29]. As shown in figure 5(b), the temperature distribution was perfectly symmetric in the y-axis. The temperature uniformity, which is defined as [30]

$$T_{\text{uniformity}} = \frac{T_{\text{max}} - T_{\text{min}}}{2T_{\text{ave}}} \times 100\%,$$

where $T_{\text{uniformity}}$ (%) is the temperature uniformity and $T_{\text{max}}$ and $T_{\text{min}}$ are the highest and lowest temperatures, respectively.

Table 1 shows the temperature of the waveform-patterned FTO as the voltage changes. While a higher voltage causes a higher maximum temperature, the temperature's uniformity deteriorated due to the high heat flux intensity in a narrow waveform pattern.

4. Conclusions

In this paper, we designed the waveform-patterned FTO and evaluated the properties for the microwave transparent heater. Based on the retrieval procedures, the waveform-patterned FTO was able to have an X-band transmission of 81.15%. At the same time, the saturation temperature of the waveform-patterned FTO reached 75.9 $^\circ$C when 40 V was applied, which was a relatively low voltage compared with previous studies. To overcome the trade-off relationship between the microwave transparency and Joule heating performance, the multifunctional waveform pattern was designed, and it gave an opportunity to satisfy both the X-band transparency and heating performance. In addition to the radome, in the future, the waveform-patterned FTO can be applied to various miniature remote control machinery to maintain the stable communication with a low power supply. For practical application, temperature uniformity when a high voltage is applied should be improved through future studies.

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Table 1. Maximum, minimum, and average temperature and temperature uniformity as the applied voltage changes.

| Voltage | $T_{\text{max}}$ (K) | $T_{\text{min}}$ (K) | $T_{\text{ave}}$ (K) | $T_{\text{uniformity}}$ (%) |
|---------|----------------|----------------|----------------|----------------|
| 10 V    | 259.4          | 255.5          | 257.0          | 0.8%           |
| 20 V    | 278.5          | 262.9          | 269.1          | 2.9%           |
| 30 V    | 310.4          | 275.2          | 289.1          | 6.1%           |
| 40 V    | 355.2          | 292.6          | 317.3          | 9.9%           |
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