Feasibility of Using an Absorptive Cover for Ice, Snow or Water Removal from Radome Surface

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Abstract— **The feasibility of using a thin layer of absorptive and/or conductive dielectric cover for the ice, snow or water removal from the radome outer surface was investigated. Constrains on the design parameters and usability of such de-icing system were derived. The new de-icing approach that employs the effect of total internal reflection of radome outer skin is introduced.**

I. INTRODUCTION

To prevent or remove the ice, snow or water build-up from the radome surface (referred further as a de-icing) a chemical, mechanical, and thermal de-icing approaches were introduced at the early stage of radomes development [1]. This paper investigates the feasibility of the particular type of thermal de-icing approach when the radome outer surface is covered by a heating layer of absorptive and/or conductive dielectric. The similar method that uses the heating wire mesh embedded into the radome outer skin was used for the reference.

The infrared [2] and hot air blowing [3] de-icing approaches were not considered because those methods are suitable only for the metal space frame or thin solid laminate radomes whose wall has no thermo insulating core. For sandwich radomes with a low density core that works as a thermo insulator those approaches can be used only if the infrared radiators or hot air blowers are installed outside of the radome, which is impractical for most radome applications.

II. EVALUATION OF SURFACE POWER DENSITY REQUIRED FOR RADOME DE-ICING

Extensive experimentation with various environmental conditions [3] indicates that 0.16 – 0.48 W/cm^2 of heating power density applied to the radome surface can prevent up to 38 mm/hr ice build-up. The same power density evaluated from the ice melting latent heat is 0.34 W/cm^2, which results in the conservative estimate of the radome surface heating efficiency η = 70%. Thus, for melting the ice at 0°C i.e., just for the ice build-up prevention, the ice melting rate is:

$$r_{ice\ melt} = 12.7\,\frac{mW}{cm^2}\Big/\frac{mm}{hr} \tag{1}$$

To remove an existed ice build-up at a temperature below 0°C, the ice should be warmed before melting. Based on the same heating efficiency and the specific heat of ice, the ice warming rate can be evaluated:

$$r_{ice\ warm} = 0.078\,\frac{mW}{cm^2K}\Big/\frac{mm}{hr} \tag{2}$$

Similar considerations for the water warming and evaporation (if required) give:

$$r_{water\ warm} = 0.166\,\frac{mW}{cm^2K}\Big/\frac{mm}{hr} \tag{3}$$

$$r_{water\ evapo} = 90.1\,\frac{mW}{cm^2}\Big/\frac{mm}{hr} \tag{4}$$

The snow is a blend of an ice, air and water (if wet) thus, depending on snow density and wetness, its melting and warming rates should be less than those for an ice or water.

From (1) – (4) it can be concluded that (13 – 17) mW/cm^2 for the ice removal and an additional (90 – 107) mW/cm^2 for the water evaporation (if needed) should be applied to the radome surface per 1 mm/hr precipitation. So, from the overall power consumption standpoint (up to 1.3 kW/m^2 per 1 mm/hr precipitation) the thermal de-icing approach is feasible for the radome de-icing areas up to a few tens square meters.

III. RADOME DE-ICING USING HEATING WIRE MESH

As is well known from the car window de-icing experience, for the effective de-icing the distance between horizontal heating wires should be close to 3 cm. To propagate through such conductive mesh having just an optical blockage limit of the transmission loss, the antenna polarization should be either a) vertical (VP) or b) horizontal or circular (HP, CP) with the wavelength that is much lower than 3 cm.

This is illustrated in Figure 1 for the wire diameter 0.7 mm. The HP transmission loss, being unacceptably big at low frequencies, approaches the optical blockage limit when its wavelength becomes much less than the distance between wires. On the contrary, the VP transmission loss, being negligibly small at low frequencies, approaches that limit when its wavelength is a much smaller than the wire diameter.

If σ is the specific conductivity of the wire material (copper or aluminium), $h \approx 3$ cm is a distance between wires, and q_s is the surface power density that is needed for the proper radome de-icing (see Section II), then the power balance between powers emitted by wires and needed for the radome de-icing defines the product of the wire diameter d and the effective value of vector of electric strength E:

$$dE = \sqrt{4q_s h/\pi\sigma} \tag{5}$$

Because value of d is determined by an acceptable level of optical blockage, the value of vector E can be found from (5). This value of E is shown in Table I against the wire diameter and the corresponding optical blockage limit of the transmission loss for 1mm/hr precipitation. Since according to (1) – (5), the value of E is proportional to the square root of the precipitation level, values of E shown in Table I can be easily recomputed for any precipitation level of interest. The minimum value of E shown in each cell of Table I corresponds with an ice melting at 0°C, while the maximum value of E corresponds with melting of a cold ice at -50°C with subsequent water evaporation.

TABLE I
WIRE DIAMETER AND APPLIED VECTOR OF ELECTRIC STRENGTH NEEDED FOR PROPER DE-ICING USING HEATING WIRE MESH APPROACH

Optical Blockage Limit of Wire Mesh	**Vector of Electric Strength and Diameter of Heating Wires**	
Transmission Loss, dB	***d, mm***	***E, V/cm***
0.02	0.069	0.043 – 0.14
0.05	0.17	0.017 – 0.054
0.1	0.35	0.0086 – 0.027
0.2	0.70	0.0043 – 0.013

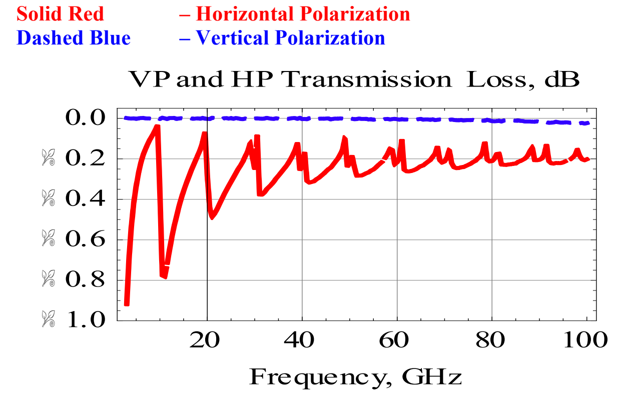

Fig. 1 VP and HP Transmission Loss Through Heating Wire Mesh with 3 cm Distance between Horizontal Wires at Normal Incidence.

As is seen from Table I even for the biggest value of E, the maximum distance between electrodes that apply voltage to the heating wires and therefore, the wire length might be up to a few meters, depending on maximum voltage allowable and the precipitation level. These few meters long wire mesh sections have no restriction in width and can be replicated many times to cover the entire radome surface. Thus, apart from the overall power consumption, the heating wire mesh de-icing approach has only one limitation concerning the HP and CP antennas: to have an acceptable level of transmission loss the antenna frequency must be significantly more than 10 GHz. Fine tuning of a heating mesh below the 10 – 20 GHz for the HP and CP radiations using minima of the transmission loss curve shown in Figure 1 is possible for rare cases of single, narrow band antennas that illuminate the radome surface with a very limited range of incident angles.

IV. RADOME DE-ICING USING DC/50/60 HZ CONDUCTIVITY CURRENT THROUGH ABSORBER LAYER

To overcome the limitations of the heating wire mesh de-icing approach, the use of a thin layer of conductive absorber that covers the radome outer surface was investigated. To introduce just a small transmission loss at the antenna frequency band, such cover should be highly absorptive either well below or far above of this band. At very low, DC/50/60 Hz frequencies it might be achieved through the conductivity of the absorber, while at high frequencies the polarization of the absorber cover should be employed.

A. Surface Power Density Generated by DC/50/60 Hz Conductivity Current Through Absorber

When the DC/50/60 Hz voltage is applied to a thin layer of the conductive absorber, the polarization portion of the transmission loss must be negligible. Otherwise, the absorber will not be transparent at the antenna frequency band, where the polarization losses are much greater than at the DC/50/60 Hz. Thus, the surface power density q_s generated within the absorber layer by the DC/50/60 Hz conductivity current is:

$$q_s = \sigma_a t_l E^2 \tag{6}$$

where, σ_a is the absorber conductivity, t_l is the thickness of the absorber layer, and E is an effective value of vector of electric strength.

B. Transmission Loss of Layer of Conductive Absorber

The analytical solution for the transmission coefficient S_{21} through the flat layer of a conductive dielectric is given in [1]. Although general expressions for the S_{21} are fairly complicated, for the absorber layer in vacuum (air) whose thickness is much less than the wavelength it can be reduced:

$$\begin{aligned} |S_{21TE}| &= 1/(1 + 0.5\sigma_a t_l Z_c/cos\theta) \\ |S_{21TM}| &= 1/(1 + 0.5\sigma_a t_l Z_c cos\theta) \end{aligned} \tag{7}$$

where, $Z_c = 120\pi\ \Omega$ is the characteristic impedance of vacuum (air), and θ is the angle of incidence. From the practical standpoint the desirable thickness of the absorber layer is better to be a tiny fraction of mm and thus, the expressions (7) are valid at least up to 40 GHz, depending on particular dielectric constant and thickness of the absorber layer.

C. Constrains on DC/50/60 Hz Conductivity Current De-Icing System Design and Absorber Material Parameters

According to (7), the absorber transmission loss defines the value of $\sigma_a t$. Then from (6), where q_s is defined in Section II, the effective value of the vector of electric strength E can be determined. An example of values $\sigma_a t$ and E that correspond with the transmission loss of an absorber layer in vacuum (air) at normal incidence is shown in Table II. In reality, such an absorber layer either covers the radome outer surface or might be an integral part of the latter (when the radome outer skin is intentionally made conductive, for instance). However, as it was investigated, this as well as a possible oblique incidence of the EM wave to the radome surface, makes no qualitative or even significant quantitative difference in values shown in Table II.

The absorber transmission loss is shown in Table II against the corresponding absorber material parameter $\sigma_a t$. Since the value of E depends on the precipitation level, the range of its values is shown in Table II for 1mm/hr precipitation. Based on (6) and (1) – (4), values of E can be easily recomputed for any precipitation level of interest. The smallest value of E in each cell of Table II corresponds with the ice melting at 0°C. The biggest value of E corresponds with melting of a cold ice at -50°C with subsequent water evaporation.

TABLE III
ABSORBER MATERIAL PARAMETERS AND VECTOR OF ELECTRIC STRENGTH FOR RADOME DE-ICING USING DC/50/60 HZ CONDUCTIVITY CURRENT

Acceptable Level of Absorber Transmission Loss, dB	**Vector of Electric Strength and Absorber Material Parameters**	
	$\sigma_a t_l$, 10^{-6} $1/\Omega$	**E, V/cm**
0.02	12.2	32.6 – 99.1
0.05	30.6	20.6 – 62.6
0.1	61.4	14.5 – 44.2
0.2	123.6	10.3 – 31.2

D. Feasibility of Radome De-Icing Using DC/50/60 Hz Conductivity Current Through Thin Absorber Cover

As is seen from Table II, for the 0.025 – 0.25 mm paint or spray like absorber (preferable from the cost standpoint), the range of absorber conductivity is (0.05 – 5) Si/m depending on thickness of the absorber layer and the acceptable level of the transmission loss. These values of absorber conductivity do not look unachievable [4].

However, as is also seen from Table II, even the smallest magnitude of vector E is equal to 10 V/cm, though it corresponds with noticeable transmission loss through the absorber layer, minimal thermal de-icing requirements and just 1 mm/hr of precipitations. This means that the maximum distance between electrodes that apply voltage onto absorber layer should be no more than 1 – 10 cm depending on voltage allowable and precipitation level. Thus, for the proper de-icing the radome surface must be covered by 1 – 10 cm wide strips of absorber powered by two parallel conductive electrodes attached to each side of those absorber strips.

Because unlike the heating wire mesh case, the heat released by the absorber layer spreads uniformly across the radome surface, the orientation of the absorber strips does not affect its de-icing capability. Thus, by proper orientation of the absorber strips, the DC/50/60 Hz conductivity current de-icing approach can be used at any frequency for linearly polarized radiation (VP, HP or slant). That gives this de-icing approach an edge over the heating wire mesh one since the latter can be used at any frequency only for the VP radiation. With respect to CP radiation both of these approaches are the same (the frequency has to be significantly more than 10 GHz and the length of heating wires or the absorber strips can be up to few meters).

V. RADOME DE-ICING USING HIGH FREQUENCY POLARIZATION CURRENT THROUGH ABSORBER LAYER

For further enhancing the applicability of thermal de-icing approach, the use of a high frequency polarization current was investigated. In that case the absorber conductivity should be minimized to avoid an additional unwanted transmission loss at the radome frequency band of operation.

A. Polarization Current Induced by Quasi-Stationary Electric Fields Between Two Parallel Electrodes

The surface power density released by the polarization current flowing through the non-conductive dielectric absorber layer can be calculated as follows:

$$q_s = Re\left[(\varepsilon - 1)\varepsilon_0 \frac{\partial E}{\partial t} E\right] = 2\pi f t_l \varepsilon_r \varepsilon_0 E^2 tan\delta \qquad (8)$$

where, f is the frequency of applied electric fields, ε_r is the real part of dielectric constant and $tan\delta$ is the loss tangent of the absorber. The quasi-stationary electric fields between two parallel thin conductive strip or wire electrodes embedded into the absorber layer can be approximately evaluated as:

$$E = \frac{V}{2\,ln[h/r_w - 1]}\left(\frac{1}{r} + \frac{1}{h-r}\right) \qquad (9)$$

where, h is the distance between electrodes, r_w is the radius of electrode wire (or the radius of the curvature of a strip edge), V is the voltage applied between electrodes and r is a distance from either one of two electrodes.

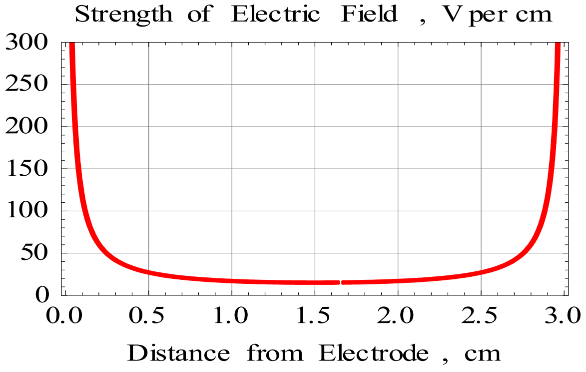

Fig. 2 Case of Two, 0.7 mm Diameter Electrodes Embedded into Typical Radome Outer Skin at 3 cm Distance Apart. For Proper De-Icing Frequency of Applied Voltage Should Be At Least 2.2 GHz.

Based on (8) and (9) it was found that for any realistic values of radius of electrode wire (or strip edge) and absorber material parameters, the electric fields and therefore, the heat emission are highly concentrated in close proximity to the electrodes (see Figure 2). Thus, from a surface heating prospective the quasi-stationary polarization current de-icing approach has no advantages over the heating wire mesh one. Moreover, to produce the amount of power that is needed for proper de-icing, the frequency of applied voltage should be at least at hundreds of MHz range making the quasi-stationary polarization current de-icing approach uncompetitive with the heating wire mesh one from the cost standpoint.

B. Polarization Current Induced by Propagating Fields

Unlike the quasi-stationary fields, the propagating fields in a media with a small dissipation factor could spread heat emission more evenly. If the radiating antenna (printed strip or wire dipole, for example) would be embedded into the radome outer skin whose dielectric constant is bigger than the dielectric constant of the surrounding media (air, foam, ice or snow), its radiating power will be partly captured within the skin due to the effect of total internal reflection.

For a typical radome skin with the dielectric constant close to 4.0 the critical angle is about 30º and thus, approximately from one to two thirds of the radiated power will be captured within the skin and moved around by the surface wave. If the skin outer surface is covered by an ice or water, the fraction of power carried by the surface wave would be closer to one third; otherwise it would be rather close to two thirds. For a typical radome skin the dissipation factor is relatively low ($tan\delta < 0.02$) and therefore, before its complete fading, the surface wave could travel many times around the radome surface (for spherical or cylindrical radomes) or create the standing wave within the skin (for flat radome panels with the reflective boundaries). That would result in almost uniform heat distribution across the radome outer surface. For big radomes several strip or wire type of dipole antennas (or linear arrays of antennas, depending on the radome size) should be embedded into radome outer skin at certain distance to insure the proper radome de-icing.

To quantify this idea let's estimate the area of the radome surface that can be adequately heated by just one radiating dipole. According the classic theory of dipole antennas [5], the maximum power radiated by a thin half-wave dipole is proportional to the square of applied voltage and for 100 V to be applied the power radiated by one dipole is close to 150 W. Being conservative let assume that just one third i.e., 50 W would be carried by the surface wave and eventually absorbed by the radome outer skin. Then, the power balance between the absorbed power and the power needed for the radome de-icing gives the following relation between frequency f of the applied voltage and distance h between the dipoles (or linear arrays of dipoles):

$$h[cm] = (25 - 250)\, f[GHz]/r_p\, [mm\ /\ hr] \qquad (10)$$

where, r_p is the precipitation rate and range of h corresponds with the range of surface power density needed for the radome de-icing under different de-icing scenarios (see Section II).

As is seen from (10) for the de-icing approach that is based on the polarization current induced by the radiating fields at 1 GHz the distance between the conductive strips or wires that constitute the dipoles and its feeder lines is higher by at least one order of magnitude than for the heating wire mesh or DC/50/60 Hz conductivity current approaches. Because the heat released by the absorber layer spreads almost uniformly across the radome surface, the orientation of the radiating elements does not affect its de-icing capability. Thus, the de-icing approach that uses the polarization current induced by the radiating fields has no frequency limitation for linearly polarized antennas and for CP antennas it can work above 1 GHz range depending on the particular de-icing scenario (Section II). That gives this de-icing approach an edge over both the heating wire mesh and the DC/50/60 Hz conductivity current approaches.

VI. CONCLUSIONS

1. The feasibility of a particular thermal ice, snow and/or water removal approach when the radome outer surface covered by thin absorptive and/or conductive dielectric heated by either low or high frequency current was investigated.

2. From the overall power consumption standpoint any thermal de-icing approaches required up to 1.3 kW/m^2 per 1 mm/hr precipitation and thus, are feasible for radomes with the de-icing area up to a few tens square meters.

3. The well-known heating wire mesh de-icing approach can be used for the VP radiation at any frequencies and for the HP and CP radiations only at frequencies that are much higher than 10 GHz. The distance between heating wires should be about 3 cm with the wire length up to few meters, depending on voltage allowable and precipitation level.

4. The de-icing approach that uses the polarization current induced by the quasi-stationary fields is uncompetitive with the heating wire mesh approach.

5. The DC/50/60 Hz conductivity current de-icing approach can be used for linearly polarized radiation (VP, HP or slant) at any frequency. This gives it an edge over the heating wire mesh de-icing approach. With respect to the CP radiation, the DC/50/60 Hz conductivity current and the heating wire mesh de-icing approaches are the same.

6. The new radome thermal de-icing approach is introduced. It uses the strip or wire type radiating antennas embedded into radome outer skin and employs the effect of total internal reflection. Although the most expensive, this approach can be used for linearly polarized radiation (VP, HP or slant) at any frequency and, depending on particular de-icing scenario, above 1 GHz for the CP radiation. That gives it an edge over both the heating wire mesh and the DC/50/60 Hz conductivity current de-icing approaches.

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